1 The Founding of Modern Science

Intended Learning Outcomes for Lecture 01
You should be able to do the following after this lecture.

(1) *Describe* what is science and explain the scientific method "in a nutshell", illustrating your explanation with a straightforward example.
(2) *Describe* the roles scientific observations play in the scientific method.
(3) *Explain* what are the main concerns that should be addressed when making scientific observations.
(4) *Explain* why anomalous phenomena are important for science, illustrating your explanation with some examples from the scientific revolution.
(5) In the context of the scientific revolution, *discuss* the difference between an evidence-based understanding of the natural world versus one based on authority.
(6) *Discuss* the steam engine's contribution to the Industrial Revolution and its impact on population growth in industrialized nations.

1.1 What is Science?

Hi all, welcome to the first video in this series. This lecture, which is made up of several videos, is about what science is and is a cut-down bare-bones explanation of the scientific method "in a nutshell" – which we will see illustrated with a few examples. We will take a closer look at the first step in the scientific method (again illustrated with an example) and then briefly review the founding of modern science and what one could say was a direct consequence of that – the Industrial Revolution, and it's here we'll see the beginning of mankind's dependence on fossil fuels.

I hope you have had a look through the intended learning outcomes for this lecture. They are listed right before this video, so let's get straight into addressing our first learning outcome, which is to answer the question:

"What is science actually?"

I bet most people think of science in terms of "subjects", like Chemistry, Physics, Biology, Medicine, and Pharmacy, just to name a few. But is this actually science? Knowledge in textbooks? Where did this knowledge come from anyway? Most people would say that the facts, ideas, and concepts in science textbooks is true to the best of our knowledge, but how do we know it's true? In fact, just how do we know what we currently know, at all? By answering these questions, we get closer to figuring out what science is.

1.1.1 What is Science and the Scientific Method in a Nutshell

At this point, we'll take a look at what science is from our course textbook *A Beginner's Guide to Scientific Method*. Right here in Chapter 1, page 5, we read:

> *"Science is that activity which aims to further our understanding of why things happen as they do in the natural world. It accomplishes this goal by applications of the scientific method."*

So, what exactly is the scientific method?

Our textbook goes on to explain, *"…it is the process of observing nature, isolating a facet that is not well understood, and then proposing and testing possible explanations."* **Observe. Explain. Test the explanation.**

The facts, ideas, and concepts we find in textbooks have all been put through this process. The knowledge in textbooks is really only one part of science – it's essentially the explanation part with some observations usually thrown in here and there. Rarely do we read about the rigorous testing the explanations went through. Nor do we hear much about those wrong explanations given earlier, and how testing, or experimentation, was used to eliminate them and home in on what now lies within science textbooks.

1.1.2 Science is Self-Correcting

You see, science is self-correcting.

The vast majority of the knowledge found in today's textbooks was all hard won, with multiple wrong explanations being proposed and then discarded until arriving at the current version. This may yet be undone if some new test of that understanding reveals it's lacking in some way.

This testing and refinement of our knowledge and understanding is the nature of Scientific Inquiry, the main topic of this course. The best way to understand scientific inquiry is through examples and application. The topic we've chosen to look at to gain an understanding of scientific inquiry is perhaps the single most important problem facing our species today – that is, climate change and loss of biodiversity. It is science that offers us our best chance at figuring out how we can get out of this mess – and what all of us need to do to get there.

OK, before we get into this serious problem, we need to get a good understanding of this "**observe, explain, test**" approach to knowledge discovery.

Did you know that any time you troubleshoot something you're actually applying the scientific method? For example, let's take a look at troubleshooting a laptop that doesn't bootup in our next video.

1.2 A PC Won't Work

1.2.1 Troubleshooting a Laptop

We find that our laptop doesn't boot, so we troubleshoot it, which is an example of a straightforward application of the scientific method.

Observation	Laptop doesn't boot
Explanation	Battery dead
Test the explanation	Plug in external power
Result of test	Laptop seems to boot, so the battery must have been dead

But now there's a new problem.

Re-running through our "observe, explain, test" steps again we find:

Observation	Laptop seems to boot, but there's nothing on the screen
Explanation	Laptop monitor not working
Test the explanation	Try connecting the external monitor with HDMI cable 1
Result of test	Laptop seems to boot, but there's nothing on the screen. (a) Either the graphics card or motherboard has issues, or (b) Something was wrong with our test.

Perhaps there is something wrong with our test. The external monitor clearly worked because we used the external monitor before conducting this test, albeit with a different cable, and it worked! We change our HDMI cable and retry the "Test the explanation" step below.

Observation	Laptop seems boot, but there's nothing on the screen
Explanation	Laptop monitor not working
Test the explanation	Try connecting the external monitor with HDMI cable 2
Result of test	Laptop definitely boots and the external monitor shows the start screen.

After performing a series of tests in the "real world", that is, by testing our explanations, we discover the following things we didn't know before performing any tests:

We had a dead battery.

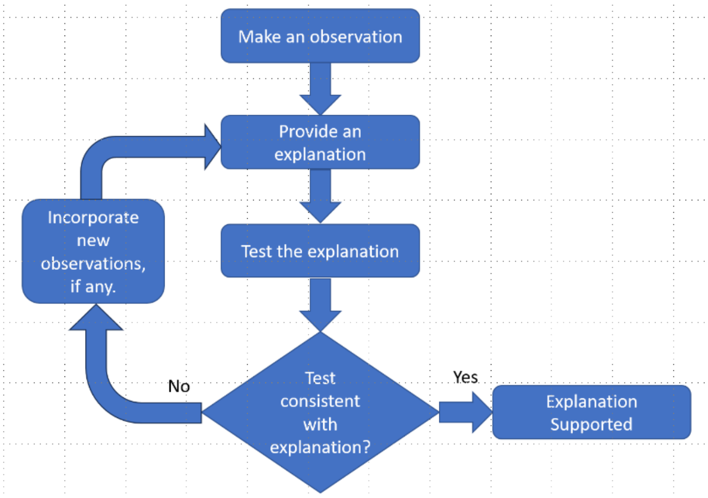
The graphics card and motherboard are working fine.

The laptop's monitor doesn't work.
A bad connection?
Screen broken?

We have a faulty HDMI cable.

1.2.2 Troubleshooting and the Scientific Method

Troubleshooting is an example of the scientific method. It is in a sense a trivial example of it – the scientific method is a lot more powerful than that. The scientific method can be used to probe and discover brand new things about nature. This, of course, relies on our explanations and then testing those explanations. If our explanation ends up not being falsified, then we have support for our explanation and the more we test our explanation the more confidence we have that our explanation is, in fact, true.



This is how things are discovered using the scientific method, and this is the way we have discovered many things about the world today. All the content in science textbooks have been subjected to this procedure. This example illustrates how science is self-correcting, where our steps taken above can be summarized in the following flow chart.

We also note that every time we loop through this chart, regardless of whether the test is consistent with the explanation or not, we gain new information about the world around us.

1.3 Teabag Experiment

In the previous video, we saw that troubleshooting a laptop was an example of the scientific method. In fact, troubleshooting anything in general represents an application of the scientific method. You observe that there is clearly something wrong. You come up with possible explanations as to what might be the cause of the problem. Finally, you go through the process of checking if the thing you thought might be wrong is indeed the cause of the problem. If it isn't then you try something else, i.e., you toss aside your previous explanation of what the problem was and make a new explanation for the cause. You continue doing this until you can at least narrow down what's the cause of the problem.

Observe, explain, and test the explanation – the scientific method in a nutshell. The point is by running through this process you will discover things you didn't know before. Now I'll illustrate this again, but in the household environment. This time we'll use the scientific method to discover something new about nature, or at least something that might be new to you.

Observations	(1) Tea bag bloats and floats on top of the water when boiling water is poured directly on top of it. (2) Tea bag doesn't bloat and sinks in the water when boiling water is poured on the side and **not** directly onto it.
Explanation	Water poured on top of the tea bag fills the pores of the teabag itself, trapping any gas inside before it can escape. The hot water heats the trapped air, causing it to expand. The trapped air prevents the tea bag from being dunked.  *Pores of the tea bag can get sealed up with water and prevent air from escaping.*
Test the explanation	Quickly seal the tea bag in cold water, trapping the air, then pour boiling water near to but not directly onto it.
Result of test	Tea bag bloats and floats on top of the water supporting the explanation.

The test *supports* our explanation, rather than confirm it. If we really wanted to check whether this explanation is correct, we would need to do a lot more tests. Compared to troubleshooting the laptop in the previous section, the results of the test with the tea bag are a lot more tentative since we generally know more about the way a laptop works and our tests are more directly indicative of the explanation being correct (or not) than the tea bag. We don't know that much about what's going on exactly. We have this speculative explanation that water is somehow filling up pores, sealing that tea bag, and our test *is* supportive of this explanation. But ideally, we would find out a lot more about this phenomenon before we can say for sure that this explanation is correct.

There are lots of additional interesting questions we can now ask about this phenomenon of liquid water stretching across tiny gaps in the teabag and effectively sealing the air inside:

- If there really is water sealing the pores, then can we see it?
- How thick is the film of water sealing the pores of the teabag?
- How long does this film last?
- How strongly does the water seal in the air? i.e., what level of air pressure is needed to break the seal?
- How big do the pores need to be so that the water can't seal air inside them?
- Does adding other substances to the water change this behavior?
- What about other liquids? Do they behave in the same way?

In science, answering one question often leads to more questions, and an investigation can sometimes take wild and unanticipated twists and turns that lead to new knowledge and understanding of nature.

1.4 Cadaverous Poisoning

You may not have realized it, but in the previous video we were just starting to scratch the surface of two entire branches of science: "Interface Science" and "Colloidal Science" – extremely important areas within chemistry, food science, biology, and physics, etc. A good understanding of these areas is also of great importance to industry and for most of the products industry produces.

1.4.1 Semmelweis and Childbed Fever

I have one last example of a fairly straightforward application of the scientific method, taken from our textbook and drawn from the annals of science. Our example will be from the area of medicine and we're going to wind the clock back to 1846, to a time when science had yet to discover the "germ" – that is, those nasty little disease-causing organisms so small they are invisible to the naked eye.

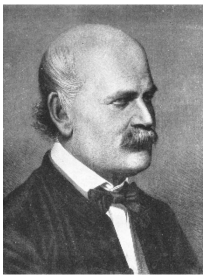


Figure 1 Semmelweis from Wikimedia: Jenő Doby, Public domain, via Wikimedia Commons

Dr. Ignaz Semmelweis (Figure 1) was hired on a three-year contract into the Vienna General Hospital's maternity clinic from 1846 – 1849. At the time "childbed fever", aka puerperal fever, was running rampant in hospitals all over Europe and the US. This disease affected mothers after they gave birth or had a miscarriage. Without going into details, it was a particularly nasty disease with a number of easily recognizable signs and symptoms.

It usually occurred after the first 24 hours and within the first ten days following delivery. The fever was deadly, killing up to 80% of those diagnosed and sometimes reached as high as 40% of all mothers admitted to the hospital. As with all physicians, Dr. Semmelweis was particularly concerned, so he studied the data on mortality rates within his hospital dating from 1841 – 1846 looking for something, anything, that might give a clue on how to stop the fever.

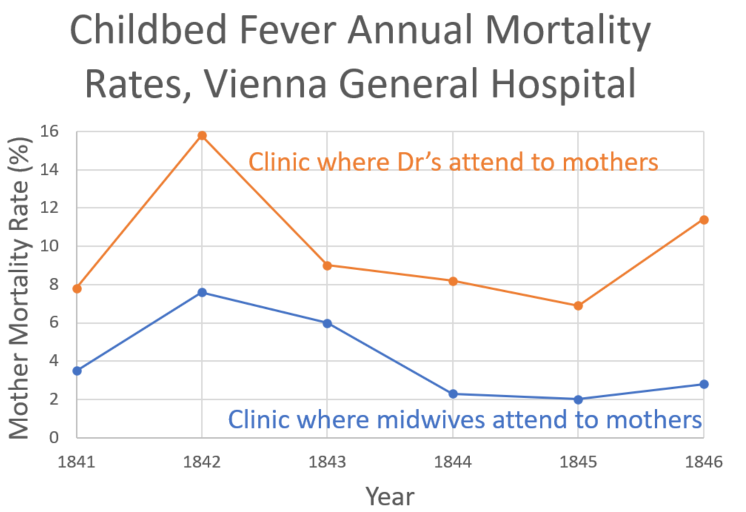


Figure 2 Mortality rates in two clinics in the Vienna General Hospital from 1841 - 1846.

He noticed something when comparing the mortality rates between two different clinics in his hospital (Figure 2). Now there was no obvious difference between the two sets of mothers in each clinic, so why were a lot more women dying in his clinic where doctors attended to mothers (orange curve in Figure 2)?

He showed the findings to his colleagues, but everyone was at a loss as to why this should be so. Was it something the doctors were doing wrong? or perhaps something the midwives were doing right? Maybe it was due to a difference in the clinical environments? Perhaps the patients in his clinic were somehow more prone to illness?

At this time, in the middle of the 19th century, the "germ" or pathogen, was not known to be the cause of disease. Germs had not been observed, and any speculation of their possible existence was not taken seriously. The reining theories for how disease was spread, caused, and treated at the time were quite wrong.

1.4.2 A Key Observation

Figure 3 [Kolletschka from Wikimedia](): Unknown author, Public domain, via Wikimedia Commons

Then a rather unfortunate incident occurred in 1847 in an anatomical pathology lab. Dr Semmelweis' friend, who he greatly admired, died after being accidentally pricked by a scalpel being used by a student doctor while he was assisting in performing an autopsy. Professor Kolletschka (Figure 3) suffered identical signs and symptoms as the mothers who died of childbed fever. Dr Semmelweis wrote about the incident:

"Day and night I was haunted by the image of Kolletschka's disease and was forced to recognize, ever more decisively, that the disease from which Kolletschka died was identical to that from which so many maternity patients died."

There is another very pertinent fact, or observation, in this case. Right after the student doctors attended the anatomical pathology lab, where they dissected badly infected corpses, they would go to Dr Semmelweis' maternity clinic to assist in the births of expectant mothers.

Do remember that the way disease was spread, caused, and treated in those days was completely misunderstood. No one knew about germs, so there certainly were no antibiotics and there was no disinfecting of anything – no hand washing of one's hands especially when, by just looking at them, they were quite obviously clean.

So now we have our careful observations, or facts,

(1) The mortality rate of mothers due to childbed fever in a clinic attended by doctors was, on average, five times higher than what appears to be a similar clinic with similar mothers but attended by midwives instead of doctors.
(2) Doctors attend to mothers in the clinic directly after having been engaged in autopsies of infected corpses in the anatomical pathology lab.
(3) A doctor dies from identical signs and symptoms to childbed fever after having been stuck with a scalpel used to dissect infected corpses in the anatomical pathology lab.

1.4.3 A Possible Explanation

Following the scientific method: observation, explanation, testing, what could be a possible explanation for these observations? Semmelweis felt that the only sensible explanation must have something to do with the corpses. Something unseen. He called this something "cadaver matter", so he speculated that invisible cadaver matter was picked up by the student doctors touching corpses while working in the anatomical pathology lab. This matter wasn't visible to the naked eye, but it was deadly if it entered the body via a wound. When these same doctors assisted mothers while giving birth, they transferred it to them through the usual wounds suffered during such a process.

1.4.4 Testing the Explanation

At the moment, this explanation is pure speculation. It could certainly be wrong, with some other unknown explanation being the right one. Following the scientific method, he needed a means of testing this proposal to see if he was indeed wrong. If his explanation was right, and cadaver matter existed, he decided that, quite obviously, it needed to be removed from the student's hands before attending to the mothers in his maternity clinic.

Therefore, he instituted a policy of using a solution of chlorinated lime (calcium hypochlorite, or swimming pool chemical in water) for washing hands between autopsy work and the examination of patients. He chose this chemical because he found that the same solution worked best to remove the putrid smell of infected autopsy tissue.

Now if his explanation was correct and the chlorinated lime solution was effective, then the mortality rates of childbed fever should drop to the same levels as the midwife's clinic or lower. Despite some resistance to the hand washing, and whispers that he had instituted a waste-of-time hand washing for crazy reasons (like a theory that corpse particles could turn the living into a corpse!), the mortality rates in his clinic dropped remarkably, as shown in the following graph.

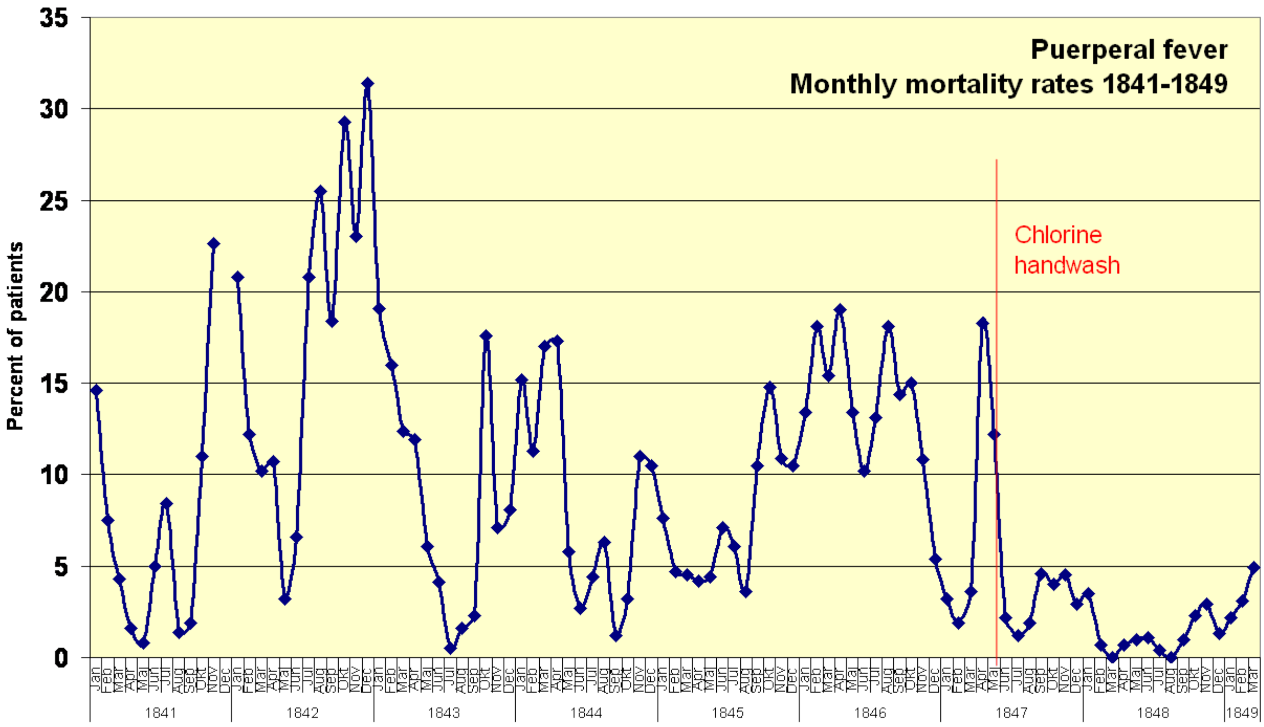


Figure 4 [Monthly Mortality Rates 1841-1849 from Wikimedia](): Power.corrupts, Public domain, via Wikimedia Commons

If you'd like to read more about Dr. Semmelweis and this interesting case, just follow the link in the box below.

https://en.wikipedia.org/wiki/Ignaz_Semmelweis

1.4.5 In Conclusion

To summarize, Dr. Semmelweis made observations and provided an explanation for those observations. Based on that explanation, he performed a test of it with the results supporting his explanation. Of course, there was no explanation of what was "cadaver matter". Furthermore, since his explanation ran against the generally accepted scientific theories of the time and it wasn't completely accepted until 30 years later when the cadaver matter was actually discovered by Louis Pasteur in 1879. A revolutionary new theory of disease was then established which remains as the prevailing explanation for diseases to date – germ theory.

1.5 Observation

Now that we have a handle on what science is and an overview of the scientific method, let's address our second intended learning outcome for this lecture, which focuses on the first step of the scientific method – "scientific observation". Observation is absolutely critical to conducting any kind of scientific inquiry. In fact, without any observations, or experiments – which are just observations themselves – the inquiry isn't even considered scientific!

Observation fulfills the following crucial roles in any scientific inquiry:

1. To identify and focus on the relevant facts about the phenomena under investigation.
2. Provide clues as to what might explain the phenomena – this one's really important if the phenomenon you're investigating is really mysterious.
3. Provide the evidence by which we can determine whether various explanations succeed or fail.

However, making useful observations can sometimes be tricky. For example, we might not know which data will be relevant to the solution to the problem at hand. Even if this is known, we can run into trouble just gathering the necessary data in the first place!

The second chapter of our textbook discusses everything we need to know about making useful observations. I suggest you read it in combination with this lecture. The chapter has several accessible real-life examples illustrating five main concerns that need to be addressed when making useful scientific observations. Pay close attention to the "Concept Quiz" on page 25 and try and answer the 9 questions asked there. In fact, I've given you a head start by answering the first question for you here.

To illustrate most of these five concerns, we'll use an important example from one of the greatest scientific minds that ever lived. This scientist was a pioneer of the scientific method and instrumental in ushering in a permanent change in the way in which knowledge and understanding of nature were acquired. The next video will show how the one and only Galileo Galilei figured out the law of inertia, which Newton later incorporated into his first law of motion.

It's important to note here that it's *not* the actual law of motion we are particularly concerned with – I won't be asking you to do any problems using it. What we're interested in in our next video is **how** Galileo worked it out from his observations of motion.

In particular, how he addressed the following concerns when making his observations:

1. Do we have a clear sense of what the relevant phenomena are?
2. Have we found a way to ensure we have not overlooked anything in the process of making our observations?
3. Do we know for sure what is based on fact and what on conjecture or assumption?
4. Have our observations been contaminated by expectation or beliefs?
5. "Have we considered any necessary comparative information?"

The 5th concern is – "Have we considered any necessary comparative information?" We have already seen a nice example of this through the observations made by Dr. Semmelweis. You should be able to recall what those comparative observations were and why they were critical to his investigation.

1.6 The Keen Eye of Galileo

When a whole bunch of different objects are spilled across the floor, we notice something. Some come to rest almost immediately, while others continue to move, then come to rest, and a few take quite some time before inevitably ceasing to moving. Observing such motion with an Aristotelian worldview simply reinforces the idea that all objects when given a push will come to rest because coming to rest is the nature of solid objects. This is because solid objects are of the Earth, and the Earth doesn't move, in the Aristotelian world view. In this worldview, pushing an object and making it move is against its nature, so it will come to rest as soon as the pushing stops. Because of this (wrong) idea, in order to have an object continue to move forever, it would need to be continually pushed forever.

The thing is, when Galileo observed this exact same thing he came to the exact opposite conclusion, and this was because of his objective, careful, and thoughtful observations of motion. In what follows we will discuss just what Galileo discovered and how he did it.

1.6.1 Galileo's Key Observation and Realization

Galileo was somehow able to ignore the reining Aristotelian worldview and look more closely at the behavior of objects slowing down and coming to rest. His keen eye and intellect were *not contaminated by expectation or belief* in the Aristotelian worldview. He realized that an object's nature being supposedly stationary was *pure conjecture, a belief, and not a fact*. This enabled him to notice something that *others completely overlooked*, and that was this: Depending on the type of contact that an object made with a surface it could move more, or less, further. Figure 5 illustrates the tiny contact made between a ping-pong ball and a hard, flat surface.

Figure 5 The tiny contact made between a ping-pong ball and a hard flat surface.

This contact had nothing to do with the nature of the object itself. In fact, it was the nature of the contact between the object and the surface that caused the object to slow down, not the nature of the object itself. The influence of the contact on the motion of the object was an extraneous effect - a separate effect, that hid the true nature of what was happening. By realizing that the slowing down was due to an extraneous effect that was interfering with something about nature that was more fundamental was sheer genius. In doing so, Galileo had gained a very clear sense of what the *relevant and irrelevant phenomena were*. He then set about designing and performing experiments that could reveal what this underlying fundamental truth was about the motion of objects in the world.

1.6.2 Galileo's Experiments with Inclined Planes

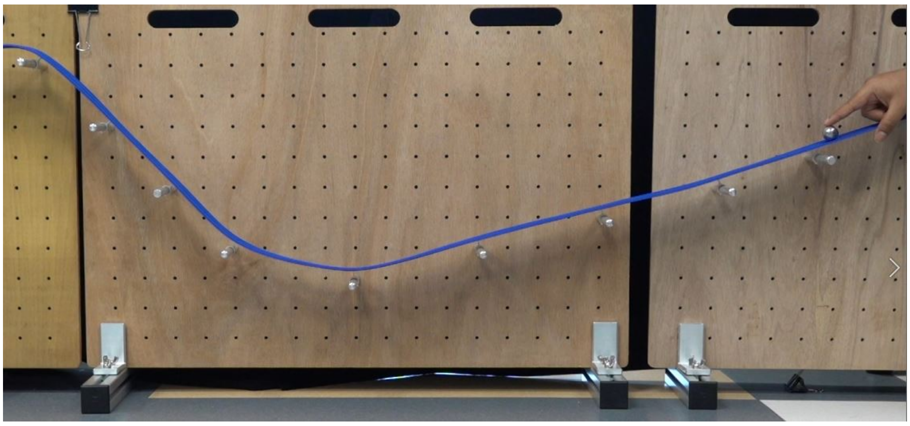


Figure 6 Experimental setup to study the motion of objects

Galileo set up some experiments not too unlike what is shown in Figure 6. We have a track that is inclined at the ends, and a ball. He released the ball a certain distance up one incline and watched carefully how far the ball rolled up the other incline before stopping and heading back down again.

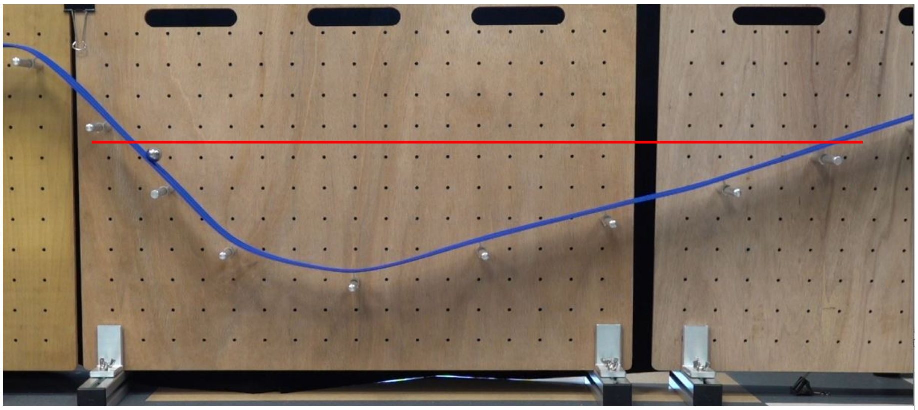


Figure 7 After releasing the ball show in Figure 6, the ball almost reaches the same height up the other incline

He found that as he reduced the influence of the contact between the ball and the track, that the ball could all but reach the same height up the other incline, and no further (Figure 7).

He found that this remained true as he reduced the angle of the incline the ball ran up on the other side.

But here's the really interesting thing. As shown in Figure 8, the lower he made the angle, the further the ball traveled before achieving virtually the same height on the other side of the track. The ball only lost height because of the extraneous effect due to the contact it was making with the track.

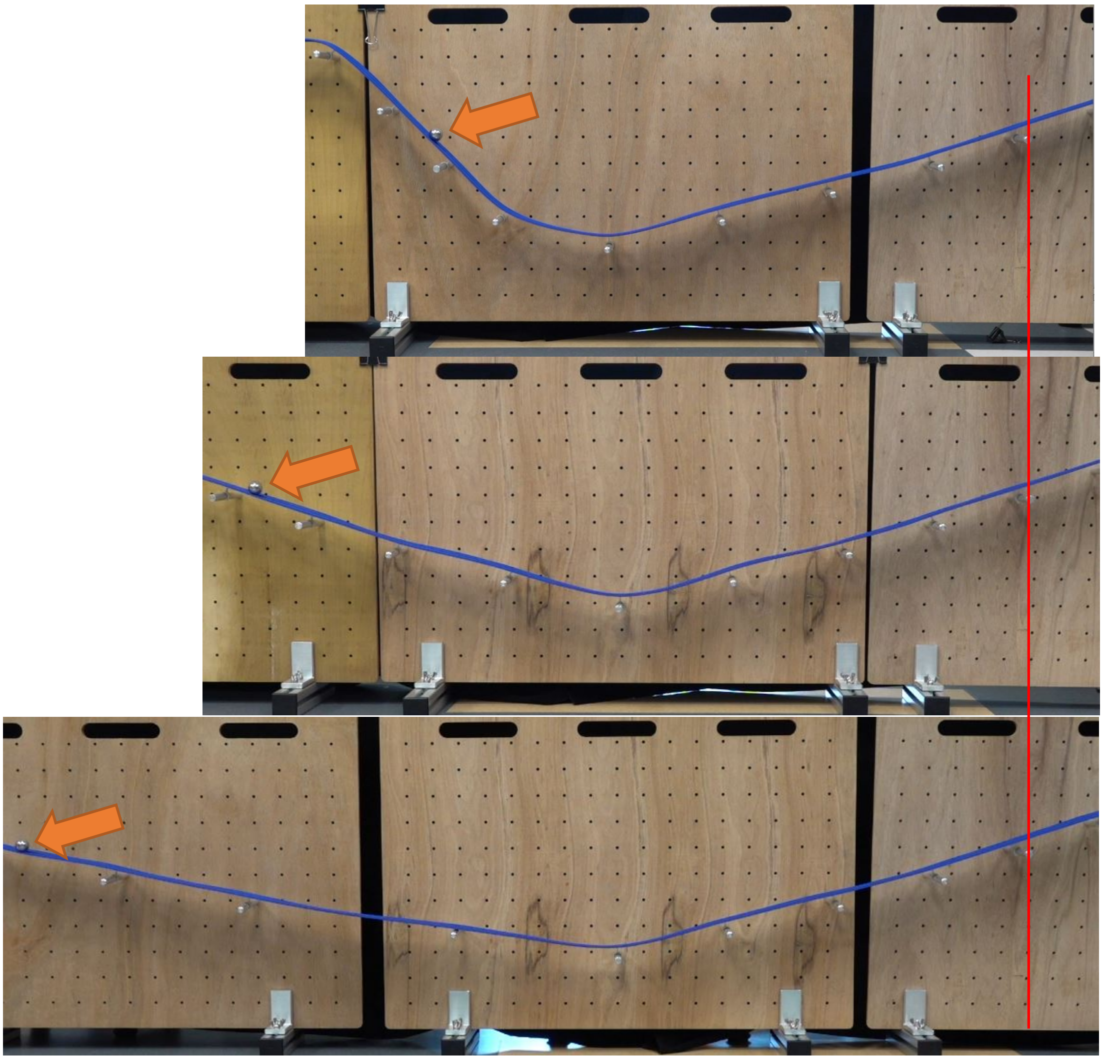


Figure 8 A ball released from the red line travels a greater and greater distance (indicated with an orange arrow) as the incline angle is reduced before turning back and heading downslope again.

1.6.3 Galileo's Conclusions

What if the angle was reduced all the way to flat, i.e., horizontal? It was the influence of the contact that slowed the ball, and **not** the ball itself that caused it to slow down. If the influence of this contact were made zero, then it would mean that the ball would continue rolling - continue moving forever. It would never slow down and stop. No force was needed to keep such an object moving forever. It would simply continue moving forever of its own accord, not speeding up, nor slowing down.

In this way, he discovered a fundamental law of nature. Any object, if given a push, will continue moving forever at the same speed unless something acts to slow it down, like a hillside, or the slowing-down contact it is making with the surface. The worse the contact, the greater the slowing down.

1.6.4 Addressing Important Scientific Observational Considerations

Galileo deduced a fundamental law of nature from his experiments, and it was the opposite result from the Aristotelean view about the motion of objects. Galileo was only able to do this because he (1) had a very clear sense of what the relevant and irrelevant phenomena were, (2) he didn't overlook anything when carefully observing how objects moved on a surface, (3) he knew all too well what was based on fact and conjecture in the Aristotelian view of how objects moved, and he certainly made sure his observations were (4) not contaminated by expectation or belief.

These were the 4 important considerations that must be taken into account when making careful scientific observations that I wanted to illustrate for you with this example. There is a 5th one, which I mentioned to you already in the last video.

1.7 The Scientific Revolution

Now that we have an idea of what science is, the scientific method and making useful scientific observations, we shall look at how this method of knowledge discovery came to be developed and accepted within a fledgling scientific community in the first place. By briefly looking at some of the history of the scientific revolution, we'll be able to address the 4th and 5th intended learning outcomes of this lecture.

Here, I am adopting the traditional view of the Scientific Revolution, i.e., when and where it began and ended. There are certainly other perspectives on this revolution, just take a look at Wikipedia on the Scientific Revolution as an example. If you scroll down the page, under the "Criticism" section, you'll find something there on the "Continuity thesis".

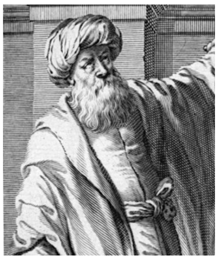


Figure 9 Hazan from Wikimedia: artwork drawn by Adolph Boÿ, engraved by Jeremias Falck, Public domain, via Wikimedia Commons

We also need to realize that other earlier scientists had also used the scientific method in discovering new knowledge, like Ibn al-Haytham ("the father of modern optics", Figure 9) who, at around 1000 A.D. during the Islamic Golden Age, made significant contributions to the principles of optics and visual perceptions.

If you'd like to get a more fully appreciate the scientific revolution, there are several reasonable videos on YouTube on this topic, and even videos on the entire history of science. I've included some of these links below if you'd like to dig deeper.

From "Crash Course"

The Scientific Revolution

- https://youtu.be/vzo8vnxSARg
- https://youtu.be/w70BkCqgyyI

The History of Science

Many videos here. Here's just the preview…

https://youtu.be/-hjGgFgnYIA

To be honest guys, I haven't watched all 47 videos introduced above by Hank Green. I'm just pointing you towards this additional material if you're really keen. I do enjoy listening to Hank Green, although I might not always agree with him. Anyway, take a look and see what *you* think.

1.7.1 Revolutions Within Scientific Subdisciplines

There's also one more point I'd like to make before our brief account of the scientific revolution- there are also revolutions *within* each of the various subdisciplines in science, like Chemistry, Medicine, Biology, Physics, etc., each of which totally changed the way people thought about and treated the subject. But it is *the* Scientific Revolution we're discussing now, i.e., the fundamental change in the way people thought about knowledge acquisition as a whole and the subsequent adoption of this approach by newly formed scientific societies.

Figure 10 *[Thomas Kuhn from Wikimedia]*

It is the American Physicist, historian, and philosopher of science, Thomas Kuhn (Figure 10) who wrote about scientific revolutions, in general, in his book "The Structure of Scientific Revolutions" (Figure 11). This book was extremely influential, but we won't be covering his ideas here. Instead, I've added two excellent 9 and a half minute videos from Leiden University on Thomas Kuhn's ideas. I recommend that you watch both of them because they are quite interesting, informative and definitely thought-provoking as they deal with the nature of scientific revolutions, "normal science" and anomalies.

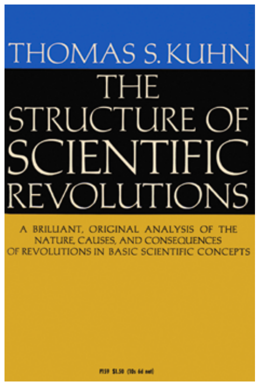


Figure 11 *[Kuhn's Book from Wikimedia]*

From Leiden University – Faculty of Humanities

- https://youtu.be/sOGZEZ96ynI (Normal Science)
- https://youtu.be/JQPsc55zsXA (Scientific Revolutions)

I personally think the presenter overstates things, but I've added these videos above for you nevertheless. There are also other videos on that channel that discusses Karl Popper, whose ideas are subtly embedded into this course (falsifiability), but this is getting off track for this course. The key idea in the videos above is the role anomalies play in scientific endeavor, and that many subdisciplines of science have their own "revolutions" – forever changing the way people thought about the topic, or even creating entirely new fields of knowledge and ways of understanding of the natural world.

1.7.2 The Beginning of the Scientific Revolution – Copernicus

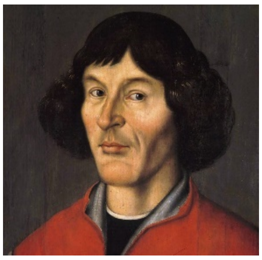
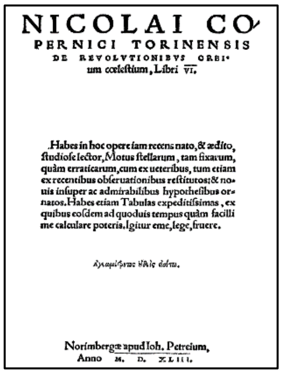


Figure 12 *[Nicolaus Copernicus from Wikimeaia]: Toruń Regional Museum, Public domain, via Wikimedia Commons*

First up we have Nicolaus Copernicus (Figure 12) who, in 1543, published an astronomy book, known in short form as De Rev (Figure 13), on how the planets orbited the Sun and NOT the Earth, and that the Earth itself rotated. This proposal was in direct opposition to the accepted idea that the Earth was the center of the universe, and that *everything* rotated about the Earth.

"Accepted idea" meant that the state religion of the time simply stated that this must be so. They were an authority – meaning that their word could not be argued with, and it was a crime to do so – a crime called heresy.



NICOLAI CO
PERNICI TORINENSIS
DE REVOLVTIONIBVS ORBI-
um coelestium, Libri VI.

Habes in hoc opere iam recens nato, & aedito, studiose lector, Motus stellarum, tam fixarum, quàm erraticarum, cum ex ueteribus, tum etiam ex recentibus obseruationibus restitutos: & nouis insuper ac admirabilibus hypothesibus ornatos. Habes etiam Tabulas expeditissimas, ex quibus eosdem ad quoduis tempus quàm facillime calculare poteris. Igitur eme, lege, fruere.

Norimbergae apud Ioh. Petreium,
Anno M. D. XLIII.

Figure 13 *[De Rev from Wikimedia]: derivative work of Johannes Petreius 1543 edition of File:Nicolai_Copernici_torinensis_De_revolutionibus_orbium_coelestium.djvu, Public domain, via Wikimedia Commons*

This authority considered astronomy and the motion of the Sun, moon, and planets to be part of their "turf", so to speak. The reason for this was that it was literally believed that the stars and planets were heavenly bodies and a part of heaven. This is why they considered astronomy as their "turf"; so there was no questioning what they said, it was just a simple fact not to be argued with.

Now Copernicus knew his idea that the Sun, and not the Earth, being the center of the Universe could get him executed, so he made sure his book was published posthumously so that there was no way they could get to him. Secondly, he stated in his book that his proposal shouldn't be thought of as real, but was just another, simpler, way of predicting where the planets would be during the year. You see, being able to make these predictions was considered particularly important to many powerful and influential people at the time.

Figure 14 [*Ptolemy from Wikipedia*](): *Unknown authorUnknown author, Public domain, via Wikimedia Commons*

For 1500 years, an extremely complicated system was devised for the motion of the planets where the Sun and the moon orbited around the Earth. This has been attributed to Ptolemy (Figure 14), a second century astronomer of Alexandria under the rule of the Roman Empire. Copernicus's view of how the planets moved replaced the complex Ptolemy system shown in Figure 15 with what is given in Figure 17.

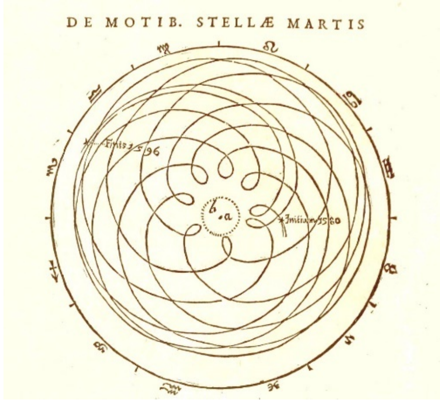


Figure 15 [*Epicycles for Mars about the Earth from Wikipedia*]()

It's important to realize that Copernicus's newer and simpler system wasn't any better at predicting where the planets would be than the Ptolemy system, mostly because Copernicus believed, as Ptolemy did, that the planets and moon must move in perfect circular orbits with uniform speed. But nonetheless, Copernicus' proposal was definitely a step in the right direction.

1.7.3 Galileo

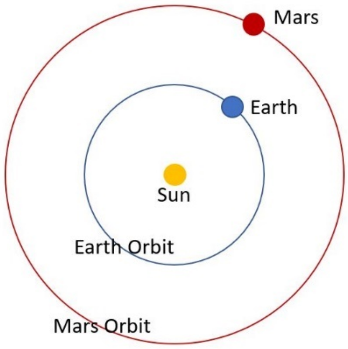


Figure 17 Copernicus' Sun-Earth-Mars System

Next, we have Galileo Galilei, who in the late 1500s and early 1600s, studied the motion of objects with experiments to test current explanations of how things moved. He also performed astronomical observations to test Copernicus' suggestion of a Sun-centered universe instead of an Earth-centered one and to test the Aristotelian view of the heavenly bodies.

Figure 16 [*Galileo Galilei from Wikipedia*](): *Justus Sustermans, Public domain, via Wikimedia Commons*

It was Galileo's work in astronomy that really got him into trouble. You see, Galileo built powerful telescopes possessing a magnification of 30 times which was much more powerful than the telescope of that time which only had 3x magnification. With this telescope, he tested the Aristotelian view of the heavenly bodies and a whole bunch of new phenomena could be plainly seen by any who cared to look.

This is another key feature of science. Some new instrument is invented that allows us to make observations that couldn't be made before. These new observations can turn up "anomalies". An anomaly being something or some state of affairs that can't be explained with the current understanding of nature. Anomalous phenomena and observing anomalies are discussed in our textbook in Chapter 2 pages 18 – 23.

Figure 19 [*Galileo's drawing of our moon from Wikipedia*](): *Galileo, CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons*

So, with Galileo's much more powerful telescope than anything that was available at the time he saw a whole bunch of anomalous phenomena. The moon was clearly bumpy and cratered (Figure 19). Obviously, it wasn't a perfectly smooth sphere, which heavenly bodies were supposed to be according to the Aristotelian view. Also, he observed moving sunspots on the sun (Figure 18), so it became obvious that the sun was (a) NOT a perfectly clean sphere, it had these spots on it, and (b) it rotated and wasn't stationary! He saw 4 moons orbiting around Jupiter (Figure 20).

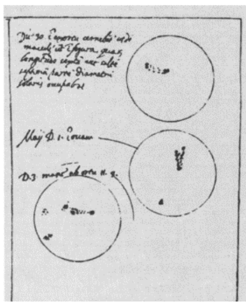
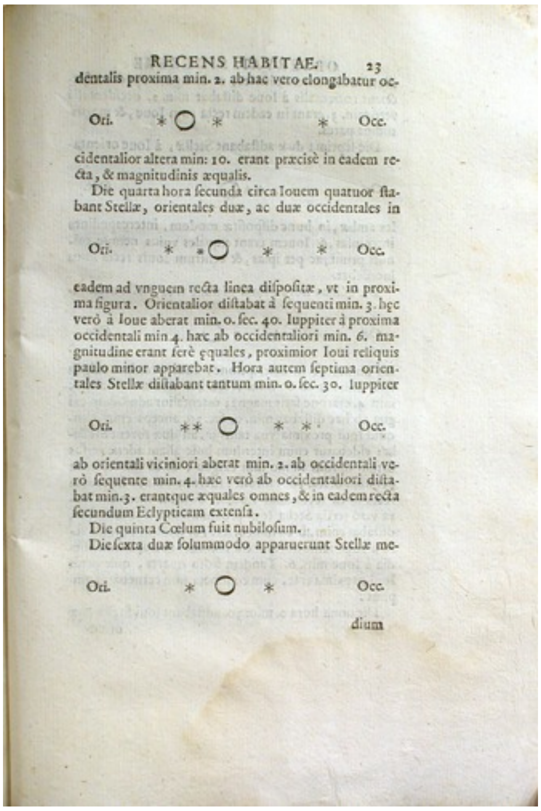


Figure 18 [*Galileo's sketchs of sunspots from Wikipedia*](): *Galileo, Public domain, via Wikimedia Commons*

This was a real problem. Up until this point, all heavenly bodies observed appeared to be orbiting the Earth, but now this planet, Jupiter, had its own moons and they are orbiting it, not the Earth!


RECENS HABITAE. 23

dentalis proxima min. 2. ab hac vero elongabatur oc-

Ori. Occ.

cidentalior altera min: 10. erant præcisè in eadem recta, & magnitudinis æqualis.

Die quarta hora secunda circa Iouem quatuor stabant Stellæ, orientales duæ, ac duæ occidentales in

Ori. Occ.

eadem ad vnguem recta linea dispositæ, vt in proxima figura. Orientalior distabat à sequenti min. 3. hęc verò à Ioue aberat min. o. sec. 40. Iuppiter à proxima occidentali min 4. hæc ab occidentaliori min. 6. magnitudine erant ferè ęquales, proximior Ioui reliquis paulo minor apparebat. Hora autem septima orientales Stellæ distabant tantum min. o. sec. 30. Iuppiter

Ori. Occ.

ab orientali viciniori aberat min. 2. ab occidentali verò sequente min. 4. hæc verò ab occidentaliori distabat min. 3. erantque æquales omnes, & in eadem recta secundum Eclypticam extensa.

Die quinta Cœlum fuit nubilosum.

Die sexta duæ solummodo apparuerunt Stellæ me-

Ori. Occ.

dium

Figure 20 Galileo records Jupiter's moons - public domain image

He also recorded all the phases of Venus (Figure 21), which was a prediction and a test of a Sun-centered universe. Seeing all the phases of Venus proved it orbited the sun because in an earth-centered universe, you wouldn't be able to see all the phases of Venus.

All these observations led Galileo to realize that the Aristotelian worldview must be wrong and that the Sun, not the Earth, was the center of the universe.

But Galileo, who based his theories on experiments and not simply the word of the ancients, flew directly in the face of authority.

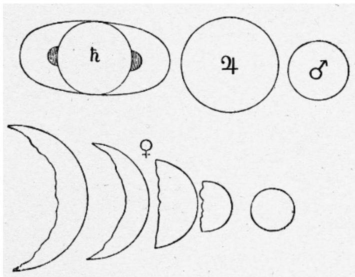


Figure 21 Galileo's phases of venus - public domain image

To cut a long story short, Galileo published a book stating his position clearly and heavily criticizing the Aristotelian worldview. His book was immensely popular.

He was arrested and charged with heresy, but "got off" on a lesser charge of "vehemently suspect of heresy" when he recanted and said he must have made a mistake. Of course, he hadn't, but house arrested for the rest of his life rather than being tortured and burnt at the stake seemed like a better option to him.

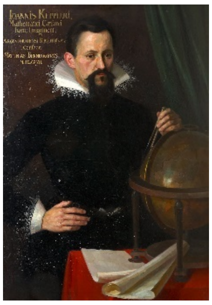


Figure 22 Johannes Kepler from Wikimedia: Unknown author, Public domain, via Wikimedia Commons

1.7.4 Kepler

Our third participant is Johannes Kepler (Figure 22), who was also working at around the same time as Galileo, proposed an improved model for how the planets moved over Copernicus' model. Kepler, who had access to some of the most accurate measurements of planet positions during the year, simply could not get the positions of the planets to match with a model like Copernicus's, where the orbits were perfectly circular executing uniform circular motion.

So, following the scientific method, he completely abandoned this explanation of how the planets moved and came up with the idea of the planets orbiting about the Sun in *ellipses*, rather than circles. Along with his other laws of planetary motion, he produced the most accurate predictions, up until that time anyway, of where all the planets would be at any time of year (Figure 23).

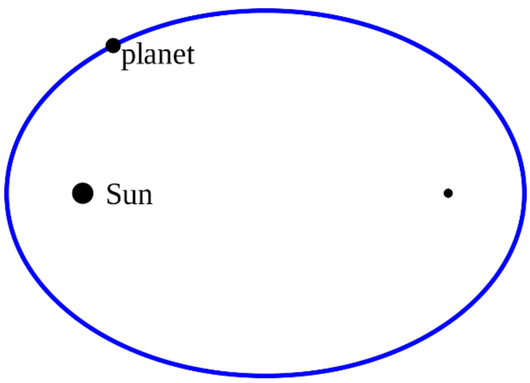


Figure 23 Kepler's planetary orbit from Wikimedia

However, there was still no explanation as to *why* the planets, sun, and moon should behave in such a manner, but considering the accuracy of the model, it did seem that this is just what they did.

So, *why* should the heavenly bodies behave in such a manner? The answer to this question marks the traditional view's end of the scientific revolution. But before ending our recount of the scientific revolution, we need to learn about the then-highly influential English politician and philosopher, Sir Francis Bacon – our fourth participant.

Figure 24 [Francis Bacon from Wikipedia](): *Paul van Somer I, Public domain, via Wikimedia Commons*

1.7.5 Bacon

Bacon (Figure 24) is commonly accepted for articulating the scientific method we have been discussing in 1620. Sometimes called the father of empiricism, Bacon convinced the fledgling scientific community that the only way to get to the truth of some explanation was by testing it through observation or experimentation. A scientist should not simply accept an explanation as true but should doubt it and try to disprove it through observation and experimentation, i.e., empiricism. Only then, when all possible testing has been conducted, could one hope that the explanation may indeed be true. Without this skepticism then there is no basis, or evidence, that the explanation is correct, we are forced to conclude that there's no way of knowing if it's true or not.

This testing of explanations – the weighing of the truth – as articulated by Bacon, remains absolutely foundational to the scientific method today, and it was during the scientific revolution that this approach was crystalized. For now, let us finish our account of the scientific revolution by considering the work of Sir Isaac Newton.

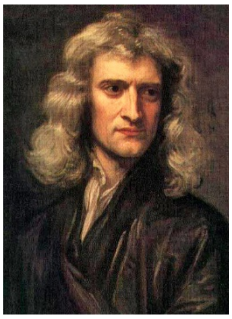
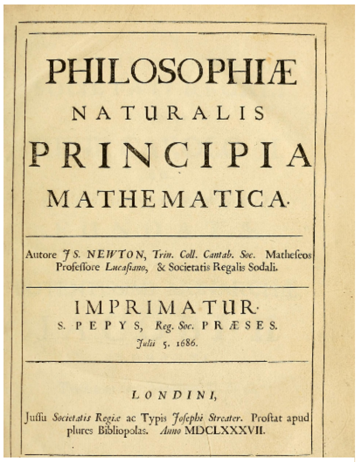


Figure 25 [Isaac Newtom from Wikipedia](): *Godfrey Kneller, Public domain, via Wikimedia Commons*

1.7.6 The End of the Scientific Revolution – Newton

Our final participant is Isaac Newton who integrated the earlier work of Galileo on how objects move and Kepler's work on how heavenly bodies move, along with the work of others and his own experimentations. Isaac Newton published his famous book Philosophiæ Naturalis Principia Mathematica, in English "Mathematical Principles of Natural Philosophy", or just Principia for short, in 1687. The book represented a stellar breakthrough in the understanding of how *all* objects moved.

Newton presented his three laws of motion, which were figured out by observations and experimentation on how objects moved on Earth. He also presented the law of universal gravitation which described how all objects with mass attracted each other. But when you combined these two things you could mathematically *derive* Kepler's laws of motion of the planets.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Figure 26 [Principia from Wikipedia](): *The original uploader was Zhaladshar at English Wikisource., Public domain, via Wikimedia Commons*

It was truly shattering because, until this time, the motion of heavenly bodies and the motion of things on Earth were thought to be entirely unrelated. Indeed, the Aristotelian worldview required that they were entirely different because the planets were literally thought to be a part of heaven. How could anything figured out on Earth be used to describe heaven? Well, evidently, the planets weren't part of heaven.

Newton's single law of universal gravitation combined what was considered totally separate types of motions, the motions taking place on Earth and those taking place in the heavens, into one unified whole. The laws of motion allowed the exact mathematical description of the motion of all objects familiar to humans at the time. The new mechanics, called classical mechanics today, accurately describes the motion of all projectiles, parts of machinery, and astronomical objects.

It was only until the extremes of nature were encountered, using new instruments of observation, like the very tiny atoms or the very dense and massive stars, or the very fast, moving near the speed of light, was there a need to improve on his physical theory of classical mechanics, which didn't happen until the 20th century.

1.7.7 The Scientific Community

This marks the end of the traditional view of the scientific revolution. At the conclusion of the 17th century, with the incredible success of Principia in explaining so much, the last vestiges of the Aristotelian worldview were swept away into the annals of history, at least in the realm of physics. But medicine, chemistry, and biology would soon follow with their own revolutions.

A brand-new era was ushered in. One in which not just individuals practiced the scientific method, but an entire community of like-minded scientists worked together for the betterment of humankind. Scientific societies were established, and discoveries discussed, debated, and put under the microscope of rigorous scientific testing.

The importance of a community in science cannot be understated. Individual scientists may be blinded by their own expectations or beliefs, or perhaps they are unable to differentiate facts from conjecture or assumption. But with a scientific community, individual work can be checked, cross-checked, and closely examined by all, accelerating the pace of knowledge acquisition manyfold.

Let’s end this section with the motto of the Royal Society (established in late 1660) “*Nullius in verba*”, which means “take nobody’s word for it”.

1.8 The Industrial Revolution

The development of the scientific method, well established and accepted by the end of the scientific revolution with the formation of a fledgling scientific community, directly resulted in further great discoveries which in turn produced the industrial revolution.

The industrial revolution was when great technological innovation literally changed the world – where we transited as a species from relying on muscle power to get things done, to machines doing the work. It set us on a course towards overpopulation, climate change and biodiversity loss we have today.

Addressing the 6th and final intended learning outcome for this lecture involves an appreciation of how scientific discoveries can transform society. In this case, it's the discovery of energy, heat, work, and the second law of thermodynamics and their application in the construction of an efficient and practical steam engine. The invention of such a machine drove the industrial revolution.

While an entire course could easily be spent discussing the Industrial Revolution, here we'll just focus on those aspects of it directly relevant to us. If you're keen to learn more about it, just look it up on Wikipedia, or even check out some of the videos on YouTube linked below.

From "Crash Course"

The Industrial Revolution
https://youtu.be/zjK7PWmRRyg (And note the importance of the steam engine)

https://youtu.be/FCpqN7GmLYk (Again, notice the importance of the steam engine)

Wikipedia
https://en.wikipedia.org/wiki/Industrial_Revolution

So, what is the industrial revolution? Well, it commonly refers to a period of great societal change that took place, first in Britain, Western Europe, followed by the US and Canada and later Japan and other countries as they too industrialized.

So, the industrial revolution is when industrialization first took place. It occurred around the late 1700s up until about the early 1800s in Europe and Northern America.

Before the Industrial Revolution, most labor was performed by people and animals – muscle power was relied upon to make things and get things done. However, this all changed during the Industrial Revolution with the invention of a practical steam engine to power machines to do the work much more effectively and efficiently.

Of course, people still needed to run the steam engine-powered machines, but the machines could be used to manufacture items in far greater numbers than people could without them. Textiles were the primary products impacted by the revolution in terms of employment, value-added, and capital investment. As an example of just how much more effective the machines were - mechanized cotton spinning, powered by the steam engine increased the output of a worker by a massive factor of 500!

Iron production was also greatly enhanced by using the steam engine to power blast air into the furnaces. This was done using coal, which was much cheaper than the previously used charcoal. Nevertheless, industrialization is all about manufacturing on a large scale in factories, which are in cities, and powered mostly by steam engines.

With this manufacturing taking place in cities, replacing the "old ways" of producing things, i.e., by hand and in cottages, a lot of work was to be found in urban centers. City populations increased rapidly. During the industrial revolution, almost every aspect of daily life was influenced in some way. Average income exhibited unprecedented, sustained growth. The standard of living for the general population increased consistently for the first time in history, and overall, there was a massive population explosion.

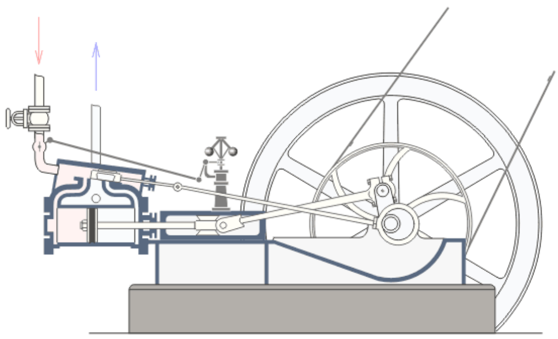


Figure 27 [Steam engine action from Wikimedia](): Panther, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

The invention of an efficient and practical steam engine (one example shown in Figure 27) was a result of understanding what energy, heat, work and the second law of thermodynamics are through scientific investigation. Engineers were then able to apply this knowledge to construct them. These machines used steam to produce power, and to make steam you had to heat water. To heat the water, you required an effective fuel, and that was coal (Figure 28). Charcoal is also good, but that needs trees, and if you've run out of those then you need something else.

In Britain, where the Industrial Revolution started, coal is abundant, and it's here that we see the start of our reliance on fossil fuels. The demand for coal to power steam engines increased dramatically. Now to get coal, you have to mine it, and Britain had lots of it.

Figure 28 Coal from Wikimedia

The thing is, as demand increased, mines needed to be able to go deeper to get the large quantities available to satisfy this demand. The problem was that the deeper you dig a mine, the more likely it fills with water, making the lower parts of the mine inaccessible. How was this problem solved? By pumping the water out, and that was achieved with the steam engine itself, fueled by the very coal it mined.

Coal needed to be transported to the machines located in city factories.
For this to happen effectively, and for the goods made in the factories to be moved out easily, roads needed to be significantly improved and transportation itself made more reliable and efficient. Steam engine-powered trains and ships were invented, vastly increasing the efficiency of moving materials around, including food which now was in great demand in the rapidly growing cities.

The improvements to agriculture, just prior to the Industrial Revolution, coupled with new machinery now available to assist in farming and effective means of getting it to where it was needed (steam engine) significantly reduced famine across Western Europe.

Figure 29 Pollution during the industrial revolution from Wikimedia

Conditions in the now extremely crowded cities were pretty bad though. Pollution from coal burning and the simple throwing of human waste directly out of windows into the streets, as you can imagine, was absolutely disgusting. Also, remember, no one knew about germs, and germ theory didn't exist yet, so hygiene was nonexistent. You can imagine, these are the perfect conditions for disease to spread, so outbreaks of cholera, typhoid and typhus were common and devastating, but the greatest killer in the cities was tuberculosis. Some relief was achieved with the construction of sewer systems in cities to carry away wastes.

Although conditions could be horrible, there was a substantial overall drop in the mortality rate of the population. People, on average, survived longer – long enough to have children of their own. So, while the birth rate was high, roughly 6 babies per woman on average across the world, the mortality rate in the industrialized countries decreased markedly.

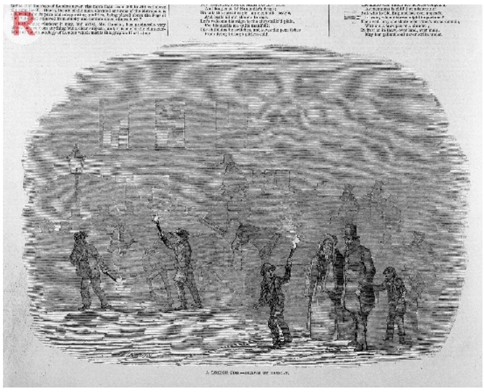


Figure 30 *[Pollution during the industrial revolution from Wikimedia](#)*: *Henry Linton, Public domain, via Wikimedia Commons*

This was because of

1. The improvements in agriculture allowing more food to be produced.
2. There were improvements in distributing that food, reducing the likelihood of food shortages.
3. Improvements in sanitation with sewage systems put in place in cities.

As a result of the fall in mortality rate during the industrial revolution, the population surged. For example, examine Figure 31 from "Our World in Data" for the population of England from 1086 until the end of the Industrial Revolution.

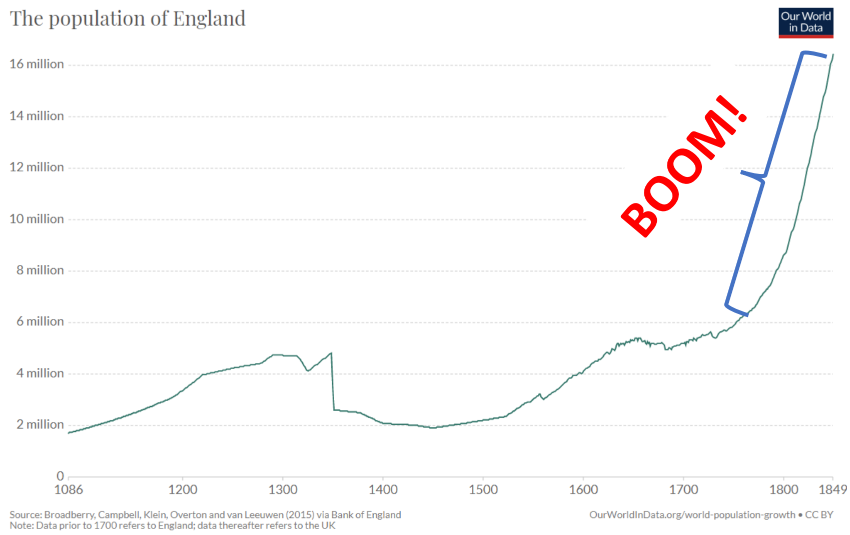


Figure 31 Population of England before then during the industrial revolution period indicated with a left-brace.

Other industrialized nations experienced similar rapid population growth leading to a surge overall in the world's population during this time.

And all of these large numbers of people needed powered machines for food production and distribution as well as for factories and transportation. That power came from the steam engine initially, followed by the internal combustion engine later, and both these types of machines all used fossil fuels to run.

No one at the time could have possibly anticipated that these changes would lead to the crisis we find ourselves in today. Who could imagine that by simply burning fossil fuels with reckless abandon we could end up altering an entire planet's climate? After all, the Earth is huge, and there is no doubt that if the world's population remained relatively small there wouldn't be enough pollution to terraform the entire planet.

But the world's population didn't remain small. In fact, there was another even more incredible population surge just around the corner, in the 20th century. And it's this surge in world population that truly takes us into the climate crisis and loss of biodiversity at rates usually only associated with extinction-level events.

We will be exploring this population surge in our next lecture.

2 The Baloney Detection Toolkit Applied in a Simple Investigation

Intended Learning Outcomes for Lecture 02
You should be able to do the following after this lecture.

(1) *Explain* the three things you should do before applying the baloney detection toolkit (BDTK).
(2) *List* the tools in the BDTK and explain how they assist in fact-checking.
(3) *Perform* a reverse image search, *critically reviewing* its results.
(4) *Apply* the tools of the BDTK in an online investigation concerning human population growth over time.
(5) *Apply* the tools of the BDTK in an online investigation of any topic of interest.

2.1 Sense Making of Scientific Claims

Summary of the Last Lecture

We learned in the last lecture that science is an activity that aims to further our understanding of the natural world. Science does this through the application of the scientific method, which in a nutshell is a three-step process: observe, explain then test the explanation.

We saw straightforward applications of this method in three examples: (i) *troubleshooting a laptop* (Figure 32), (ii) *why a teabag bloated up when boiling water was poured onto it* (Figure 33), and (iii) *Dr Semmelweis' cadaverous poisoning* (Figure 34). We then discussed in greater detail the first step of the scientific method: *making scientific observations* in video 1.5 and saw an example from Physics during the Scientific Revolution in video 1.6. This covers chapters 1 and 2 of our textbook.

Figure 32. Troubleshooting a laptop from video 1.2

Figure 33. Teabag experiment from video 1.3

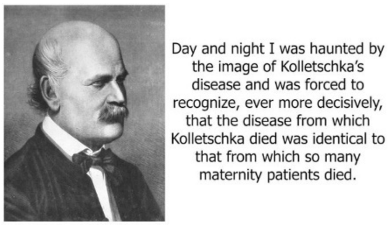


Figure 34. Cadaverous poisoning from video 1.4 (Image from Wikimedia: Jenő Doby, Public domain, via Wikimedia Commons)

We also briefly reviewed how and when this scientific approach to the discovery of knowledge was formalized and accepted within a fledgling scientific community in video 1.7. This occurred during the Scientific Revolution starting from 1543, with the publication of *De Rev*, to 1687, with the publication of *Principia*. We met some of the main players: Copernicus, Galileo, Kepler, Bacon, and Newton, and noted their contributions to the development of science and the shift away from an authoritarian, Aristotelian worldview to one in which science and the scientific method was used to better understand our world.

Lastly, in video 1.8, we saw that because of the Scientific Revolution and the ensuing slew of significant discoveries, applications of these discoveries led directly to the Industrial Revolution which occurred from the late 1700s up until the early 1800s. We saw that the steam engine, in particular, was critical for the Industrial Revolution. The steam engine powered the machines in factories, mines, and was used in transportation. This engine used coal as a fuel, and thus, our reliance on fossil fuels became embedded into an industrialized society. We also saw how the population in countries undergoing the Industrial Revolution surged due to a significant drop in the human mortality rate.

Continuing the story of human population growth and its relationship to our climate crisis

Our population has continued to climb even after the Industrial Revolution, eventually leading to another great surge starting just after World War 2. Unfortunately, we don't have time to explore this in our official lectures, but if you're interested, you're welcome to take a look at video 2.5. This video is optional and not part of this lecture. I made it on the topic for a previous version of this course.

Why is any of this important? Well, we look at climate change and biodiversity loss to illustrate how and why science works. In a world with a relatively small human population, it would seem quite unlikely that humanity could have any real global impact on the environment (even though locally it could certainly get quite nasty).

Nevertheless, we currently have a massive human population of 7.89 billion that is still increasing, and all these people require food, land for shelter, and energy. The immense number of people who use our previous methods of food and energy production has put us into the crisis we find ourselves in today. So, it really is the large human population that is at the core of our environmental problems. Do note that this is probably an oversimplification because not all large populous nations damage the environment equally. We will elaborate more on this point in the later blocks.

The growth of the human population from millions to billions over time is something we'll take a look at in the last official video of this lecture, video 2.4. We'll see that it was only very recently that our population really "exploded", doubling every 38 years in the later part of the 20th century. This explosion was largely assisted by another scientific discovery discussed in the optional video 2.5. That discovery has been said to be the detonator of the recent population explosion. This population explosion occurred as a result of a marked drop in human mortality, mostly child mortality.

We will be learning about how the world population changed since the dawn of agriculture and how it's expected to change until the end of this century. We will be doing this by referring to a couple of videos available on the web. But how will we know if these videos are accurate? Well, this brings me to the main point of this lecture, and that is to introduce you to the Baloney Detection Toolkit. We will be using it to establish the credibility of the videos.

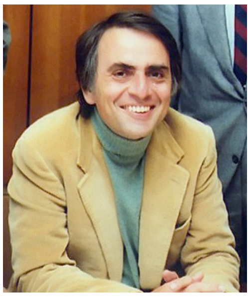


Figure 35 Carl Sagan (Wikipedia credit NASA JPL, Public domain, via Wikimedia Commons)

Baloney Detection

So, what is this Baloney Detection Toolkit? Well, firstly the word, "baloney", is an American term for "nonsense". The Baloney Detection Toolkit (BDTK) is a set of questions you ask yourself to assist you in establishing whether something you're looking at is true, or otherwise. These questions are what scientists intuitively use during any scientific investigation. Now, this toolkit was first created and discussed by the popular science author and scientist Carl Sagan (Figure 35) in the last chapter of his book: "The Demon-Haunted World: Science as a Candle in the Dark" (Figure 36).

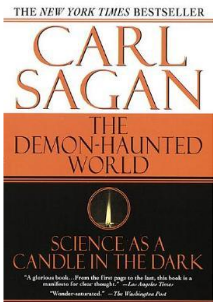


Figure 36 Carl Sagan's famous public domain image

However, we won't be using Prof. Sagan's set of tools. Instead, we've developed our own set of tools based on his work as well as that of others, which we'll talk about more in video. Our BDTK is designed for you. It's meant for you to use and apply in your daily lives. Understanding it, taking it seriously, and applying it will not only help you pass this course, but also help you navigate the veritable ocean of information coming at you constantly from all directions. I'm not kidding when I say you should pay attention to them, because they could very well save you from a lot of pain and hurt now and in the rest of your life. The BDTK really is that important.

2.2 Preparation for the BDTK

There are a few things you should know about before you can effectively apply the tools in the BDTK.

Just like in real life, when you have a set of tools you want to use, you need to have some basic knowledge before you can use them. So, this is what we'll be talking about: three things that you need before applying the BDTK, and these three things are ideally things that all good scientists should practice when conducting any scientific inquiry. I say "should" here because scientists are humans too, and sometimes it can be pretty hard to meet this ideal.

Possess a Skeptical Mindset

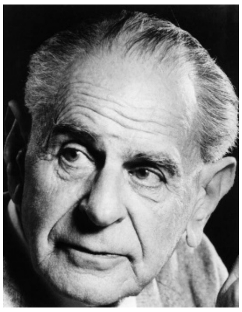


Figure 38 Karl Popper
(LSE library, No restrictions, via Wikimedia Commons)

The first thing we need to have before applying the BDTK is a skeptical mindset, which is pretty fundamental to the practice of science. If any explanation in science is to be given any credibility, it needs to be tested to see if it is false - otherwise, it is mere speculation. If we have an explanation that is falsifiable then we have a scientific explanation. Now an explanation that can't be falsified is considered unscientific, and we'll talk more about this in the next lecture. This type of thinking is along the lines of Karl Popper's (Figure 38) philosophy of science, whose ideas we implicitly follow in much of this course. Remember we mentioned Thomas Kuhn (Figure 37) in lecture 1, and he disagrees with Popper's philosophy in certain aspects, but we won't be going into Popper versus Kuhn in this course.

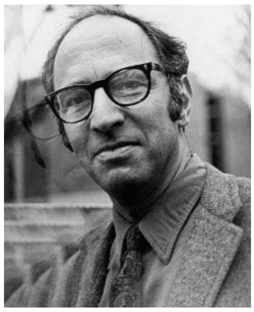


Figure 37 Thomas Kuhn
(https://www.molwick.com/en/scientific-methods/041-scientific-methodology.html)

If you don't question whether something is true or not, and take everything you're told as a fact, then you are definitely going to run into big trouble in your life. When you hear an explanation or claim, especially if it sounds "weird" (and there could be a reason for that) you need to ask: Is this really true? How do I know? If it's a supposed fact, then where's the proof? Now this is where Science can help, and the BDTK utilizes science to prompt you into thinking if what you're hearing is fact, fiction, or something in between.

I'm not saying you should go about your life not believing anything you hear. I'm also not saying you should be a cynic, or someone basically distrustful of everyone. There's a fine line between possessing a healthy level of skepticism and being a cynic. A scientist is ideally someone who is not so easily convinced, but when there's solid evidence to support something then it becomes accepted. Remember, *nullius in verba*? Don't just take people's word for it, but ask: what's the evidence for what's being claimed?

Be aware of your own biases

The second thing you really have to watch out for before using the BDTK are your own biases. Actually, this one is much more easily said than done. The practice of science is meant to be objective, but practitioners of science are human, and being human means you automatically possess a whole bunch of biases, whether you realize it or not. Biases get in the way of our critical thinking skills, and being aware of them allows us to do something about negating their effects. By doing this we will be much better equipped to make better decisions in our lives.

We will cover three very important biases that can have a negative influence on us.

2.2.1.1 Confirmation Bias

Confirmation Bias. This type of bias refers to the tendency to seek out information that supports something you already believe and is a particularly pernicious (harmful) subset of cognitive bias—you remember the hits and forget the misses, which is a flaw in human reasoning. People will cue onto things that matter to them, and dismiss the things that don't, often leading to the "ostrich effect," where a subject (metaphorically) buries their head in the sand to avoid information that may disprove their original point.

Source: https://www.masterclass.com/articles/how-to-identify-cognitive-bias

Consider the following scenario:

Some people believe that 13 is an unlucky number. These people might only keep count of and remember all the unpleasant and unfavourable events in their lives that are associated with the number 13. For all we know, there might have been more delightful and enjoyable occurrences in the lives of these individuals that are related to the number 13. But because of confirmation bias, these pleasant episodes are dismissed and quickly forgotten. So, with time, the number 13 would really appear to be an unlucky number to such people.

This is also similar to what we call self-fulfilling prophecies. We might also think that confirmation bias can be used in conjunction with emotions to influence a particular behaviour in someone.

I mean if someone is afraid of something, another person could tell a lie involving that fear. The listener would be more likely to believe it if my lie confirms your fear due to confirmation bias. Here's an example: Someone sends you a text message saying your bank account has been hacked. To stop the alleged hacking, you need to click on the provided link. So, you are likely to believe this lie because you're afraid of being hacked and this lie feeds that fear.

2.2.1.2 Availability Bias (or Availability Heuristic)

Availability Bias. Also known as the availability heuristic, this bias refers to the tendency to use the information we can quickly recall when evaluating a topic or idea—even if this information is not the best representation of the topic or idea. Using this mental shortcut, we deem the information we can most easily recall as valid and ignore alternative solutions or opinions.

Source: https://www.masterclass.com/articles/how-to-identify-cognitive-bias

The general concept behind availability bias or availability heuristics is: concluding that a topic or concept cannot be important or even true, due to not knowing of it, or being unable to recall immediate examples of it. Consider the following scenario:

A person (who has cancer and is still on medication) contracted fever and was feeling lethargic. Knowing that she is probably immuno-compromised, she went to see a doctor. Due to the ongoing pandemic, the doctor tested her for COVID-19. When it was negative, the doctor asked her to go home and rest. However, the symptoms persisted, coupled with a loss of appetite. With time, the symptoms appeared to be increasingly similar to those of dengue fever.

Figure 39 An NEA dengue red alert banner near Clementi Stadium 29-Jul-22.

Around the same time, the National Environmental Agency (NEA) had placed dengue "red alert" banners (e.g., Figure 39) around her neighbourhood. The doctor's decision to only test the person for COVID-19 (and nothing else) is an example of availability bias. Because of the pandemic, the doctor probably saw multiple COVID-19 positive patients, and likely no one with dengue fever. As such, the immediate concern the doctor had for the person who was also on cancer-related medication was to rule out COVID-19. The thought of dengue fever did not even come into the mind of the doctor.

How can we combat such a bias? We only have our memories to rely on and cannot know things we don't remember. The first step is to be aware of the bias itself.

According to those who are in the field of behavioural science, there are two major ways we make decisions. The first involves the quick and automatic decisions we make. The second involves decisions made after careful and rigorous analysis. An example of the first type of decision is to run away or hide when you see a large ferocious dog charging at you. You will not pause to analyse the velocity of the dog before deciding if you can outrun the dog. This situation requires an immediate reaction and availability bias (if this really is availability bias!) is useful.

Figure 40 A ferocious dog?

A good approach to overcome availability bias is to make decisions after carefully deliberating on the matter, checking and double-checking the sources rigorously, and taking time to examine the evidence. However, given the fact that we make numerous decisions a day, we tend to opt for a shortcut, and that is to make a quick and automatic decision based on what comes to mind first while considering this decision to be the best one.

Much depends on the importance of the decision. If the outcome of the decision that you're making is of significant importance to you or anybody else, then you're going to also have to put some effort into figuring out whether you've taken everything into consideration and not just used whatever's in your memory. You should do a little bit of research if the decision you're making really matters. The act of examining all known information would mitigate availability bias.

Another approach to counter availability bias is to make important decisions with a team. Of course, we need to ensure that the members of the team are not what we would term as 'yes-men', or 'yes-women'. The team members should always be on the lookout for reflex-based decisions. To question the rationale of such decisions, ensure that all the known evidence (not just the available evidence) has been considered before the decision is made.

2.2.1.3 Illusory Truth Bias

Illusory Truth Bias. The illusory truth bias (also known as illusion of truth effect, validity effect, truth effect, or the reiteration effect) is the tendency to believe false information to be correct after repeated exposure. When truth is assessed, people rely on whether the information is in line with their understanding *or if it feels familiar*. The first condition is logical, as people compare new information with what they already know to be true. *Repetition makes statements easier to process relative to new, unrepeated statements, leading people to believe that the repeated conclusion is more truthful*.

Source: https://en.wikipedia.org/wiki/Illusory_truth_effect

The illusory truth bias (or illusory truth effect) takes effect when one begins to accept a repeated falsehood as the truth. Consider the following (real-world) scenario: for a long time, many of us were told that the Great Wall of China is the only human-made structure that is visible (with the unaided eye) from space or even the Moon. This piece of information even found its way into textbooks used in school. However, China's very own astronaut, Yang Liwei, actually documented that he could not see the Great Wall of China with his own eyes during his space mission in 2003.

This illusory truth bias has been exploited by advertisers, marketers, and even purveyors of fake news. Whether we like it or not, they have been rather successful at it. In addition, the illusory truth effect even applies when you know originally that the statement is false. Constant repetition of the falsehood from different sources and over an extended period of time can lead to the statement now being accepted as true, despite knowing originally it was false.

There are many more biases out there, but a lot of them are very situational.

Guard your buttons

What is meant by buttons here is: something that sets you off; something that immediately makes you feel and triggers strong emotions in you. You want to try and make sure your own emotions don't get the better of you and override your own critical thinking faculties.

The ideal scientist doesn't allow emotion to cloud their judgment or objective evaluation of something. To help you avoid being sucked into a false claim or story you should be wary of any claim that makes you "feel" something. Feelings like *fear*, *greed*, *pity*, *lust*, and *"righteous" anger*, among others are typical buttons for people, and con artists and scammers are well aware of this. Claims, headlines, or text messages, can be couched in such a way that causes you to simply accept them as true due to your emotional response as well as possibly feeding your own biases. This is an extremely "dark art" that scammers will often use to get "in your head" and trick you into doing something you normally wouldn't if you were calm, rational, and thought carefully about what you were doing.

Be aware of your "buttons". When you start to feel anything as you read a post, headline, or text, just take a breath and ask: "Is this really true? How do I know?" You will explore more on guarding your buttons in workshop 1.

In Conclusion

These are the three things you really need to watch out for before applying the BDTK.

(1) You should possess a skeptical mindset, but don't overdo it and turn into a cynic!
(2) Be aware of your own biases. These can really get in the way of thinking critically, as can the last point:
(3) Guard your own buttons and don't let anyone press them. OK, well, unless you want them to, but in any case, you should be aware of your feelings, so they don't cloud your judgment.

Once you have these three things in place, you are then well-placed to be able to apply the tools from the BDTK.

2.3 What is the BDTK?

We are constantly bombarded with information coming at us, from the time we wake up in the morning to when we sleep again. Information from advertising in the streets and on vehicles. Information from news on television, radio, newspapers, magazines, and especially from the internet. Information from our smartphones in email, text messages, various messaging services, as well as social media. Information also comes to us, of course, from books, lectures like this one, and libraries.

How can we tell what is true and what isn't, and everything else in between? There are a bunch of tools that we can apply to help us sort this out. These tools emulate the way in which scientists go about conducting any scientific investigation. The tools come in the form of the Baloney Detection Toolkit, or BDTK.

What the Tools Do

The tools from the BDTK were originally developed by Carl Sagan and have been updated and modified by various people like Michael Shermer over the years. Others have considered the issues associated with figuring out whether online content is true or otherwise, like John Green's Crash Course on "Navigating Digital Information" – which I highly recommend you watch by the way.

- Carl Sagan's Baloney Detection Toolkit available here.
- Michael Shermer's Baloney Detection Toolkit available here.
- John Green's Crash Course (10 episodes) on "Navigating Digital Information" playlist available here.

For this course, we've drawn on the work of these three people and produced a simpler BDTK for you to apply in your daily life. You'll be using these tools in workshop 1, so you can get a better idea of how they work and the ways in which you apply them.

The tools themselves come in the form of questions you ask yourself to make it easier to figure out whether something is true, well-established, and accepted as a fact, or otherwise. They help you answer these three questions that "fact checkers" use to sniff out false claims, as well as scientists in the process of conducting a scientific inquiry. Those three questions are:

(1) Who is behind the information and why?
(2) What is the evidence for the claims?
(3) What do other sources say about the source and its claims?

The first couple of tools concern themselves with the source of information.

Tools of the Baloney Detection Toolkit

2.3.1.1 How reliable is the source of the claim?

Perhaps the first thing you need to do when considering any claim is to find out who is the source of this information, and if you can't, that is one strike against it. Suppose you can identify the source. Next, you'll need to figure out just how reliable it is. You can take a look at the author, or authors, professional background. Are they experts, or are they some blogger you've never heard of sprouting their own personal views or opinions? Maybe the source is an organization. You could check their "about" page to see what they say about themselves for a start but remember anyone can say anything they like about themselves, so we should keep this in mind when reading an "about" page describing themselves.

By far the best way we can use to establish the reliability of a source is to use lateral reading. This entails checking what other reliable sources say about the source you are considering. If you're online, just open up a second browser window and search for the source you are checking.

Don't just click on the first item that comes up in your search. Wait! Scroll down the list of search items to find a site that's reliable. Maybe you even have to go to page 2 of the search results. Check if they're newspapers, magazines, or digital news sites. Do note that many news organizations have their particular perspective or point of view, which we'll talk about next. You can definitely use Wikipedia as a good start for checking out the reliability of a source. Perhaps some of you have been told not to use Wikipedia. Well, that may have been good advice 15 years ago, but now Wikipedia has matured to such an extent that it very often can be considered quite reliable.

Incidentally, John Green discusses the use of Wikipedia as a first port of call on particular topics and information. I suggest you watch it.

John Green discusses Wikipedia here.

Sadly, many people, including students and professors, consider the look and feel of a particular website to be an indicator of reliability. The presence of a well-designed logo, references and citations, professional photography being used, no grammatical errors or typos, and a beautifully designed site **does not** automatically make a site a reliable source. So please be *en garde* for this classic trap for the unwary.

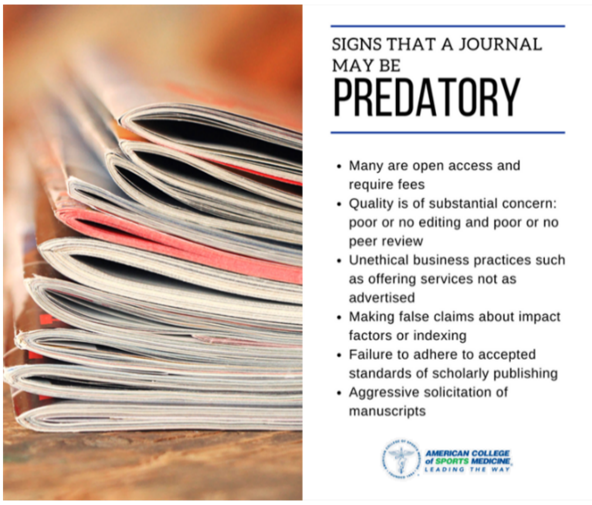


Figure 41 Signs that a journal may be predatory. *(https://www.acsm.org/blog-detail/acsm-blog/2018/08/16/predatory-publishing-avoid-exploitative-journals)*

Perhaps the source is from primary scientific literature (firsthand publication in scientific journals), but even this doesn't guarantee reliability – far from it. You should again use lateral reading to see just what other reliable sources have to say about the journal as well as the authors, or universities the authors originate from. There are predatory journals out there, and some journals have a highly questionable peer review process, if at all. A well-respected, peer-reviewed journal with authors from respectable universities are things you expect to find from a reliable source originating from the primary literature, but again, their research work could be highly controversial. Use lateral reading to figure out what other scientists have to say about the work.

Check this recent article in the world famous scientific journal, *Nature*, regarding predatory journals and a definition for them.

2.3.1.2 What is the source's perspective?

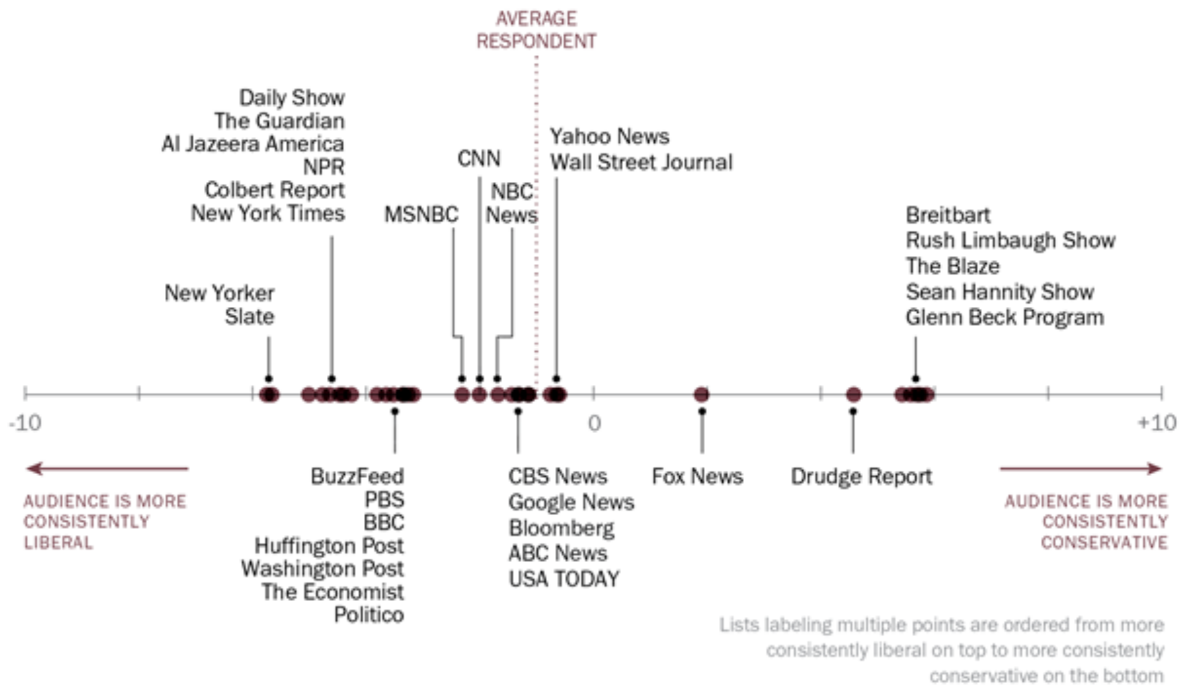
Every human being has a particular perspective when it comes to communication no matter how objective we might try to be. We are all products of our environment, and because of this we simply can't help injecting our experiences into our own communication. Even the language we use to communicate carries elements of the culture the language originates from. I know you are all aware of this, just think about the use of Singlish.

So, try as we might to be objective when communicating, at least some elements of perspective can creep into it. That said, an author's perspective, or even bias, can be overtly inserted into communication in an attempt to sway you to their way of thinking. This can even go as far as misrepresenting evidence, falsifying evidence, or just plain fabricating evidence, in an attempt to lie and cheat you into believing something that just isn't true.

So, whenever you come across new information you need to ascertain what the perspective is of the source. What is their point of view? Why was this information shared with you? What is the purpose of the information you are looking at? Many news organizations definitely have a particular perspective when reporting the news, like Fox News, which is considered conservative, or the Guardian, which is considered liberal. This graphic from the Pew Research Center helps illustrate what I mean:

Ideological Placement of Each Source's Audience

Average ideological placement on a 10-point scale of ideological consistency of those who got news from each source in the past week...



American Trends Panel (wave 1). Survey conducted March 19-April 29, 2014. Q22. Based on all web respondents. Ideological consistency based on a scale of 10 political values questions (see About the Survey for more details.) ThinkProgress, DailyKos, Mother Jones, and The Ed Schultz Show are not included in this graphic because audience sample sizes are too small to analyze.

PEW RESEARCH CENTER

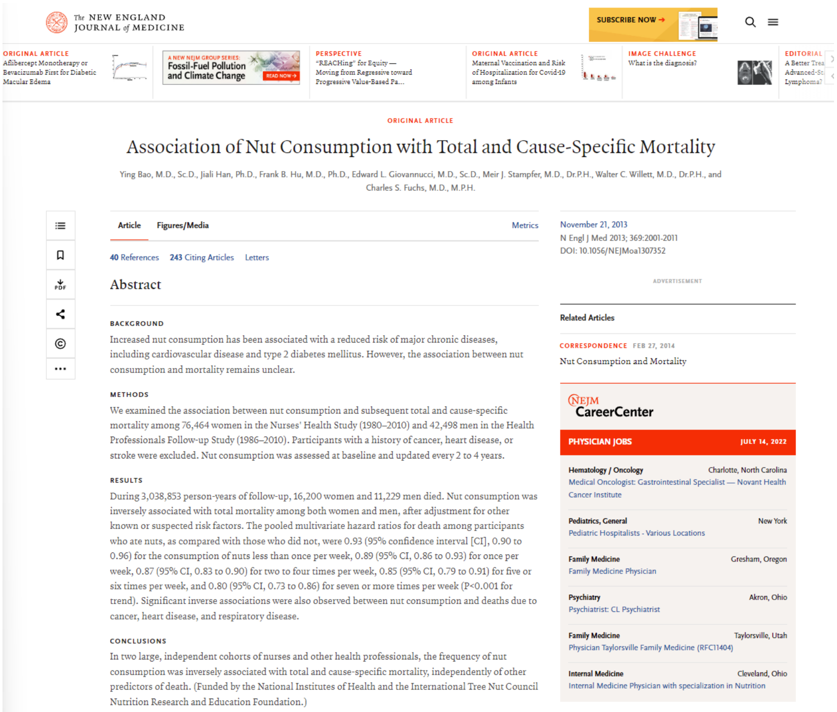
https://www.pewresearch.org/journalism/2014/10/21/political-polarization-media-habits/pj_14-10-21_mediapolarization-08/

Knowing just what the perspective is of the source of information helps you understand better the information you're looking at. This is important when you take into account how true the information may be.

You may not realize it, but you already do this in your daily life. Say you have a friend who is a complete and total fan of BTS, and let's also say that you don't care too much for their music and video clips. Now your friend might come to you and share that BTS just released a new single and that you absolutely must listen to it. Your friend says it's very clearly, and beyond doubt, the most incredible song ever written and performed. Now you know your friend's perspective on this point, so you would definitely have some reservations about just how great this new BTS single is.

You see what I mean? Perspective can colour a description of something so that it's more, or less, than what it really is. This can happen for things other than just personal taste in music – which is obviously subjective. It can even happen with facts, so please be wary of perspective when you check out a source.

The last thing I wanted to mention to you which is related to perspective is the funding of the source. I mean, where does the money come from that enables the source to provide you with the information? What you are seeing could be an advertisement to try and sell you something. Clearly, the information will paint whatever the product is in a good light, even if the product isn't really so great. You need to take into consideration who is paying for the information you are looking at, because there could be a conflict of interest involved. If that's the case, then this conflict really must draw into question just what it is that's being said.



The NEW ENGLAND JOURNAL of MEDICINE

ORIGINAL ARTICLE

Association of Nut Consumption with Total and Cause-Specific Mortality

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November 21, 2013
N Engl J Med 2013; 369:2001-2011
DOI: 10.1056/NEJMoa1307352

Abstract

BACKGROUND

Increased nut consumption has been associated with a reduced risk of major chronic diseases, including cardiovascular disease and type 2 diabetes mellitus. However, the association between nut consumption and mortality remains unclear.

METHODS

We examined the association between nut consumption and subsequent total and cause-specific mortality among 76,464 women in the Nurses' Health Study (1980–2010) and 42,498 men in the Health Professionals Follow-up Study (1986–2010). Participants with a history of cancer, heart disease, or stroke were excluded. Nut consumption was assessed at baseline and updated every 2 to 4 years.

RESULTS

During 3,038,853 person-years of follow-up, 16,200 women and 11,229 men died. Nut consumption was inversely associated with total mortality among both women and men, after adjustment for other known or suspected risk factors. The pooled multivariate hazard ratios for death among participants who ate nuts, as compared with those who did not, were 0.93 (95% confidence interval [CI], 0.90 to 0.96) for the consumption of nuts less than once per week, 0.89 (95% CI, 0.86 to 0.93) for once per week, 0.87 (95% CI, 0.83 to 0.90) for two to four times per week, 0.85 (95% CI, 0.79 to 0.91) for five or six times per week, and 0.80 (95% CI, 0.73 to 0.86) for seven or more times per week (P<0.001 for trend). Significant inverse associations were also observed between nut consumption and deaths due to cancer, heart disease, and respiratory disease.

CONCLUSIONS

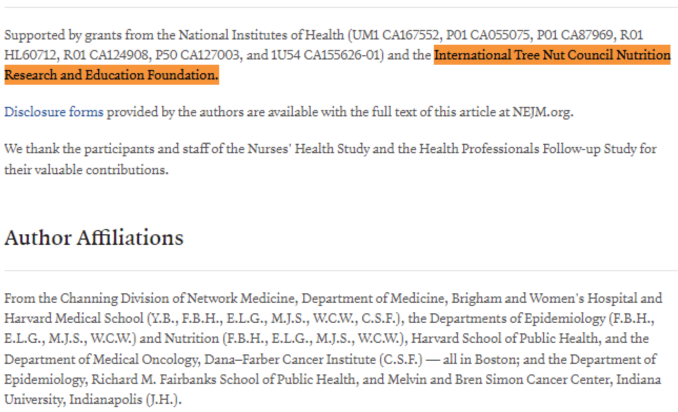
In two large, independent cohorts of nurses and other health professionals, the frequency of nut consumption was inversely associated with total and cause-specific mortality, independently of other predictors of death. (Funded by the National Institutes of Health and the International Tree Nut Council Nutrition Research and Education Foundation.)

Figure 42 Nut consumption vs mortality study

Maybe what you are looking at are findings from scientific research. Very often scientists are commissioned to perform research into something directly related to their source of funding. Does this mean that the research findings are invalid? Well maybe. It initially raises a red flag that needs further investigation because there could be a conflict of interest.

Consider Figure 42 for example. It is a 30-year study involving about 120 thousand health professionals published in the New England Journal of Medicine that finds an association between consumption of nuts and longevity. Basically, for those in the study who ate nuts every day, they found that they lived longer than those who didn't consume nuts frequently. The authors found an association between these two things, it's not the same as a causal link.

> Nut consumption vs mortality study:
> https://www.nejm.org/doi/full/10.1056/nejmoa1307352



Supported by grants from the National Institutes of Health (UM1 CA167552, P01 CA055075, P01 CA87969, R01 HL60712, R01 CA124908, P50 CA127003, and 1U54 CA155626-01) and the International Tree Nut Council Nutrition Research and Education Foundation.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

We thank the participants and staff of the Nurses' Health Study and the Health Professionals Follow-up Study for their valuable contributions.

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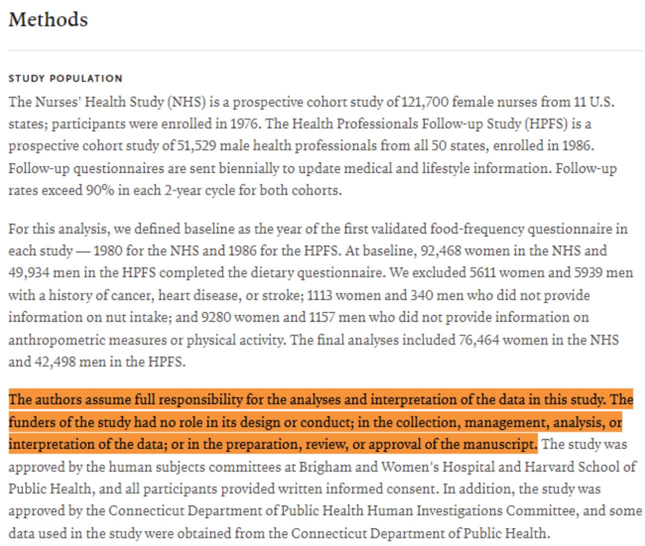
Figure 43 Funding sources and author's affiliations

If we look at who funded the study (Figure 43) we find that one of the funding bodies was the International Tree Nut Council Nutrition Research and Education Foundation, so we might start to wonder if there is a conflict of interest here. However, we first note that the journal this work is published in is the New England Journal of Medicine, and lateral reading tells us that this is a very highly regarded and well-respected peer-reviewed journal. Secondly, we note that the authors come from quite respectable institutions and are experts (Figure 43). Finally, and most importantly, we find the statement within the methods section of this peer-reviewed (Figure 44):

"The authors assume full responsibility for the analyses and interpretation of the data in this study. The funders of the study had no role in its design or conduct; in the collection, management, analysis, or interpretation of the data; or in the preparation, review, or approval of the manuscript."

All of these things point toward there being no conflict of interest here, so the findings of this study appear to be accurate. If we were keen to find out more about this topic, to see if it has been verified by others, then we would now have to do some more lateral reading to see what other scientists say about this work.



Methods

STUDY POPULATION

The Nurses' Health Study (NHS) is a prospective cohort study of 121,700 female nurses from 11 U.S. states; participants were enrolled in 1976. The Health Professionals Follow-up Study (HPFS) is a prospective cohort study of 51,529 male health professionals from all 50 states, enrolled in 1986. Follow-up questionnaires are sent biennially to update medical and lifestyle information. Follow-up rates exceed 90% in each 2-year cycle for both cohorts.

For this analysis, we defined baseline as the year of the first validated food-frequency questionnaire in each study — 1980 for the NHS and 1986 for the HPFS. At baseline, 92,468 women in the NHS and 49,934 men in the HPFS completed the dietary questionnaire. We excluded 5611 women and 5939 men with a history of cancer, heart disease, or stroke; 1113 women and 340 men who did not provide information on nut intake; and 9280 women and 1157 men who did not provide information on anthropometric measures or physical activity. The final analyses included 76,464 women in the NHS and 42,498 men in the HPFS.

The authors assume full responsibility for the analyses and interpretation of the data in this study. The funders of the study had no role in its design or conduct; in the collection, management, analysis, or interpretation of the data; or in the preparation, review, or approval of the manuscript. The study was approved by the human subjects committees at Brigham and Women's Hospital and Harvard School of Public Health, and all participants provided written informed consent. In addition, the study was approved by the Connecticut Department of Public Health Human Investigations Committee, and some data used in the study were obtained from the Connecticut Department of Public Health.

Figure 44 Declaration of no conflict

2.3.1.3 Is the claimant providing positive evidence?

We've looked at who is behind the information and why they've opted to publish it, but by far the most important thing to consider is what's the evidence? Evidence is at the very foundation of science, and it's this reliance on the evidence that has led us to where we are today in seeking the truth about how and why things happen as they do in the natural world.

Figure 45 Source: https://en.wikipedia.org/wiki/The_dress#/media/File:The_dress_blueblackwhitegold.jpg

Another important thing to realise is that scientific evidence does NOT include testimonials, eyewitness accounts, sworn statements, or signed affidavits. These things are not regarded as scientific evidence simply because people can make things up, or just be plain wrong or mistaken.

Surely you all know the now famous "The Dress", shown here. This picture went viral in 2015 as millions of people argued over its colour. Is it black and blue, or is it white and gold? Apparently, it's supposed to be black and blue, but for the life of me, I just don't see that. To me, it is absolutely bleeding obviously white and gold and anyone who doesn't see that must be nuts!

And it's not just vision or colour perception we can be wrong on. There are plenty of examples involving sounds too on the internet, just look if you don't believe me.

Anyway, if you're interested, you can read more about The Dress on Wikipedia, the link is found below.

The Dress: https://en.wikipedia.org/wiki/The_dress

In science, eyewitness accounts can point a scientific investigative team towards where to start looking for evidence of something. For example, if you've watched any of the air crash investigations on National Geographic, you would see how the investigators conduct their work as a scientific inquiry. They use eyewitness accounts to point to places where they should start their investigations. Perhaps passengers saw fire near the wing of the plane, so then the investigators would check the wing for evidence of a fire. If there isn't any, then you would have to question the validity of what was seen. Nevertheless, the point is the eyewitness account isn't regarded as scientific evidence in the investigation. If a fire was the cause of the crash, then there definitely would be unequivocal physical signs of that having occurred.

So then, what is evidence? Certainly, if no evidence at all is provided for the claim, then this has to be a really big strike against whatever it is you're looking at, so you should be suspicious immediately. After all, if there's no evidence then there's no way to know if it's true or not, and certainly no reason to believe that it is true.

Evidence must *support* the claim.

Evidence can be almost anything really, like texts, photos, videos, citations to scientific articles, data, and infographics, etc. As long as it actually supports the claim then we are looking at evidence. But not all evidence is created equal. I've already mentioned about eyewitness accounts, and their value as evidence scientifically. Expert opinion should also not be considered as evidence either, or if it is, then it's the lowest form of evidence. After all, it's just an opinion, even if it's an expert's, which surely holds more value than a non-expert's opinion, but nevertheless, it isn't direct evidence.

Evidence must be *reliable*

Once you have evidence you need to check if it's accurate. Evidence can be misrepresented, falsified, or fabricated. Here again, lateral reading is invaluable. What do other reputable sources say about the evidence? Does the evidence originate from a reliable source? You can check this by opening up another browser window and seeing what reliable sources say about the source of the evidence.

Evidence must be *relevant*

Sometimes evidence can be reliable, but it simply doesn't support the claim or argument. John Green gives a nice example of this in his video on evaluating evidence, link in the box. This was an example that involved a US senator bringing a snowball onto the US Senate Floor to show that the very cold snap happening in Washington DC at the time was evidence that global warming wasn't real. While this is hard evidence that it's cold outside during the winter in DC, this single instance of a cold weather snap isn't evidence that global warming isn't real any more than a heat wave is evidence that it is. This is because a cold snap or a heat wave is weather, and the weather refers to short term atmospheric conditions while climate is how the atmosphere behaves over relatively long periods of time. Winter, obviously, is still happening all over the world as the globe is getting warmer.

John Green's crash course video on "Evaluating Evidence" can be found here.

Figure 46 Snowball in the US Senate (Image captured from J. Green's video on "Evaluating Evidence", link in the box above.)

Anyway, even if you do find you are looking at reliable evidence, think carefully about whether that evidence is at all relevant.

Data as evidence should be reliable and not misrepresented

Now if the evidence is data presented graphically, you should ask yourself is it presented honestly and fairly? Keep a critical eye out for reliability and misrepresentation. If the evidence is a picture, do a reverse image search and see what shows up. Reverse image searches, which you can really easily do with Google, can really be invaluable in uncovering fake pictures.

Doing a Reverse Image Search

1. On the Google search page, click on the camera icon ().
2. Either drag the image onto the space provided, or paste in the image link.
3. Click the "Search" button and you're done!

Of course, photos can be doctored. Look for *context* as well as *currency* of an image. Sometimes old images are used as evidence for current events. This is a common misrepresentation which a reverse image search can often readily reveal. So again, who is behind the image and are they reliable? Lateral reading can discover this. The caption could be used as a search. If there is a link, check that also. Watch out for *spurious correlations* too. These can be often used to wrongly convince you that something is caused by something else. We'll hear more about this in a later lecture.

Videos can be taken out of context by saying they are about something else, or not show an entire sequence, or can be edited. You need to know where the video came from, who created it and whether it's been altered. But probably by far the most disturbing is the use of artificial intelligence to produce "Deep Fakes". Again, check what other reliable sources say about the video.

Lastly, we are asking with this tool, if the claimant is providing *positive* evidence. What we are referring to here when we say "positive" evidence, is evidence that is in direct support of the claim. Evidence presented that shoots down other alternative possibilities isn't evidence that the current explanation is correct. This is a common fallacy made in the name of science, which we will discuss in more detail in the last lecture. But just so you know what I'm talking about here I'll give you an example.

Figure 47 Zoomed in on picture of a "UFO", which is actually a mirage.
(https://commons.wikimedia.org/wiki/File:Fata_Morgana_Example.jpg, Timpaananen, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons)

Suppose I claim I saw a UFO* (Figure 47) and provide a blurry picture of it. One possible explanation is that it was a weather balloon and not a UFO. If I provide irrefutable evidence that what I took a picture of was NOT a weather balloon, this is not providing positive evidence that the picture is a UFO. It is only evidence that it is not a weather balloon. That's all. What I saw could be something else and not a UFO at all. All we know is that it was not a weather balloon. Here the claimant hasn't provided positive evidence of a UFO. They have just provided evidence that there is something as yet unidentified in the sky, assuming the photo isn't fake or the subject of the photo isn't an artifact of the image that occurred during photo taking. But again, even if you can prove the picture isn't a fake or an artefact, it still isn't positive evidence of a UFO. You only have evidence that the picture isn't a fake, the subject isn't an image artefact, or a weather balloon. That's all. There can still be many possible explanations for the phenomenon as well as ones we haven't thought of. Claims need positive evidence to support them, not negative evidence against alternative explanations.

> An artefact (also spelt artifact) are anomalies apparent during visual representation as in digital graphics and other forms of imagery, especially photography and microscopy.

Bottom line on evidence: You need to ask, is the evidence reliable? Does the evidence back up the claim?

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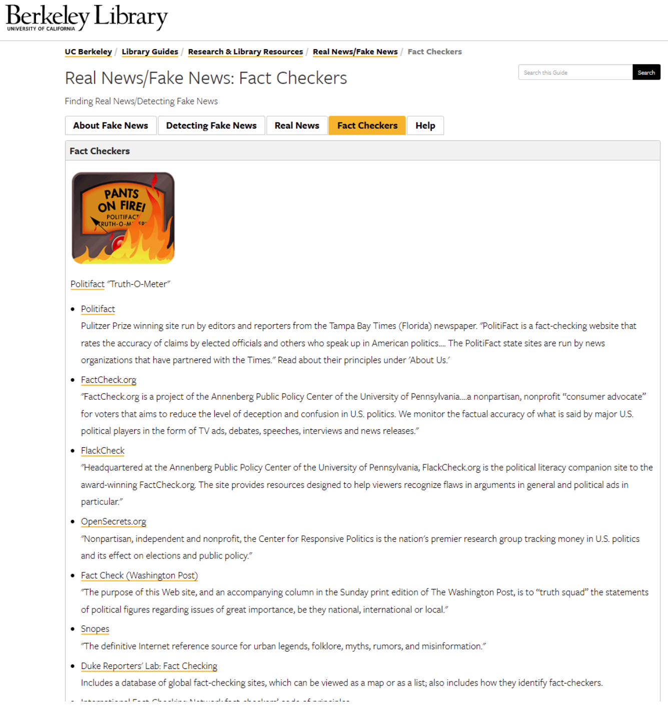
*By "UFO" here I mean the now commonly understood meaning of the abbreviation which is an "extraterrestrial spaceship". I'm *not* referring to its original meaning that is literally what the abbreviation represents, i.e., "unidentified flying object".

2.3.1.4 Where does most of the evidence point?

Sometimes what you're looking at could come from a reliable source and be backed up by what appears to be reliable and relevant evidence. Does this mean you should believe it? Well, in your lateral reading, you may well have turned up other reliable sources providing evidence in direct conflict with what you are looking at. So now you have a disagreement, and this is how science is advanced. You may be looking at some anomaly that, as yet, has not been sorted out by the greater scientific community. For something in science to become well established, claims and explanations need to be put to the test in many differing ways. Just because one group says they have proof of something, isn't enough to firmly establish that group's claim or explanation. We need a majority of evidence showing that the claim or explanation isn't wrong.

So generally, it's the explanation where the majority of evidence points, is the one that is most often correct. After all, scientists are humans and they too can make mistakes, so the one piece of research that goes against the majority could very well end up being shown to be flawed in some way, which brings us to the next tool in the BDTK.

2.3.1.5 Have the claims been verified by somebody else?


Berkeley Library
UNIVERSITY OF CALIFORNIA

UC Berkeley / Library Guides / Research & Library Resources / Real News/Fake News / Fact Checkers

Real News/Fake News: Fact Checkers

Finding Real News/Detecting Fake News

About Fake News | Detecting Fake News | Real News | Fact Checkers | Help

Fact Checkers

Politifact "Truth-O-Meter"

- Politifact
  Pulitzer Prize winning site run by editors and reporters from the Tampa Bay Times (Florida) newspaper. "PolitiFact is a fact-checking website that rates the accuracy of claims by elected officials and others who speak up in American politics.... The PolitiFact state sites are run by news organizations that have partnered with the Times." Read about their principles under 'About Us.'
- FactCheck.org
  "FactCheck.org is a project of the Annenberg Public Policy Center of the University of Pennsylvania....a nonpartisan, nonprofit "consumer advocate" for voters that aims to reduce the level of deception and confusion in U.S. politics. We monitor the factual accuracy of what is said by major U.S. political players in the form of TV ads, debates, speeches, interviews and news releases."
- FlackCheck
  "Headquartered at the Annenberg Public Policy Center of the University of Pennsylvania, FlackCheck.org is the political literacy companion site to the award-winning FactCheck.org. The site provides resources designed to help viewers recognize flaws in arguments in general and political ads in particular."
- OpenSecrets.org
  "Nonpartisan, independent and nonprofit, the Center for Responsive Politics is the nation's premier research group tracking money in U.S. politics and its effect on elections and public policy."
- Fact Check (Washington Post)
  "The purpose of this Web site, and an accompanying column in the Sunday print edition of The Washington Post, is to "truth squad" the statements of political figures regarding issues of great importance, be they national, international or local."
- Snopes
  "The definitive Internet reference source for urban legends, folklore, myths, rumors, and misinformation."
- Duke Reporters' Lab: Fact Checking
  Includes a database of global fact-checking sites, which can be viewed as a map or as a list; also includes how they identify fact-checkers.

Figure 48 Berkeley Library fact checker list

We've mentioned this a few times already, and in a sense, it's closely related to what do other reliable sources say about the claim. So, when you open another browser page, perhaps to check some headline, you could also try one of the reputable fact-checking sites like www.snopes.com.

The Berkeley library lists quite a number of fact-checking sites (Figure 48), but most of these are associated with US politics. However, we see that this site, Duke Reporters' Lab on fact-checking, includes a database of global fact-checking sites, which is particularly useful (link in the box below). If we go to Singapore, we will find two active sites listed. One is the Straits Times ASKST, shown here, and the other is this, from AFP Singapore, and scrolling through you can see a number of fact-checking articles of local relevance.

Now in science, of course, research findings need to be reproduced by others. Being able to reproduce scientific findings, or the principle of reproducibility, is absolutely fundamental to science and how it works. You see, irreproducible findings are not considered findings at all in science.

- Snopes fact-checking: www.snopes.com
- Berkeley library list of fact checkers found here.
- Duke Reporters' Lab global fact checking site database here.
- Straits Times ASKST: www.straitstimes.com/askst
- Fact checker AFP in Singapore here.

Figure 49 Pons & Fleischmann at press conference (image from the blog: https://francisworldinsideout.wordpress.com/2011/04/06/pathological-science-in-goodstein%e2%80%99s-%e2%80%9con-fact-and-fraud%e2%80%9d/)

A classic example of this sort of thing was an announcement made by the scientists Pons and Fleischmann (Figure 49). In 1989 they claimed that they had discovered something called cold fusion. Basically, they said they were able to get nuclear fusion working on a lab bench at room temperature. Nuclear fusion is quite different from nuclear fission, which is what occurs in nuclear reactors. Unlike nuclear fission, nuclear fusion is very safe and clean, and if it could be got to work at room temperature on a lab bench then it would be a huge breakthrough that could potentially produce cheap, clean, and abundant energy for all humanity.

> For the difference between fission and fusion, check out the site: https://www.energy.gov/ne/articles/fission-and-fusion-what-difference, video therein, and info graphic.

A huge media frenzy occurred at the announcement of this unpublished work, much to the skepticism of nuclear physicists working on the problem. Many scientists tried to replicate the experiment with the few details available. The scientific community's hopes faded with a large number of groups unable to reproduce the results, the withdrawal of many reported positive reproductions, as well as the discovery of flaws and sources of experimental error in the original experiment, and finally, the discovery that Pons and Fleischmann had not actually detected nuclear reaction by-products. By late 1989, most scientists considered cold fusion claims dead and not real at all, so that was the end of that.

2.3.1.6 Does the claimant use flawed reasoning?

The last tool in our BDTK is here to remind you to think carefully about what the claimant is saying. Does what they say actually make sense? Is there a flaw in the logic? Here's a simple example to show you what I mean. Often when people make arguments using data, they provide absolute numbers, when they really should be using a rate. By "rate" I mean the numbers they give should be "per" something else.

As a concrete example, you can easily find on the internet arguments stating that China is the largest polluter of CO_2 in the world, and then a graph like Figure 50 will be shown. This certainly makes it look like China is the biggest polluter.

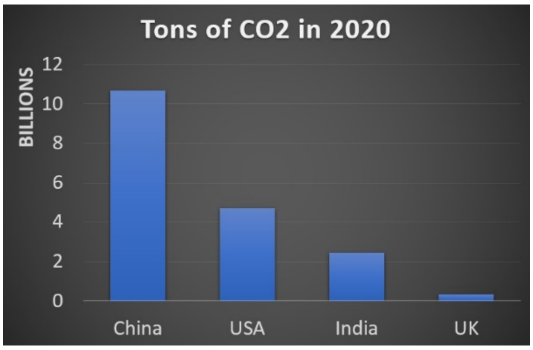


Figure 50 Tons of CO_2 pollution emitted by country

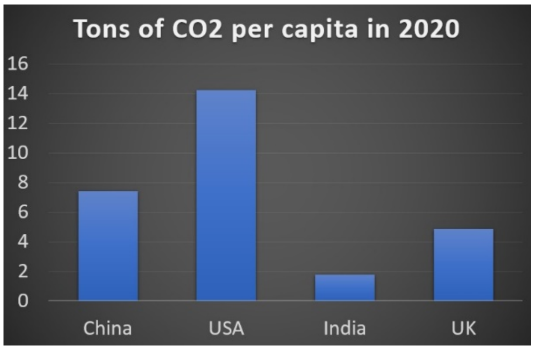
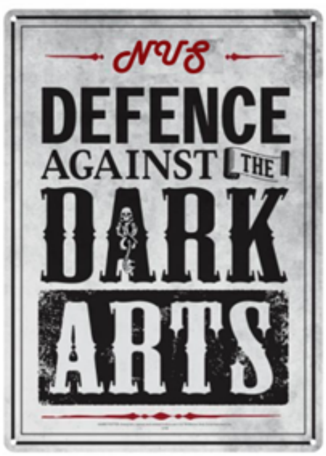


*Figure 51 Tons of CO_2 pollution emitted **per capita** by country*

But is it correct? Surely you should be comparing the amount of CO_2 emitted per person. Doesn't that make more sense? If we now show the same data but taking into account the population of these countries in 2020 we get a very different graph (Figure 51), which now gives the impression that the USA is the largest polluter. However, there are a bunch of smaller polluting countries that vastly exceed the USA on a pollution per capita basis (not shown in this graph).

Anyway, the point is, you need to think carefully if what is being said really makes sense. In this case, should a per capita basis be used to determine who's the greatest polluter, or maybe something else? Often when people use numbers to try and present their case, they mask the truth by not properly accounting for an appropriate rate, which actually invalidates their argument. As this BDTK tool says, you need to think about if what the claimant is saying actually makes sense.



In Conclusion

As we've seen, the Baloney Detection Toolkit is a list of questions you can ask to help you decide if some information you've received is true or otherwise. These are the types of questions scientists ask when conducting any scientific investigation. Here we've ported them over and applied them to everyday life. Our six tools serve to help us answer who is behind the information and why? What is the evidence for the claims, and what do other sources say about the source and its claims? While applying our tools we first should try to be not so easily convinced of the first thing we read. We should also be aware of our own biases and try not to allow our emotions get the better of us and cloud our judgment or decisions.

I've mentioned lateral reading quite a number of times, and it simply can't be overemphasized just how important this is. If you're just going to take a single source at face-value and read vertically down the page, then you can become ensnared in the organisation's or author's message regardless of its truth. You need to apply the BDTK as a solid defence against the dark arts practiced by the unscrupulous who lurk amongst us online and elsewhere in our daily lives.

2.4 Applying the BDTK

In this video we apply all the tools of the BDTK to a site (https://www.gapminder.org/) and three videos on the site:

1. https://www.gapminder.org/answers/how-did-the-world-population-change/
2. https://www.gapminder.org/answers/how-reliable-is-the-world-population-forecast/
3. https://www.gapminder.org/answers/how-can-the-world-population-forecasts-be-so-good/

We do this because a Google search revealed that they should be able to answer a couple of questions we're asking. Those questions are, "How did the world population change from the dawn of agriculture (8000 BCE) up to the present day, and what's the prediction up until the end of the century?"

Rather than provide a full edited transcript of video 2.4 here, below is a summary of what we found, which is also given toward the end of the video.

Summary of an application of the BDTK

OK, so let's summarize our application of the BDTK. We found a site with a Google search that appeared to answer our question. We also noted other reliable sources that discussed the same topic. These sites were Our World in Data and Wikipedia. Going back to our original site, we then applied tool 1 of the BDTK, which is, "How reliable is the source of the claim?" We didn't find any immediate issues. In fact, we were given the impression here that the site was reliable and was even used for school teaching purposes.

We then briefly considered the perspective of the site and co-founder, Prof Rosling. Checking on perspective is the second tool in the BDTK (This discussion overlaps with the previous one but can be thought of as starting with checking on Prof Rosling.) Again, we didn't note anything particularly significant that might colour the information presented, except for maybe the criticism that Prof Rosling could be considered optimistic in his views. We also noted that Rosling disagreed with this characterization.

After this, we actually watched the videos from Gapminder and proceeded to check on the evidence presented, which is tool 3 of our BDTK. While checking the evidence we also considered tools 4 and 5, which were "Where does most of the evidence point?", and "Have the claims been verified by somebody else?". We did this by referring to various sources discussing the exact same thing, which were presented in Our World in Data and Wikipedia.

We also considered whether any flawed reasoning was used, which is the last tool of the BDTK. We did this by carefully thinking about how the world population data was visualized. We noted that an alternative choice of axis helped us better understand Prof Rosling's presentation. However, it didn't reveal any flaw in his statements. We also fact-checked his evidence regarding the reliability of the population projections, and again couldn't find any issues.

So here we applied all the tools of the BDTK and were able to discover that the videos we watched were pretty reliable as well as the site itself. If you're interested to learn more about how the world population is changing and why it will slow down, feel free to check out other videos on that website. I've added a few of interest in the box below.

Anyway, this concludes our lecture on the BDTK. From now on each week's quiz will have an additional question that involves the application of the BDTK, which includes the quizzes in blocks 2 and 3. You'll also be applying the BDTK in workshop 1, so you can get more practice in using it.

Further Gapminder videos for Interested Students

Keep in mind these videos are dated 2012.

- How did babies per woman change in the world?
- How did babies per woman change in different regions?
- You can check on the claimed fertility rates yourself as well as inspect the fertility rates of individual countries at OurWorldInData here. As an exercise, what's Singapore's fertility rate? How does it compare to other countries? NB. A fertility rate of about 2.1 is needed to keep a population constant without immigration or emigration.
- The rapid growth of world population, when will it slow down?
- Where do people live?
- Will saving poor children lead to overpopulation? (I'm not exactly sure why, but this last video I've suggested I found moving.)

Our next lecture will continue on where we left off in our textbook and take a look at Chapter 3 – Scientific Explanations.

OPTIONAL VIDEO from legacy HSI1000 lectures

For those who might be interested to learn a little more about the population explosion after WW2.

2.5 The Population Surge from 1945 Onwards

The whole topic on world population represents entire fields of study, and we're very briefly looking at it in this section. We just want to get some idea as to why our population suddenly increased after World War 2 (WW2). While we could keep going deeper and deeper into the reasons, and even look at how individual countries affected the world population during this time, we're not going to do this. We just want an overview, and since this is a science course, we're also interested in any specific discovery or technology that might have made a significant impact, e.g., like the steam engine during the Industrial Revolution.

The number of people living today is the result of two basic things.

1) The fertility rate – how many people are being born.
2) The mortality rate – how many people are dying.

If more people are born than people that die, the population goes up. The opposite causes the population to go down. Therefore, if there is a surge in population then there must be either a sudden increase in the fertility rate, or a sudden drop in the mortality rate, or some positive combination of the two. During the Industrial Revolution, fertility rates remained high and unchanged, at least for a time, but then the mortality rates suddenly dropped for industrialized nations. So, what's going on after World War 2?

Well, you might be thinking "Ah, that's surely the baby-boom, everyone knows about that. A big increase in the fertility rate will surely lead to strong world population growth." While this definitely made a contribution, not all countries underwent a "baby boom". Moreover, this boom was also not sustained indefinitely.

A major contributor to this big population surge was a marked drop in mortality in most of Asia and Latin America. Why did mortality decrease in these already quite populated nations? It's because significant improvements occurred in public health, sanitation, and nutrition that were mostly imported from the developed countries. Here we see again, just like with the Industrial Revolution, fertility rates remained high, but mortality suddenly drops and BOOM, the world population surges, but this time it's in Asia and Latin America instead of the Europe and Northern America.

A growing need for food

Is there a scientific discovery and consequent technology that stands out as having a huge impact on human mortality? Medical advancements helped a great deal, but it is advances in food production and the resulting improvement in human nutrition that had a massive impact. Science and technology played an enormous role, especially with the so-called "green revolution" or the third agricultural revolution. During the 1950s and 60s food production worldwide increased dramatically due to a number of reasons, like the adoption of modern scientific methods of farming, pesticide use for crop protection and a few other important factors. But one of the main contributors was the introduction and widespread use of synthetic fertilizers.

Plants form the base of the food web on land, and plants need nutrients to grow. One of these nutrients is nitrogen, which is often a limiting nutrient for plants. A limiting nutrient means that if you add it to plants, they grow better producing increased crop yields. If the nutrient isn't limiting, then adding more doesn't result in healthier, stronger plants with greater yields.

The issue is, most of the Earth's nitrogen is locked up in the atmosphere in the extremely stable molecule of molecular nitrogen, or N_2. N_2 makes up 78% of the Earth's atmosphere, but it is so very stable and unreactive that very few organisms can break the molecule apart for their own use. Of course, nitrogen isn't just an important nutrient for plants. All living organisms require nitrogen for their DNA, proteins, and enzymes, all of which are essential for functioning. Animals get their nitrogen from eating plants, or eating other animals, which in turn get their nitrogen from plants.

Plants can't access nitrogen from the air, so they need something else to break the stable N_2 molecule apart to obtain the more useable reactive nitrogen. The process of converting N_2 into usable forms of nitrogen is called "nitrogen fixation", and nitrogen fixing bacteria present in the soil and in the nodules of legumes are responsible for carrying out this process.

We find that by the end of the 1800s there were real concerns as to where the exponentially growing population was going to get their food. More people means more food needed, but to harvest more food, you needed greater crop yields. Where was the nitrogen going to come from to generate these higher crop yields? You can certainly use recycled organic waste, like animal manure, but the nitrogen content of it is very low, especially after the high nitrogen losses before and after application. Huge amounts need to be applied to achieve any level of significant success. Additionally, pests, blights, and adverse weather were unpredictable and reduced yields considerably – even causing famines in some cases. The bottom line was that in the late 1890s, none of the options available could solve this challenge.

Haber-Bosch Process

Figure 53. Fritz Haber from Wikimedia: The Nobel Foundation, Public domain, via Wikimedia Commons

Fortunately, in early July 1909, a German Physical Chemist, Fritz Haber (Figure 53), after years of intensive experiments, succeeded in synthesizing ammonia from nitrogen in the air using hydrogen gas.

$$N_2 + 3H_2 \rightleftharpoons 2\,NH_3$$

Within four years, the chief engineer at BASF at the time, Carl Bosch (Figure 52), managed to scale up the small lab experiments to an industrial level. This synthesis, known as the Haber-Bosch process, made it possible to mass-produce inexpensive nitrogenous synthetic fertilizers. However, the use of this fertilizer remained limited between WW1 and WW2. Ammonia synthesis really took off after WW2, and it is said that this process was the detonator of the world population explosion from the 1950s onwards.

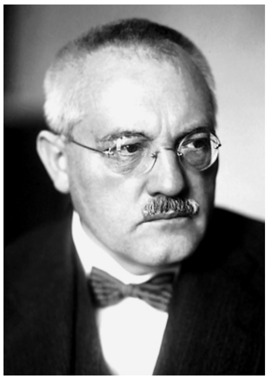


Figure 52. Carl Bosch from Wikimedia: Nobel Foundation, Public domain, via Wikimedia Commons

> Veritasium's YouTube video on the tragic life of Fritz Haber found here.

Application of synthetic fertilizer, along with crop protection from pesticides, and most importantly the use of new breeds of wheat and rice, increased crop yields dramatically across the planet. Crop yields of wheat in the US increased three times, and corn by more than five times. France saw yields for wheat rise by almost six times, and for China it was almost four times. Rice yields in Japan increased almost three times. Yields increased everywhere fertilizer was used with the appropriate staple breeds throughout Latin America and Asia.

In fact, according to a world expert on this topic, Vaclav Smil (reference in the black box below for those interested), I quote:

> Reference to Vaclav Smil article: http://vaclavsmil.com/wp-content/uploads/docs/smil-article-worldagriculture.pdf

"With average crop yields remaining at the 1900 level the crop harvest in the year 2000 would have required nearly four times more land and the cultivated area would have claimed nearly half of all ice-free continents".

Our world in data has quite a lot of material on this particular topic. Figure 54 shows how much of the current world population is fed due to synthetic nitrogen fertilizer. The red part represents the number of people fed by synthetic nitrogen fertilizers. It's basically half the world! We have become utterly dependent on the Haber-Bosch process – in fact, without it, half of us wouldn't even be here!

Our World in Data reference: https://ourworldindata.org/fertilizers

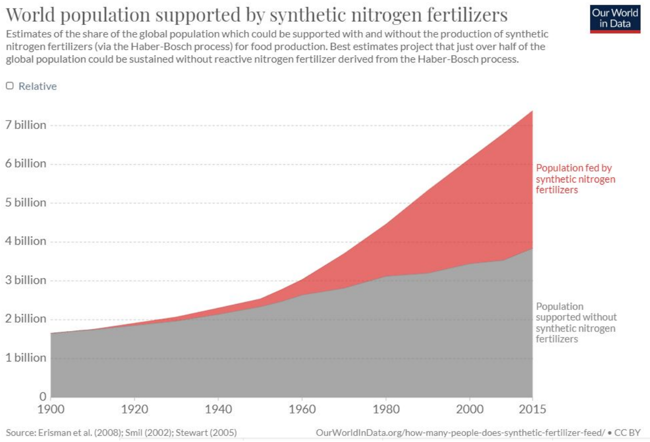


Figure 54. World population supported by synthetic fertilizers from Our World in Data

Our World in Data reference: https://ourworldindata.org/famines

We can also see the effects of this greater supply of food by looking at deaths in the world due to famine. Again, Our World in Data helps us find the relevant data (Figure 55). Here we have the annual rate of people dying due to famine globally per decade per 100,000 people in the world since the 1860s.

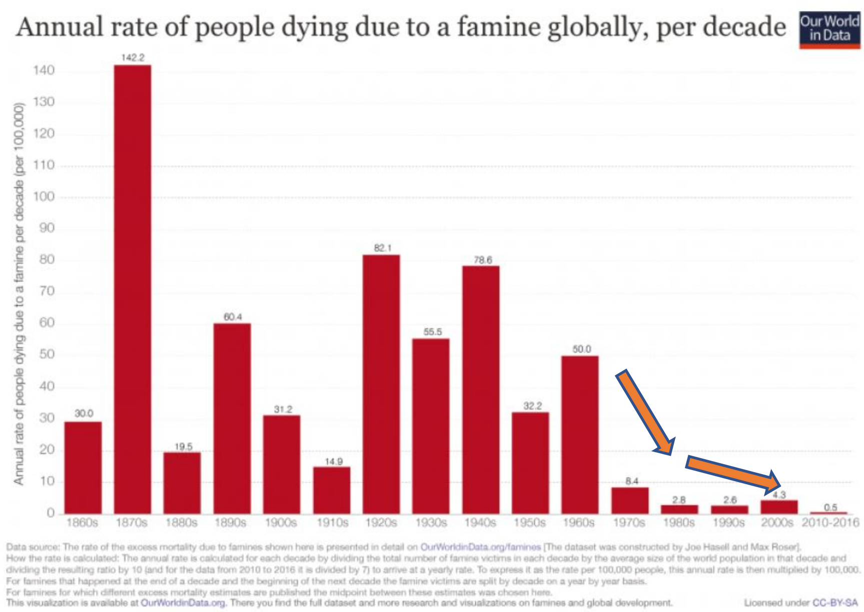


Figure 55. Annual rate of people dying due to famine globally per decade from Our World in Data

A number like 142 in the 1870s means that for every 100,000 people living in the 1870s, 142 people died each year on average due to famine. We notice immediately that once the green revolution ends by the 1960s, there is a very obvious and marked drop in the rate of deaths. So much so, that in the most recent period from 2010 – 2016 we have less than 1 person per 100,000 people in the world dying from famine each year.

Although Figure 55 shows that the number of deaths due to famine has fallen remarkably, it is important to realize that a number like 0.5 deaths per 100,000 per year from 2010 – 2016 is still a very large number of people. Taking the average population of the world over that time to be 7 billion, this works out to be 35,000 deaths per annum – that's a lot of unnecessary deaths because there's more than enough food in the world today to feed everyone. This is also just the tip of the iceberg. Wherever there is death due to famine, there's also many, *many* more people suffering from severe hunger and malnutrition (millions in fact). This is a problem even in developed countries. Problems related to food security is made worse by the pandemic affecting access to food. Climate scientists also project further complications due to climate change that will affect the current food supply. For those interested to find out more, the UN Department of Economic and Social Affairs is a good starting point: https://sdgs.un.org/goals/goal2.

Consequences of unsustainable practices associated with synthetic fertilizer production and application

Of course, all these developments have impacts on the natural world and consequently, humans. The Haber-Bosch process requires a lot of energy to run because it's conducted under high temperature and pressure conditions. It's estimated that 1% of the total world energy production is consumed by just this one industrial process! Moreover, the hydrogen needed to react with the nitrogen is stripped from methane and water with the carbon from the methane being converted ultimately into polluting CO_2. Combined with the CO_2 emissions from the energy consumption, this process accounts for 1.4% of the entire world's global CO_2 emissions!

This is made worse by the considerable inefficiency in the application of the synthetic fertilizer. Due to this, at most, only about half the nitrogen is taken up by the plants, but more typically only a third or even less is used. The rest of the nitrogen either evaporates, gets converted back to N_2 via denitrification, goes into the water supply, or is lost by soil erosion. In principle, up to 85 – 90% of the applied nitrogen could be utilized, but inefficient fertilization practices result in considerable environmental damage. The article by Smil mentioned before discusses this as well.

In Conclusion

This wraps up the section on understanding how we got to a point where the planets climate and biodiversity is affected by a large human population coupled with the need for food and energy. The next section summarizes our findings on human population growth and addresses the final intended learning outcome of this lecture.

3 Scientific Explanations and Models

Intended Learning Outcomes for Lecture 03
You should be able to do the following after this lecture.

(7) *Define* a scientific explanation and *discuss* the two basic ways in which a theory differs from a hypothesis.
(8) *Explain* the difference between two events being correlated and being related as cause and effect.
(9) *Discuss* the basic features of the following types of scientific explanations: (a) cause and effect, (b) causal mechanism, (c) underlying processes, (d) laws, (e) function.
(10) *Explain* Occam's Razor, illustrating its use with an example.
(11) *Discuss* what is a scientific model, the different types and their purpose, and *explain* the difference between a model and a theory illustrating your explanation with an example.

3 3.1 Scientific Explanations – Theories and Hypotheses

In this lecture we'll be continuing our in-depth look into the scientific inquiry by following chapter 3 of our textbook entitled "Explanation". The five intended learning outcomes, or 5 ILOs for short, for this lecture are listed above, and we shall be addressing each of them with its own video. In this video we'll be tackling the first ILO, so we'll be discussing what a scientific explanation is and examining the meaning of the scientific terms "theory" and "hypothesis".

3.1 3.1.1 Scientific Explanations Must be Testable

What is a scientific explanation? It's an account of how or why something is the case, but what makes the explanation scientific is that it MUST be testable. We've already seen a number of examples of this in our first lecture. In that lecture we saw explanations tested in several situations. If the tests failed, then the explanation needed to be revised, or an entirely new one provided. But let's consider an example of an explanation that can't be tested.

You and your friend are having a coffee together. Just as you finish your last drink of coffee, you misplace your mug on the table, it teeters and then falls. You quickly try to catch it, but miss, and it smashes on the floor. Your friend then explains,

"Ah, never mind, it was fate that the mug should be broken. It was meant to be."

Here we have an explanation of why the mug broke— it was fate. But what if you had caught the mug, wouldn't that also be fate? In such a case, you were apparently meant to catch the mug. In fact, no matter whether you catch or miss the mug you could say that it was fate and meant to be.

Do you see? Here we have a situation where no matter what happens, the explanation stands. There's no way of testing whether it really was fate that was responsible for you not catching the mug. Fate could be the explanation for why you missed catching the mug, but it's not a scientific explanation because it's untestable. Therefore, there is no way for us to know for sure whether the explanation is correct or not.

The bottom line is that a scientific explanation for something must be subject to falsification. If there's no way of demonstrating that the explanation is false through experimentation, or "reality checks", then the explanation is not scientific.

3.2 3.1.2 Theories and Hypotheses

Now scientific explanations are frequently associated with two terms – "theory" and "hypothesis". Let's talk about hypotheses first.

3.2.1 3.1.2.1 Hypotheses

What characterizes a hypothesis is that it is tentative or unproven, that is, it hasn't yet been subjected to any testing or falsification. A hypothesis could be just a simple vague hunch about what might be going on, or it could be a finely detailed (but still speculative) account of how or why something is the case. Regardless of the form of explanation a hypothesis might take, it is always tentative or unproven, and it's usually the first step to discovering something new about nature.

3.2.2 3.1.2.2 Theories

Now let's talk about the term "theory", which is a bit trickier. In regular English usage, the term "theory" is often used to denote what is actually a hypothesis. However, from the scientific standpoint, that usage it wrong. In fact, it's because of this misunderstanding that many lay people believe that a scientific theory is unproven or hasn't been subjected to testing.

A scientific theory does NOT imply a wholly untested idea, or worse, a complete guess about the reasons for a limited range of phenomena, a single event or fact. Such explanations are hypotheses, as I've already said. A scientific theory is characterized by the breadth and depth of its explanatory power. Scientific theories are more general structures capable of explaining a much wider variety of phenomena than a hypothesis. A theory is a conceptual framework for providing explanations.

A scientific theory will often contain experimentally well-tested, and therefore, well confirmed rules and principles that reveal underlying explanatory similarities between what might seem to be quite diverse phenomena. Let's consider some examples to understand what this means.

3.2.2.1 Well-established Theories

Consider Newton's three laws of motion and the law of gravitation introduced in the first lecture during the scientific revolution. These laws constitute a scientific theory – an extremely powerful one that has been tested over and over again, and only breaks down under the most extreme conditions. These laws can, and still do, explain and predict the motions of virtually all objects on earth and in space. They serve as a "conceptual framework" for providing explanations for how and why a vast number of things move about all around us.

Recall the germ theory mentioned in the first lecture. This theory, having been tested repeatedly, now explains a vast array of diseases exhibited in not just people, but all kinds of organisms. Again, it represents a conceptual framework for explanations of a vast array of diseases and provides insight into their treatment.

Science contains many such theories – theories that have been repeatedly put to the test and provide breadth and depth in their explanatory power. Theories like the theory of evolution, the big-bang theory, atomic theory, statistical mechanics, the kinetic theory of gases, the theories of special and general relativity, quantum mechanics. The list goes on and on.

The theories I just mentioned all represent "well-established theories". They are "well-established" because they have been tested numerous times in many ways and continue to pass all the tests, but not all theories are like this.

3.2.2.2 Obsolete or Superseded Theories

Often these well-established theories have superseded previous, older theories. Theories that were thought to be correct at the time, but eventually came undone because of new evidence that proved them wrong – like the Aristotelian world view we discussed during the first lecture. These superseded theories, now known to be wrong, are still, to this day, called theories. Here's just one example.

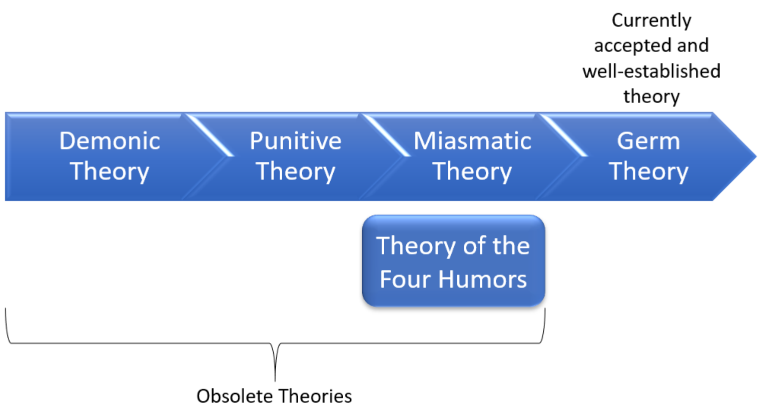


Figure 56. Progress in theories of disease

I mentioned germ theory as currently being the reining theory for the cause of many diseases. But for the longest time, the reigning theory for the cause of disease was demonic theory. Devils and demons were thought to be the cause of disease. This theory gave way to punitive theory, which explained disease as punishment by the gods for evils committed.

Next was something a little more scientific. It was called Miasmatic theory – a theory that you could catch a disease from "bad air" or even "night air", i.e., disease was caused by a gas. In addition to this possibly being the cause of a disease, the theory of the four humors was also employed to diagnose and treat diseases. Incidentally, this was often applied to mothers suffering from puerperal fever as we discussed in the first lecture. One of the treatments was to literally bleed the patient of the "bad blood", which was not the smartest thing to do to someone already severely weakened by the pathogens invading their body.

So, as you can see, even superseded or obsolete theories are still called theories.

3.2.2.3 Novel or Newly Proposed Theories

But in addition to well-established and obsolete theories we also have, of course, novel or newly proposed theories. These are theories that can not only explain phenomena that are already explained by well-established theories, but also explain, or at least hope to, anomalies that the current theory has a hard time supporting. These theories are currently under investigation and being subjected to testing. Whether they survive the rigors of the scientific method and acceptance within the wider scientific community remains to be seen.

3.3 3.1.3 In Conclusion

Of course, well-established theories also have to undergo revision when new evidence is uncovered because science is self-correcting. This is how we end up eventually homing in on the right explanation for things.

As you can see, the term 'theory' is a little more complicated than the term 'hypothesis'. The term 'theory' can apply to well-established and currently accepted explanations, but it can also apply to contested explanations or even obsolete and wrong explanations. As such it's always important when learning or hearing about a theory to clarify the stage of the scientific theory it is at.

Next, we'll learn about a very common type of explanation used to account for observed phenomena: causation and its relationship to correlation.

For those interested, here's a well written article from the New York Times discussing W. Jason Morgan who developed the Theory of Plate Tectonics. It uses "theory" and "hypothesis" correctly and very easy to read.

4 3.2 Causation and Correlation

4.1 3.2.1 Causation

Causation is a very common explanation of phenomena, not just in science, but in everyday life. You were late for a class because the bus you were meant to catch was very crowded and simply drove by your stop. You were then forced to catch a second later bus. The effect is you being late for class and the cause was the first crowded bus not stopping to pick you up. It should go without saying that cause precedes the effect – always. Which is what makes Figure 57 funny.

Figure 57. Author unknown. Shared many times over WhatsApp

Providing a causal explanation may allow us to understand why such phenomenon exist, but causal explanations may not be straightforward or simple. Here's six reasons why.

4.1.1 3.2.1.1 A combination of causes leading to an effect

Firstly, effects can be the result of a *combination* of causes. Let's go back to the crowded bus example again. Say the next bus that comes soon after the crowded one, such that you could catch it and just make it to class on time. BUT, let's also say that you drank quite a lot of water before trying to catch the bus, and now you need to go to the toilet. If the first bus wasn't crowded, you could have caught it, then you could go to the toilet just before class and still get there on time.

HOWEVER, because you were unable to board the first bus, you catch the second one AND are forced to rush to the toilet before class. You end up being late. It's the combination of both the bus being crowded and your need to, err, relieve yourself that makes you late. In this example, only the combination of causes produces the effect of being late.

4.1.2 3.2.1.2 Cause and effect can refer to groups

Secondly, and on a more serious note, cause and effect can be about groups rather than individual facts or events. For example, smoking causes lung cancer means that lung cancer occurs more frequently among those who smoke.

4.1.3 3.2.1.3 More than one cause can result in a specific effect

Thirdly, the same effect can result from separate and distinct causes. Lung cancer can also be caused by elevated levels of radon – a natural radioactive gas, asbestos exposure and elevated levels of other chemicals like arsenic, beryllium, cadmium, coal and coke fumes, silica and nickel. It can also be caused genetically, especially if it is present in the family history.

4.1.4 3.2.1.4 An effect might not result from a given cause in every case

Fourthly, effects need not always be invariably associated with a given causal factor. For example, although smoking is the leading cause of lung cancer, not all smokers contract lung cancer. Incidentally, you sometimes hear people say that smoking is fine because my grandfather smoked like a chimney all his life and he didn't get lung cancer. That's like saying charging an enemy machine gun picket with 100 soldiers is safe because you know the one guy that happened to make it through the hail of bullets.

Another example is children drinking fluoridated water have fewer problems with tooth decay compared to those that don't. There is a causal link between fluoride and tooth decay. However, it isn't true that children who drink fluoridated water will be completely free from tooth decay.

4.1.5 3.2.1.5 Causal explanations can be negative

The previous example brings us to our fifth complication. Sometimes causal explanations can be negative. For example, fluoridation of water helps **prevent** tooth decay, or wearing a mask helps **prevent** COVID transmission.

4.1.6 3.2.1.5 Causal explanations can involve a series of linked causes and effects

Lastly, causal explanations can involve a series of linked events, like *A* causing *B* which in turn causes *C*. Terms like proximate and remote are sometimes used to describe the relationship between these causes. *A* is a proximate cause of *B*. Likewise, *B* is a proximate cause of *C*. *A* can be termed as a remote cause of *C*. As an example, I've embedded a YouTube video illustrating how a butterfly causes a boat to crash through a roof with this video. After watching the video, you should be able to state the proximate causes and effects as well as give some examples of a remote cause and effect.

A butterfly causes a boat to crash through the roof of a house: https://youtu.be/u6dAvtbjFKQ

4.2 3.2.1 Correlation

Now that we've considered cause and effect and some of the subtleties that can arise when thinking about causes, let's discuss correlation. Causal explanations are closely related to correlation, but what exactly is correlation?

Correlation is the degree to which two properties, traits or characteristics move in coordination, or in sync, with one another. For example, let's take the height of adult men and shoe size as our two properties. There is, in fact, a tendency for taller men to have larger shoe sizes. I use 'tendency' here because the relationship isn't perfect. I can also rephrase this as a correlation between adult male height and shoe size. While I can't predict an exact shoe size by only knowing a male adult's height, I can give a range of shoes sizes that are likely to fit.

4.2.1 3.2.1.1 Perfect, positive, negative and no correlation

An example of **perfect correlation** is when there is a direct 1 to 1 correspondence between changes in the two properties. An example of this can be found in many tree species where the age of the tree in years is perfectly correlated with the number of rings in the tree's trunk. The older the tree, the greater the number of rings – no exceptions. Perfect correlation is rare though. It's much more common, if there is a correlation, for there to be only a *tendency* for the two properties to move in coordination with one another like the height of adult males and shoe size.

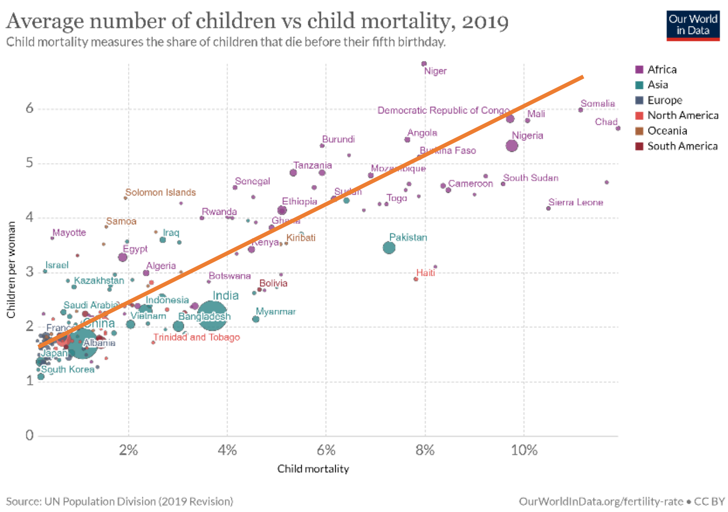


Figure 58. From [Our World in Data](). Scroll to section "Increasing well being and status of children".

Such a tendency, or a correlation, can be seen with fertility rate and child mortality, things discussed in the last lecture. Recall that when mortality dropped, and this was largely due to children not dying as much, the population surged. This happened during the industrial revolution and again after the green, or third agricultural, revolution. Initially, once the children start surviving, the fertility rate remains high for a short time producing a population surge, but then the fertility rate falls rapidly. As a result, there is a correlation between fertility rate and mortality rate of children. Take a look at the data for this correlation found in [Our World in Data]() for the year 2019 (Figure 58).

In Figure 58 child mortality is on the horizontal axis, and, total fertility rate, measured as children per woman, is on the vertical axis. Can you see the tendency for countries with high child mortality to also have high fertility and vice versa? The solid line drawn through the data on the figure represents the correlation between these two quantities. Most of the countries are randomly scattered above and below this line, so it's not a perfect correlation. If it were, all the countries would lie perfectly on the line.

Figure 58 is an example of a **positive correlation**— when one of the quantities goes up, the other quantity also goes up, or, when one goes down, the other also goes down. **Negative correlations** can also exist — when one of the quantities goes up, the other quantity falls. For example, we might expect that the number of hours spent gaming in a week to be negatively correlated with the number of hours spent studying. Lots more gaming hours means less time studying – a negative correlation.

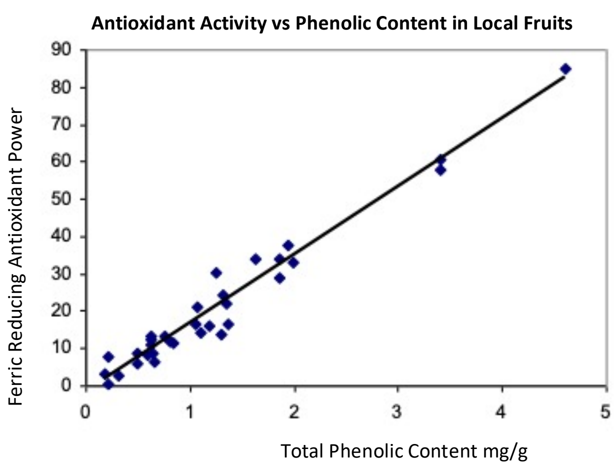


Figure 59. Strong positive correlation found in research conducted by NUS' Department of FST

You will also have to consider the strength of a correlation. Figure 59 is an example of a strong positive correlation. See how the data isn't scattered very much away from the line? This means it's a strong correlation. Remember, when it's a perfect correlation all the points are on the line. A weak correlation is when the points are significantly scattered away from the line. Figure 60 is an example of a weak negative correlation. It becomes very hard to even draw a trend line through the data.

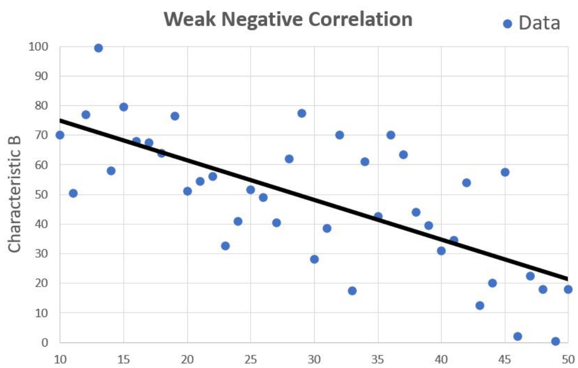


Figure 60. A weak negative correlation

Of course, we can also have **no significant correlation** at all. In this case there is be no significant relationship at between the two properties, and the plot would look pretty random, like Figure 61.

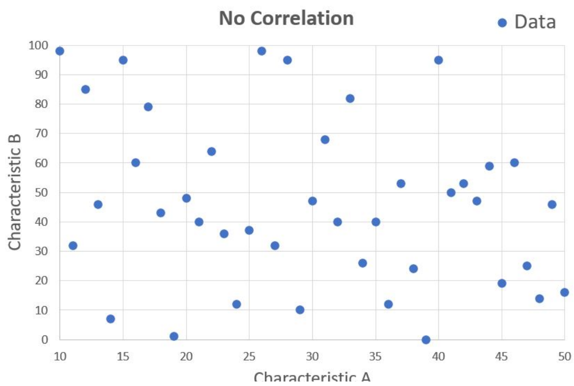


Figure 61. No correlation found

Some people mistake no correlation with negative correlation, but they are not the same. No correlation literally means no relationship, whereas negative correlation means there **is** a relationship and that is where one property goes up, the other goes down. For example, there's no correlation between a student's grade and how tall a student is. A student scoring well could be short or tall or average – it does not matter.

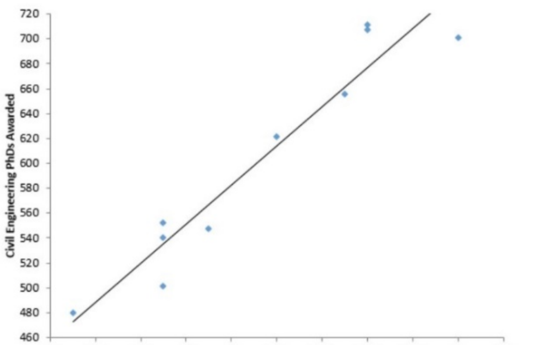


Figure 62. Correlation between per capita consumption of mozzarella cheese and the number of civil engineering PhD's awarded in the U.S.A. Data is reformatted to be consistent with our presentations of correlations in this video. Data from [Tyler Vigen's web site](#).

4.2.2 3.2.1.2 Relationship between cause and correlation

When we identify a cause for an effect, we expect there to be some kind of correlation – positive or negative. HOWEVER, and this is important, **just because two things are correlated doesn't mean there is a causal relationship**.

You might be surprised to know that it's not that hard to find correlations. Basically, anything that increases as time goes by will be correlated with something else that increases, or decreases, as time goes by. An example is given in Figure 62. Look at the strong positive correlation between per capita consumption of mozzarella cheese and the number of civil engineering PhD's awarded in the US! This is a nonsensical correlation that certainly doesn't represent any causal relationship. In fact, there's a web site dedicated to such silly correlations by Tyler Vigen, linked below. Check it out if you're interested.

Tyler Vigen's website: https://www.tylervigen.com/spurious-correlations

The bottom line is, for causal relationships, like the fertility rate linked to child mortality rate, you expect there to be a correlation. BUT, finding a correlation between two properties certainly doesn't mean they are causally linked in some way. Oh, and just for the record, while child mortality is a cause of lower fertility rates, it isn't the only cause.

In the next section, we'll look at other ways scientists explain observations.

5 3.3 Types of Scientific Explanations

In this section, we'll be discussing different strategies scientists can adopt to explain some phenomena. Often, these strategies enhance a cause-and-effect type explanation, leading to a greater understanding of the phenomenon being studied. For example, explaining that carbon dioxide emission causes global warming, or cigarette smoking causes lung cancer, or low child mortality causes low fertility rates are all useful, but we would also really like to know *how* one causes the other.

5.1 3.3.1 Causal Mechanism

Our first strategy is to provide a causal mechanism. A causal mechanism is a linked chain of causes, taking us from the remote cause, through a series of proximate causes, eventually leading to the effect we're explaining. Sometimes this chain is currently under investigation, so you might hear scientists say they have established a link, but don't yet know the mechanism involved. For example, we know that smoking causes lung cancer, but the exact physiological mechanism of how the carcinogens in cigarette smoke ends up causing uncontrolled cell growth in the lungs isn't yet understood.

Below, I briefly interview Professor Lee who's the next lecturer in this course. In his section of the course he'll be talking about climate change and global warming and its relationship to scientific inquiry. I've asked to interview him here so he can give you an example of a causal mechanism linking CO_2 emission to global warming.

Prof Bettens: So, what I was wondering, Professor Lee, could you explain to us how we get from the cause, which is CO_2 emissions, to the remote effect of global warming?

Prof Lee: Right, so this is an incredibly complicated system that we need to describe. I'm not going to describe it in the complexity that would probably be necessary to be accurate, but we can think about it in a simple mechanism. Certainly, the reason why the Earth is hot is because it receives energy from the sun. The solar radiation heats up the Earth's surface.

Prof Bettens: So, the sun causes the Earth to warm.

Prof Lee: Yes, the sun causes the Earth to warm. Because the Earth is warm, it is also radiating energy and it radiates it upwards, back towards space and back towards the atmosphere. That radiation is going to get absorbed by the atmosphere because there is carbon dioxide in the atmosphere.

Prof Bettens: So, the Earth causes the atmosphere to warm.

Prof Lee: Indeed.

Prof Bettens: Because there's CO_2 in it.

Prof Lee: Yes, so we have a mechanism now where the sun causes the Earth to warm, and the warm Earth causes the atmosphere to warm. Because the atmosphere is warm it also radiates energy, and some of that radiation is going to be directed back towards the Earth's surface, and that causes the Earth's surface temperature to warm even more than it would otherwise be in the absence of the atmosphere.

Prof Bettens: So, there you go, that's how CO_2 emissions causes the Earth to warm up even more. I suppose if there was *even more* CO_2 in the atmosphere there would be *even more heating up of the atmosphere* and *even more heating of the Earth* in turn.

Prof Lee: Indeed, yes.

Prof Bettens: OK, thanks.

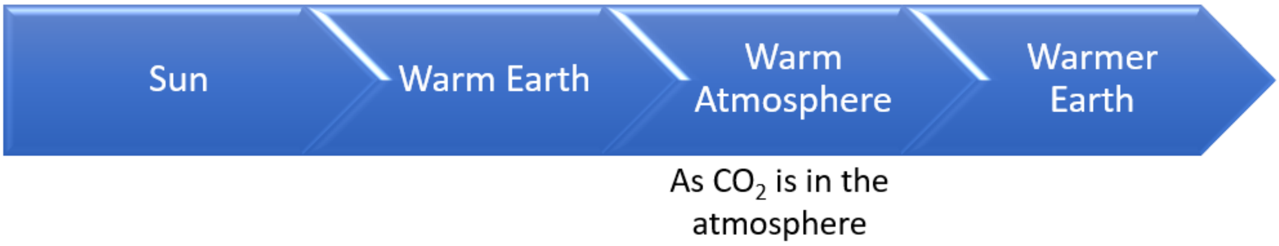


Figure 63. Highly simplified causal mechanism of how CO_2 emissions causes global warming

Providing a causal mechanism clearly enhances our understanding of the phenomenon and may even provide us with a means of reducing the effect if it is bad, enhancing it if it is good, or protecting it if the effect is important and must be maintained, etc.

Just knowing a remote cause and its effect is only the first step in any scientific inquiry. Working out a causal mechanism provides a much clearer picture of what's going on. But this type of explanation can still leave us wondering why and how any particular proximate cause results in an effect.

5.2 3.3.2 Underlying Process

This brings us to the second type of explanation for a phenomenon, which is to appeal to some underlying process. In this case we are *not* looking to say something causes something else to happen. Here we go down a level and describe the observed phenomenon in terms of a more fundamental process. It's a reductionist approach— the description of the observed phenomenon is reduced to a basic level and then *re-described* in terms of processes taking place at this more basic level.

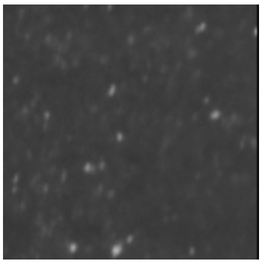


Figure 65. Brownian motion taken from Wikimedia: Jkrieger am Deutschen Krebsforschungszentrum in der Arbeitsgruppe B040 Biophysik der Makromoleküle

Let's utilize an example from the textbook to understand this more clearly. It's about something called Brownian motion (Figure 65), which was quite mysterious when first discovered in 1828 by Robert Brown (Figure 64).

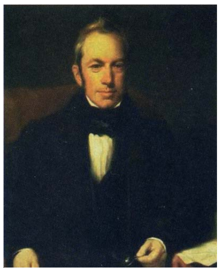


Figure 64. Robert Brown from Wikimedia

Figure 65 illustrates Brownian motion and in this figure we have really tiny fluorescent latex spheres in water. Notice how they are all moving about apparently of their own accord, almost as if they were alive. This type of haphazard motion of particles in liquids is called Brownian motion. For almost 100 years no one had any idea how it could happen until Albert Einstein explained it in 1905.

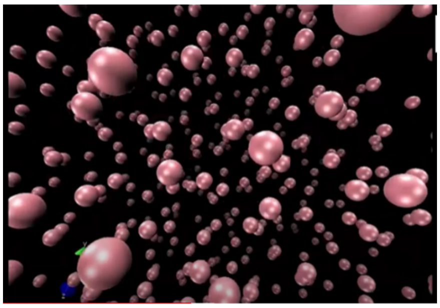


Figure 66. Simulated water with the molecules shown as spheres. Taken from the video created by Prof Bettens.

In water, the water molecules are crowded in on each other and they are all moving about in the solution banging, crashing and bouncing off of each other. Figure 66 is an example of that sort of thing. Each sphere represents a water molecule (water isn't a sphere, but physically it is nearly that shape). It's very crowded, so I've had to cut down the actual physical extent of the spheres so that you can see what's happening. If I show you how crowded it really is, it looks like Figure 67.

Figure 67. Same as previous simulation image, but with the spheres their "true" size in the liquid.

If we now put a particle in with the water, it too is going to be crashed into by all the water molecules surrounding it, making the particle wobble and randomly "walk" about. Figure 13 shows a 2D simulation of that happening for 5 particles (highlighted in yellow) that collides with a set of 800 particles. The 5 yellow particles leave a blue trail. The motion the yellow particles are undergoing is the Brownian motion. Note that in this example the explanation of the phenomenon literally involves the description of the underlying process and not a series of linked causes and effects.

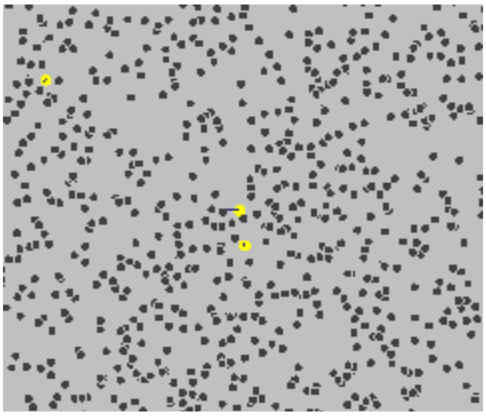


Figure 68. [Simulation of Brownian motion from Wikimedia]: Lookang Author of computer model Francisco Esquembre, Fu-Kwun and lookang (this remix version)

5.3 3.3.3 Laws

Some phenomena are explained through scientific laws. These are just generalized descriptions of regularities that have been found to occur in nature. For example, what happens if the volume of a container of gas is reduced while its temperature remains constant? The pressure increases. Why?

Figure 70. [Robert Boyle from Wikipedia.]

Robert Boyle (Figure 70), in 1662, showed, through experiments on air, that the pressure of a gas varied in inverse proportion to its volume, provided the temperature remained fixed (Figure 69). This is known as Boyle's law. So, as we reduce the volume, the pressure increases in inverse proportion. The explanatory power of laws like these comes from their ability to reveal how particular events are instances of generally understood regularities in nature.

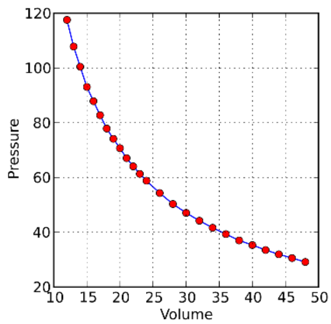


Figure 69. [Robert Boyle's original data from Wikipedia]: Krishnavedala

This law, like others, tends to be thought of as universal, so we expect Boyle's law to hold for all gases, although we know now that gases under extreme conditions can deviate significantly from this law. As another example, we mentioned Newton's laws of motion and law of gravity in the first lecture – again these are expected to hold universally.

These types of laws will be familiar to students of science. In the humanities, there are other types of laws that exist which are statistical in nature. For example, the law of supply and demand is quite fundamental to economics, or the law of reciprocity in psychology. There are many such laws, and again they are rooted in how particular events are instances of regularities that are observed to occur.

So you can see what I mean by a law being "statistical in nature", let's consider the law of reciprocity which says (in simple terms); when someone does something nice for you, you will have a deep-rooted psychological urge to do something nice in return. In fact, you may even reciprocate with a gesture far more generous than the original good deed. This type of law is statistical in nature, meaning that you don't expect it to be obeyed in every case, but there is a tendency for it to occur more often than not. Such laws can also be used to explain human behavior, just like Boyle's law can be used to explain the behavior of gases.

5.4 3.3.4 Function

The final strategy scientists use to explain a phenomenon is function, that is, to explain something based on the purpose it fulfils. Why am I wearing this black shirt? Because it covers my torso as required by social norms. The black also gives a good contrast to the background in the lecture video and doesn't make me look so, err, large shall we say. I explained my wearing of a black shirt based on the function it performs.

Why do we have a heart? Because it is the organ needed to pump blood around the body. Why does a particular trait dominate in a certain species? Because that trait confers a definite evolutionary advantage to members of the species with that trait. These are examples of function being used to explain why something is.

Figure 71. Congee taken from Wikimedia: Daiju Azuma

It is also used to explain human behavior, like why someone might be eating rice porridge (Figure 71) for lunch. Maybe the person is not feeling well. Or one country went to war with another because the first lacked a necessary resource the second had but refused to trade. Functional explanations are often used, not just in the physical, biological and medical sciences, but in the humanities and social sciences as well.

5.5 3.3.5 Explanatory strategies can be interrelated

All these ways of explaining things tell us how and why something is the case, but these explanations often lead to more questions requiring explanations. Why is the sun hot in the first place? How does the sun heat the Earth? Why does sunlight not significantly heat the atmosphere, but the warm Earth does?

Consider Boyle's law for a moment. Why do gases follow this inverse proportion law? Providing an explanation requires us to go deeper, and we realize that our list of strategies for providing explanations are interdependent. As an example, let's consider the case of Boyle's law. We can explain further by considering the following.

Gases are made of huge numbers of molecules, or atoms, depending on the type of gas, and they are moving about in a haphazard manner in the container they are in. They strike the walls and bounce off. The huge number of collisions occurring with the walls each second produces a constant outwards force on the walls—this is pressure. By reducing the volume of the container, you increase the frequency of the collisions with the walls, thus increasing the outwards force on the walls, that is, the pressure goes up.

This explanation for Boyle's law is a call to the underlying process of this behavior of molecules and atoms. It's a very crude description of the kinetic theory of gases – a theory that explains the behavior of all gases and their corresponding laws and can even be used to help understand the behavior of liquids.

We can see a definite interdependence between the different ways of explaining phenomena. The type of strategy adopted will depend on the questions we ask and the level of detail needed in the explanation. In science the questions seem never ending, but each time we explain something we achieve a deeper and fuller understanding of nature and the universe around us.

We'll finish up this section on the types of scientific explanations, all of which are testable, and consider in the next section how we might go about choosing competing explanations for the same phenomenon.

6 3.4 Occam's Razor

Often there can be more than one explanation for a phenomenon. If that's the case, then on what basis do we have to choose one over another? We could devise tests of each explanation, which we know is part of our scientific method, and eliminate any explanation that fails the test. But this may require considerable effort and expense, when it may not even be necessary. What we can first do when sorting through possible explanations is to apply Occam's Razor.

Figure 72. [Willian of Ockham from Wikimedia](): self-created (Moscarlop), CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Occam's Razor is named after William of Ockham (Figure 72), an English monk, philosopher, and theologian believed to be born on Ockham in 1285. He has been credited with the Occam's Razor, a methodological principle, that we still apply today. It can be used to help figure out which explanation is most likely to be correct.

The version of Occam's Razor we shall use can be found in our textbook in Chapter 3, page 43. It states, "Given competing explanations, any of which would, if true, explain a given puzzle, we should initially opt for the explanation which itself contains the least number of puzzling notions.". The rationale behind making this choice is that if a puzzle can be explained without introducing any additional puzzling notions, then there's no good reason to introduce the aforementioned additional notions.

Another way of stating Occam's Razor might be to choose that explanation which is least complex and/or most plausible. Again, why add additional complexity to an explanation when a simpler explanation will suffice? The greater the complexity, we might expect, the greater than chance that something is wrong.

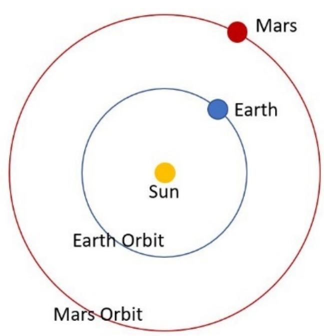
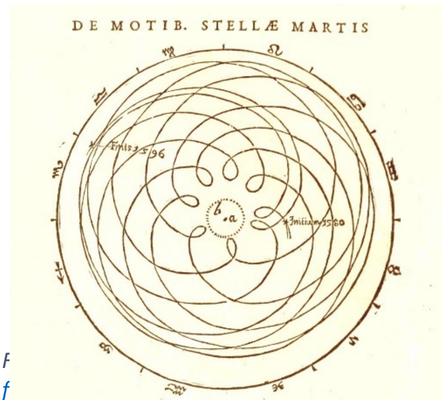


Figure 73. Copernicus' Sun-Earth-Mars System



We have already seen an example we could've applied Occam's razor to. Recall in lecture 1, during the scientific revolution, Copernicus came up with a model of the known solar system (Figure 73) that at the time was considerably simpler than the currently accepted one by Ptolemy (Figure 74).

Both explanations for the motions of the planets equally explained their locations throughout the year. So which explanation is more likely to be correct? Applying Occam's razor, we would have to cut away Ptolemy's model and focused our efforts on trying to test Copernicus' model – which Galileo did.

Of course, there's no guarantee that the simplest explanation or the explanation with the least number of puzzling notions, is the correct explanation. But it is wise to first consider the simplest and least puzzling explanation until we can prove it wrong. Only then are we forced to move onto more complicated explanations.

For example, you come home late one evening, dump your Ez-link card on the table then crash on your bed. The next morning you wake to find your Ez-link card isn't on the table where you're pretty sure you left it. Where could it be? Is it on the floor? Maybe you didn't leave it on the table, and put it someplace else? Maybe another family member took it? Maybe someone crept into your flat while everyone was sleeping and stole just your Ez-link card? Perhaps it simply disappeared?

Occam's razor would say first check under the table – it's the simplest and least puzzling explanation, but if it's not there, then you have a mystery, and we're forced to consider the more complex explanations. Depending on how certain you were about leaving it on the table, you could either just ask your family members if they took it or start looking for it in plausible locations. Someone creeping into your house to steal just your card seems pretty unlikely (why steal only the card?) and there's no evidence of a break in. The card disappearing into thin air is just not possible. Applying the BDTK here helps us by using the last tool "Does the claimant use flawed reasoning?" Matter can neither be created nor destroyed. Objects simply do not disappear.

I'll finish up this section with an example of a conversation borrowed from Carl Sagan. It helps illustrate the use of Occam's razor and highlights the idea of an explanation being testable, which I discussed in the first video of this lecture. I'll be asking Prof Lee again, the next lecturer in the course, to help me out.

6.1 Conversation with Prof Lee

Prof Bettens: OK I have here with me Professor Lee who's the next lecturer in this course after my part of the course, so I'm going to ask him a few questions because he has a rather unusual claim, and that claim is that he has a dragon in his flat. Now that's a pretty wild claim because I don't think any dragons been seen at all, ever, but anyway let's just accept that that might be true. [Prof Bettens turns to Prof lee and asks] So can I come over Adrian and see this dragon of yours?

Prof Lee: Yeah, you can definitely come over. Of course, you can come over.

Prof Bettens: And can I see it?

Prof Lee: Ahh, no. No you can't see it; it's an invisible dragon. I told you it was an invisible dragon.

Prof Bettens: OK, right, right. Yeah, I forgot. OK, so it's an invisible dragon. Yes, it's invisible so I can't see this dragon?

Prof Lee: That's right. You can't see it.

Prof Bettens: But I surely can feel the dragon, right?

Prof Lee: If only. It's an ethereal, invisible dragon.

Prof Bettens: Ethereal, what does that mean actually?

Prof Lee: You can't touch. It's not corporeal.

Prof Bettens: I see, so my hand would pass right through this dragon, right. So, it's invisible and it's ethereal. But it's a dragon though, it'll probably make quite a lot of noise I expect.

Prof Lee: No, no, no. This is specially trained ethereal, invisible dragon. This is a ninja, ethereal invisible, dragon.

Prof Bettens: Ha! A ninja dragon. Really?

Prof Lee: Completely silent, really, yeah, yeah.

Prof Bettens: OK, so we've got an invisible, ethereal, ninja dragon. OK let me think what else I can do. OK, it surely walks on the floor, so I could put some flour on the floor, right, you should be able to see the footprints of the dragon.

Prof Lee: Well, apart from the fact that it is ethereal, it's also flying. It always flies, it never lands on the ground.

Prof Bettens: OK this is starting to sound a bit funny, but what about the heat? The thing gives off heat, so if I had an infrared camera I should surely be able to see the thing, right? It should be able to be detected with an infrared camera.

Prof Lee: No, no. The IR camera won't detect it because its breath is heatless.

Prof Bettens: It's heatless?

Prof Lee: Yeah, Yeah. Now it's an ethereal, invisible, ninja, always flying, heatless dragon – it's very special.

Prof Bettens: Yes, yes. It *is* very special, and how do you know it's there actually?

Prof Lee: You trust me? Why don't you believe me?

Prof Bettens: Uh, because I can't think of any test that could possibly… Well maybe I should just simply believe you.

Prof Lee: Yeah. I think so. We've had a friendship for a long time. Why wouldn't you believe me?

Prof Bettens: Yeah, yeah, well at least that's true.

6.2 Summary of Conversation with Prof Lee

Do you see the issue here? The claim that there's a dragon in his flat is clearly untestable. Every experimental test that I come up with, he has a reason for why it won't work. I'm sure if I continued, he would have an excuse as to why I can't test his claim any further.

So, we have a situation where we can either simply believe Prof Lee that he has an invisible, ethereal, ninja, flying, heatless dragon in his flat, or we can apply Occam's razor and say it's all in his head. I admit that's one puzzling notion because apart from this one thing I know Prof Lee to be quite a reasonable and logical person, but at least it's only one puzzling notion. To accept his claim, I would have to require a whole bunch of puzzling notions to be true. Many of which simply don't match with our idea of the way the world works.

That's it for this section on deciding how we can choose between competing explanations for puzzling phenomena. In the next section we'll be discussing scientific models. This topic isn't covered in our textbook, but we actually think it's important enough that it warrants its own section.

7 3.5 Scientific Models

Models are under the topic of "explanations" because very often this is exactly what models are about – and we'll see shortly where models fit into the various explanatory strategies we mentioned earlier this lecture. However, models aren't just about their ability to explain phenomena. They can also be used to test those explanations, make predictions and projections, and enhance our understanding of nature and even aid in the research of figuring out what is going on. That is, they can be a tool used to better analyze what's occurring in the real world.

So, what is a scientific model? A scientific model is a cut-down and simplified representation of real-world objects, systems or events. They are idealizations of reality, with the extraneous and hopefully irrelevant parts of reality ignored, or treated very crudely or simply. Scientific models can be broadly classified into three categories: Physical models, mathematical and/or computer models, and conceptual models. To get a clear idea of what these are, I'll talk about each of them now with examples.

7.1 3.5.1 Physical Models

Figure 75. [A globe, from Wikimedia](): John Phelan, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

These are actual physical objects representing some aspect of nature. For example, a globe – a model of planet Earth (Figure 75), or some other planet or star, is a physical model. It can be used for all sorts of things, like helping you understand why it's a different time of the day at different places on Earth, or why in Summer, north of the Arctic circle, the sun doesn't set, and in winter it never rises. It is a tool that assists in understanding reality.

To understand why it can be daytime in Singapore, and nighttime in New York at the same time, you could refer to a globe and describe the underlying process of how the sun and the rotating earth system leads to different times of day for the same moment in time.

But physical models, like all models, can also be used to help analyze and study the real system they are meant to represent. There are many such examples, like architectural models of buildings can help with visualization of internal relationships within the structure or external relationships of the structure to the environment. Figure 76 is a picture of a scale model of Singapore's Marina Bay area from 2006 exhibited at the URA Gallery Museum.

Figure 76. Physical model of the Marina Bay area taken from Wikimedia: No machine-readable author provided. Calvin Teo assumed (based on copyright claims)., CC BY-SA 3.0 <http://creativecommons.org/licenses/by-sa/3.0/>, via Wikimedia Commons

To assist in better understanding reality, the physical model can be augmented with instruments to make measurements of what's happening in and around the model. Such measurements can assist in optimization and the design of equipment or processes. For example, the instruments may measure the external flow of air or water around model buildings, vehicles, people, or hydraulic structures. The physical models can be placed inside a wind tunnel (Figure 77), like the one on campus, or water tunnel (Figure 78) or a wave tank (Figure 79) for the testing and making of measurements. Internal flows can also be studied using physical models with instruments. For example, in the design of ductwork systems, pollution control equipment, food processing machines, and mixing vessels.

Figure 77. [Wind tunnel from Wikimedia](): NASA Ames Research Center, Public domain, via Wikimedia Commons

Figure 78. [Water tunnel from Wikimedia](): U.S. Navy, Public domain, via Wikimedia Commons

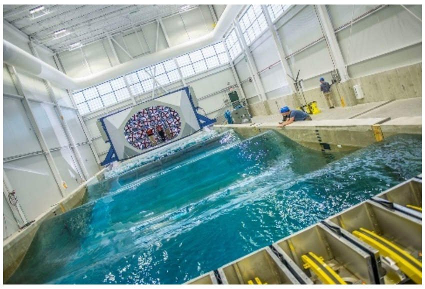


Figure 79. [Wave tank from Wikimedia](): Jplourde umaine, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

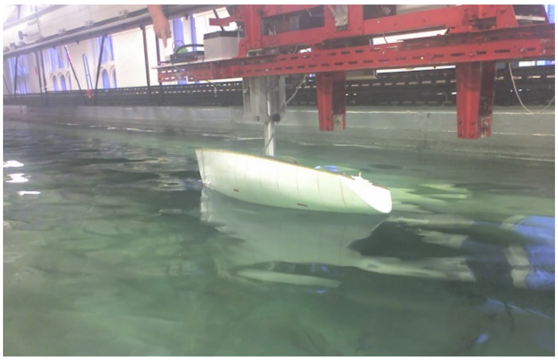


Figure 80. [Towing tank from Wikipedia](): Xtrememachineuk at English Wikipedia, CC BY-SA 3.0 <http://creativecommons.org/licenses/by-sa/3.0/>, via Wikimedia Commons

Of key importance in all these models is getting the scale right, because the forces and physical laws that operate in the larger real-world environment don't simply reduce and apply equally on a smaller scale. Nevertheless, when done properly (Figure 80), physical models can simulate complex air and water flow to a degree of accuracy that is not possible with other types of models.

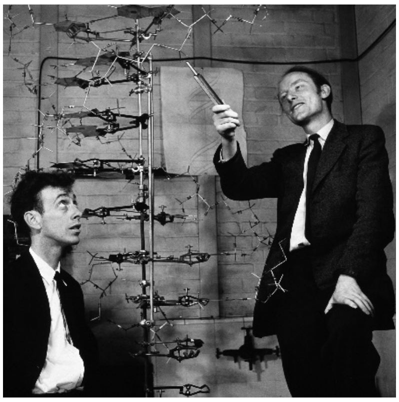
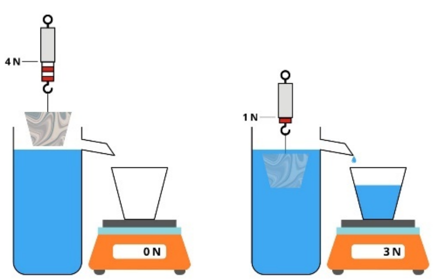


Figure 81. Watson and Crick with DNA physical model. Picture in the public domain.

Physical models need not only be smaller than the thing they represent. They can also be larger. For example, chemists often use different types of physical models to better understand the relationships between atoms, or groups of atoms in a molecule, or to assist in understanding chemical reactions. The discovery of the structure of DNA by Watson and Crick was greatly faciltated by physical models of the molecules involved, and in Figure 81 we see them pictured next to a physical model of DNA.

So, physical models are actual physical objects that assist scientists and engineers to better understand the real world in several ways.

7.2 3.5.2 Conceptual Models



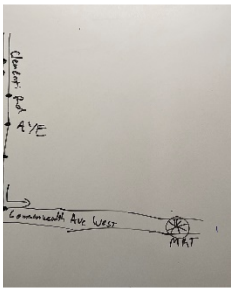


Figure 82. Crude map for getting from Frontier to Clementi MRT

Conceptual models are cut down versions of reality with only the parts of interest included. A map is one example. It's a conceptual representation of real-world physical locations and relevant objects. If someone asks you for directions from, say, the faculty of science to Clementi MRT, you might sketch them out a map (Figure 82). You wouldn't include all the things on the map between FOS and the MRT, just the relevant features needed for someone to find their way there. It conveys the necessary concepts and ideas to navigate in the real world.

Diagrams and figures representing ideas and concepts in science can be thought of as conceptual models. A diagram used to help explain and even analyze Archimedes' Principle (Figure 83) is an example of a conceptual model. It doesn't necessarily directly represent what might be happening in a lab – some extraneous details are left out. But it does contain all the important information needed to understand what's going on.

Figure 83. [Archimedes principle from Wikimedia](): MikeRun, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

A diagram of a block sitting on an inclined plane, with all the forces indicated (Figure 84), is a conceptual model of a real block (Figure 85) sitting on a slope. Again, there's some things missing from the diagram, and the objects and surfaces might not even be the same as the diagram. Yet, it contains what's needed to describe what is happening, even if the block is not moving.

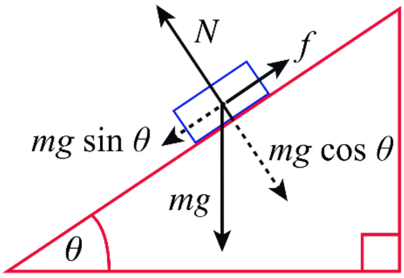


Figure 84 [Block on inclined plane from Wikimedia: Jer S](#).

Figure 85 Real-world block on inclined plane.

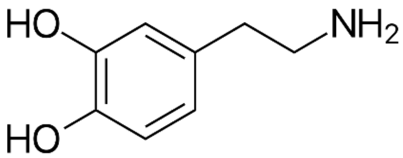


Figure 86. [*Lewis structure of dopamine from Wikimedia*](#)

Conceptual models can be quite abstract, and not physically look at all like the real-world objects they may represent. For example, Lewis's chemical structures of molecules are conceptual models (Figure 86). Chemists use them to explain all kids of phenomena including why some chemical reactions can occur, and others not, or even use them to make predictions of what chemical transformations could take place.

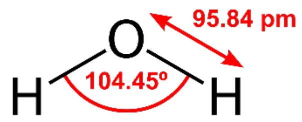


Figure 87. [*Lewis structure of water from Wikimedia*](): *Dan Craggs*

A chemist knows there's no lines between atoms in the real-world molecules (Figure 87), and that the structures themselves bear no resemblance at all to the macroscopic material they represent (Figure 88). Yet for their intended purpose, these chemical structures are critical for understanding, interpreting and predicting a lot of chemistry.

Figure 88. [*Real drop of water from Wikimedia*](): *José Manuel Suárez, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons*

Conceptual models of reality might appear quite similar to real world objects, but they could also be diagrams illustrating processes, even one as abstract as a circuit diagram. All conceptual models depict ideas and concepts within science and can be used to explain phenomena and make predictions in the real world, just as physical and mathematical/computer models can.

7.3 3.5.3 Mathematical/Computer Models

We group math and computer models together because very often the math involved in the models is coded up on a computer. This is done so that the computer can do all the tedious calculations necessary to apply the mathematics. Indeed, sometimes the mathematics is so complex that only a computer *can* solve it.

So, what are these types of models anyway? It's when math can be used to describe nature in some way. We've actually already met some mathematical models. When we discussed Boyle's law earlier in this lecture, we could have expressed this law in a math formula. Pressure of a gas varies in inverse proportion to its volume when the temperature is kept constant, i.e., $p \propto \frac{1}{V}$, or put another way, pressure equals a constant divided by volume, i.e., $p = \frac{A}{V}$. These math formulae models how the real-world pressure and volume of all gas varies when the temperature is fixed.

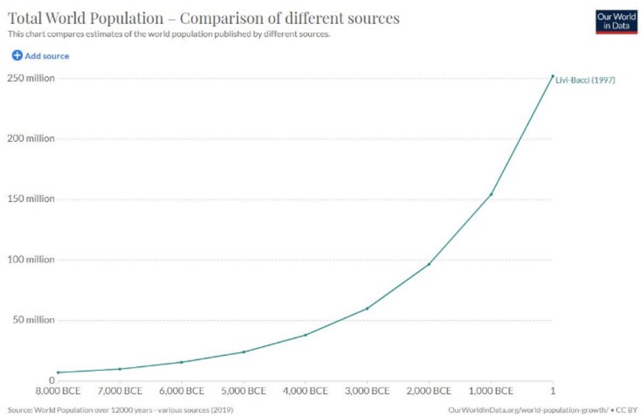


Figure 89. Plot of world population from 8000 BCE to 1 CE from Our World in Data

Recall in lecture two, we saw the population of the world plotted against time. The curves drawn to connect the population estimates given by different researchers on the Our World in Data site were drawn using simple straight lines, which are math functions. These math functions ($y = mx + c$) were used to model how the world population varied between the estimated population points given by the researchers. Here math was used to model how the world population varied over time by filling in the gaps between population estimates.

When we looked at the correlation between two properties (Figure 60, for example), and we drew a trend line through the data, we were mathematically modelling the ideal relationship between the two properties. We learnt only when the correlation is perfect will the points lie perfectly on the line, but the correlation may not be perfect in the real-world, so our line, which is a math formula, only represents a trend.

Many laws in science can be expressed using mathematical formula. These formulae can then be used to derive even more expressions via the rules of mathematics. Taken together the equations represent how nature behaves, from the motion of large objects, to the tiniest atom and even sub-atomic particles, to how fluids flow around objects, or current passes through circuits, or heat is exchanged between parts of machinery or the ocean and atmosphere, or how waves propagate through space and time, or diffract around objects, and even how fast chemical reactions are occurring in a flame or even the biochemistry taking place in organisms. There are just far too many applications of mathematics to represent or list here.

Nevertheless, when a scientist wants to model something, say the climate, he or she will need to consider all the necessary laws relevant to the phenomenon in question. This can involve a lot of data and equations, including chemical reactions. Each of the equations can all be interrelated, making these models inherently quite complex. When all these equations and data are taken together, they then constitute a mathematical model. To solve such a complicated model the equations will often need to be programmed up on a computer for them to "number crunch" the data with the equations and produce meaningful output.

7.4 3.5.4 Predictions versus Projections

Now this output could be a prediction of the future, given current data, or it could be a projection – a "what if" type scenario. Projections differ from pure predictions in that they utilize "what if" scenarios. For example, we could use a COVID-19 forecast model to project the number of deaths that is likely to occur if no safe management measures are taken, or use a climate model to project what will likely happen if no action is taken regarding carbon emissions.

A write up on the difference between predictions and projects and "The Truth about Scientific Models" was given in *Scientific American* recently. Here's the link if you're interested: https://www.scientificamerican.com/article/the-truth-about-scientific-models/

By now you probably can appreciate that each of these model types, physical, conceptual and math/computer models can be interrelated. For example, the physical model with instruments attached could have the data read from the instruments and fed into a computer model. It would then evaluate the performance of the object being modeled and predict how it could behave in the real world.

A conceptual model could help to establish what equations should be used in a computer model meant to mimic the real-world thing the conceptual model represented. You'll get a better idea of this in the second workshop.

Workshop 2 – Integration of Lectures 5 & 6 (held in weeks 7 & 8)

- The conceptual model presented in Lecture 5 will be used to build a model to reproduce the greenhouse effect. This model will be used to illustrate climate change.
- A coupled daisyworld–climate-change model will be used to illustrate the importance of biodiversity in maintaining homeostasis.

Of course, we should never lose sight of the fact that models, being cut-down and simplified representations of reality, can actually leave too much of the real-world out and end up producing the wrong results. However, because science is self-correcting, once such an error is discovered, the ignored effect can then be included in the model to make an improved version.

7.5 3.5.5 Models versus Theories

Models can be created from the concepts and principles provided in a theory or a hypothesis. As such, these models are concrete applications of the principles or concepts outlined by the theory or hypothesis. Because of this, the results of these models can actually be used to test a hypothesis. That is, the model can make a prediction of what should happen if a hypothesis is correct. We can then check and see if it really does happen in the real-world, and if it doesn't, and the model is accurate, then the hypothesis is wrong.

Because models are constructed from the concepts and principles provided in a theory, and therefore represent a concrete and specific application of a theory, we can think of them as being subordinate to the higher-level theory which just expresses the concepts and principles. For example, Newton's statement of the three laws of motion and the law of gravitation can be used to construct a computer model of our entire solar system, i.e., the Sun, planets and all their moons, to predict where the Earth and all of these heavenly bodies will be moving into the future. The model is a specific concrete application of the higher-level theory of Newton for the motion of objects with mass and how they attract each other.

Despite this type of subordination of a model to a theory, you still often hear scientists interchangeably use the terms "theory" and "model". Like big-bang theory or big-bang model. Nevertheless, from the context of their discussion and if you have understood this section, you should be able to decide for yourself what they mean.

With that, we conclude this lecture on scientific explanations and chapter 3 of our textbook. We shall be moving onto chapter 4 and a little of chapter 5 in the next lecture where we will consider the testing step of the scientific method.

4 Experimentation and Uncertainty

Intended Learning Outcomes for Lecture 04

You should be able to do the following after this lecture.

(12)*Describe* the basic process of experimentally testing a scientific explanation and *explain* the importance of eliminating false confirmation and rejection from an experimental test.
(13)*Discuss* how contemporary scientific research is conducted and its relationship to testing explanations.
(14)*Explain* the meaning of meaning of accuracy, precision, and uncertainty illustrating your explanation with examples.
(15)*Explain* the relevance of experimental and control groups and the purpose of randomized controlled double-blind experiments.
(16)*Explain* the meaning of the following terms, (a) margin of error, (b) confidence level, (c) statistically significant, (d) effect size.
(17)*Apply* the 3 rules of thumb to decide if a study has established a statistically significant difference between an experimental and control group.

In this lecture we will be talking about scientific testing of explanations via experimentation, as well as the closely related topic of uncertainty. A lot of this lecture is discussed in chapter 4 and some of chapter 5 of our textbook.

8 4.1 Testing Scientific of Explanations

Let's discuss the basic process of performing an experimental test of a scientific explanation. Sometimes, but really not that often, you can test an explanation by simply making an observation. We saw an example of this in our first lecture when Galileo used his more powerful telescope to look at the planets.

Remember, he saw moons around Jupiter, instantly disproving the Aristotelian view that all heavenly bodies orbited the Earth. His observations of other heavenly bodies also ran directly against the currently accepted view of the heavens. This is certainly the easiest way to test a theory when all you need to do is "look", or make observations.

However, most of the time testing scientific explanations isn't that simple. When just making an observation can neither support nor reject an explanation, you have to do a lot more work. Let's take a look at this flow chart found in Figure 90 to see what we need to do.

Testing an Explanation

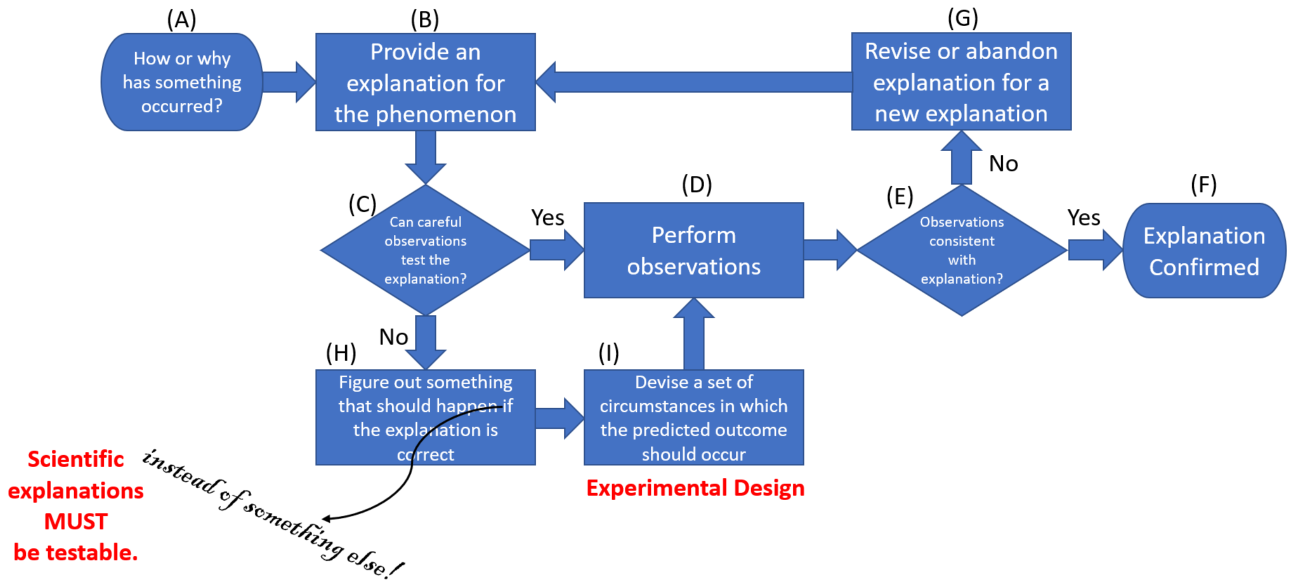


Figure 90. Testing a scientific explanation

The first step after observing a phenomenon is to ask how or why it has occurred (A in Figure 90). If we don't know, we should take an educated guess and come up with a hypothesis which could account for the phenomenon (B in Figure 90). Then we consider if just making more observations can confirm or reject our hypothesis (C in Figure 90). If it can, as in the case of Galileo, we perform those observations (D in Figure 90) and consider the results.

Are the new observations consistent with the hypothesis (E in Figure 90)? If yes, then we've now got more observational evidence that the explanation is correct (F in Figure 90). But if the observations are inconsistent with the explanation, then we need to revise our explanation, or come up with a completely new one and start again (G in Figure 90).

But what if careful observations can't confirm or reject the explanation? We will need to figure out something that SHOULD happen if the explanation was actually correct (H in Figure 90). This can sometimes be quite hard and may take a lot of creativity and imagination.

It's important to realize that to be a proper test of the explanation, there needs to be the possibility that something else could happen instead, and thus show that the explanation needs revision. Remember, all scientific explanations MUST be testable, or falsifiable. If the explanation can't be falsified, then it's not a scientific explanation, and a new one needs to be considered.

The next challenge after having figured out something that should happen if the explanation were true is to devise a set of circumstances in which the predicted outcome should occur (I in Figure 90). That is, figure out an experiment to perform to check if the thing you predicted to happen happens. This part of science, experimental design, can also be quite difficult.

Once you've figured out your experiment to perform, the next thing to do is to obviously do it (D in Figure 90). However, this is often easier said than done. Sometimes experiments are expensive, so finding funding becomes necessary to perform the tests. There are all sorts of other obstacles that could get in the way also, but that's getting off topic.

Once you perform your experiments, you're back on track (E in Figure 90). We can see from this flow chart how science self-corrects. You keep running through the flow chart until something works and only then you will be on your way to learning something new about nature.

Incidentally, how does our scientific method in a nutshell – observe, explain, test – fit into this diagram? This is indicated below in Figure 91.

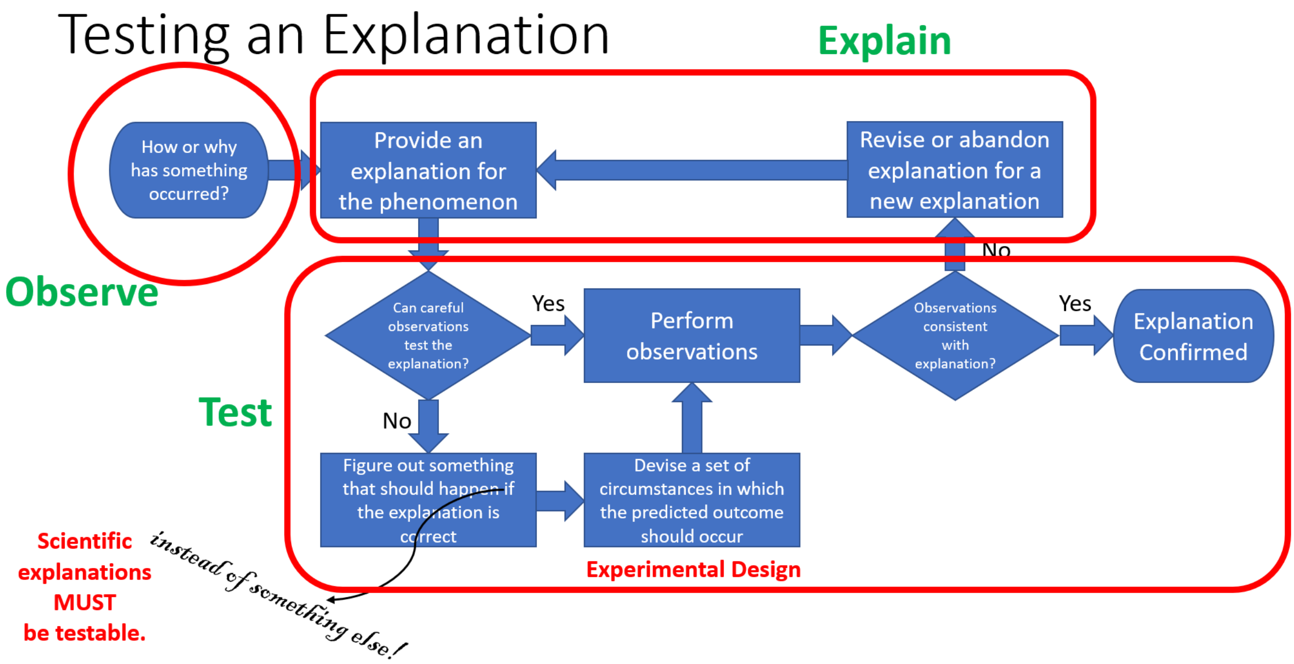


Figure 91. Where "observe, explain, test" fits in

Let's talk a little bit more about the step "figure out something that should happen if the explanation is correct" (H in Figure 90). We saw some easier examples of this in the first lecture when we were trouble shooting the PC, or when the teabag bloated up then floated on the water. Copernicus' model, presented during the scientific revolution, is another such example. Copernicus' model predicted that all the phases of Venus should be observable and not just some of them as predicted by the Earth centered model of the solar system.

8.1 4.1.1 Using Models to help Test an Explanation

We can also make a connection here to scientific models discussed in the last lecture. Recall that scientific models have the power to "test" an explanation (as we just saw with). They can be constructed from the concepts and principles provided in an explanation to yield a concrete application of it. The output, or prediction, of a model tells us what should happen if the explanation was correct. We would then have to devise an experiment to check that prediction.

Big-bang theory illustrates this well. This well-established theory explains the existence of the observable universe from the earliest known periods to its subsequent large-scale evolution. A model can be created from this theory that shows how the universe expanded from an initial state of high density and temperature to the current overall structure we see today, 13.8 billion years later. Amongst a bunch of difficult-to-explain phenomena, the model predicted that there is weak background radiation throughout the universe – a remnant of the initial "big-bang" that started everything.

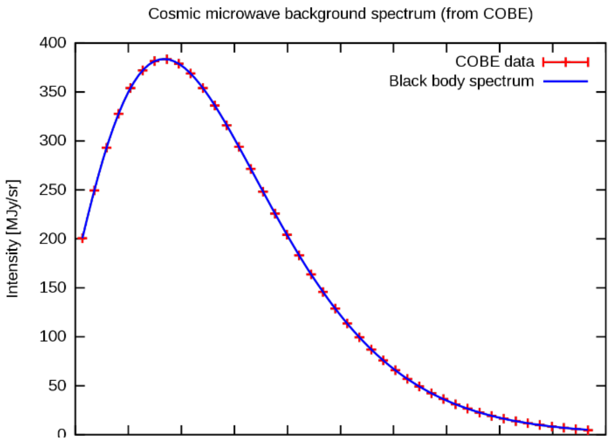


Figure 92. Background radiation left over from the big bang. Prediction (blue curve). Experimental tests (red crosses) [from Wikimedia](): Quantum Doughnut, Public domain, via Wikimedia Commons

Figure 3 shows a comparison of the prediction of this radiation made by the model as well as the experimental test of it. The blue curve is the prediction from the model of the strength of the radiation (vertical axis) versus the frequency of the radiation (horizontal axis). The red crosses are the experimental test of this prediction. You will notice that both the prediction and the test match perfectly.

Incidentally, there's a whole other story associated with the first observations of this background radiation. Nobel prize winning scientists, Penzias and Wilson, who first "noticed" it thought their sensitive horn antenna wasn't working properly because it kept detecting a small amount of "noise" from all directions in the universe. As a result, they spent an awful lot of time trying to figure out what the "problem" was.

Here we have an example of scientists trying their best to make sure they haven't overlooked anything in the process of making their observations, one of the five concerns that need to be addressed when making scientific observations. It's closely related to two important issues that need to be addressed when designing an experiment to test an explanation, i.e., box I in Figure 90.

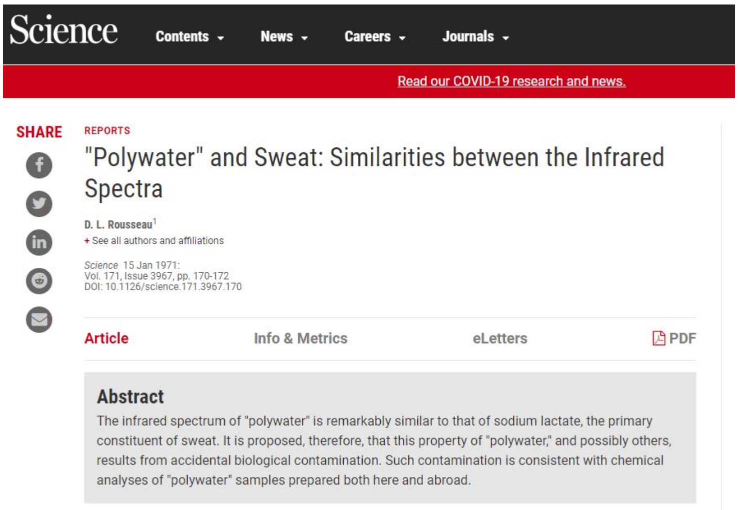
8.2 4.1.2 Flawed experiments can lead to false confirmation or rejection of an explanation

False confirmation of a scientific explanation, and false rejection of a scientific explanation are the two aforementioned issues. Suppose the experiment you designed to test the theory is flawed in some way. After performing the experiment, you believe the results of it support the scientific explanation, when, in fact, it doesn't. This is false confirmation. This can happen if the result of the experiment can readily be explained by something else. For the experiment to support the explanation, we'll need to prove that the alternative explanation for the result of the experiment can't be the case.

8.2.1 4.1.2.1 False Confirmation

Believe it or not, this type of thing happens regularly, and sometimes in a very public manner. The first example is one you've already heard about. It was the claim that "cold fusion" was real and could essentially be produced by a chemical reaction on a bench. It was mentioned in the Baloney Toolkit video. Anyway, the experiment was flawed, which lead to false confirmation that cold fusion was real.

Another example is that of "polywater". Polywater was a hypothesized polymerized form of water. Only ever tiny amounts of polywater could be made, but it was reported to possess a density similar to syrup, a much lower freezing point of -40 ^{0}C, and a boiling point of 150 ^{0}C. It was first reported in 1961 by Soviet scientists, but gained a lot of attention in the late 1960s. By 1969, the American public and military were very concerned that the Soviets had a new technology that could be used against them. As this was happening at the height of the cold war, the fear and paranoia surrounding polywater intensified. It was hypothesized that if polywater came into contact with regular water, it could turn all the regular water into it, utterly devastating the country.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REPORTS

"Polywater" and Sweat: Similarities between the Infrared Spectra

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+ See all authors and affiliations

Science 15 Jan 1971:
Vol. 171, Issue 3967, pp. 170-172
DOI: 10.1126/science.171.3967.170

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Abstract

The infrared spectrum of "polywater" is remarkably similar to that of sodium lactate, the primary constituent of sweat. It is proposed, therefore, that this property of "polywater," and possibly others, results from accidental biological contamination. Such contamination is consistent with chemical analyses of "polywater" samples prepared both here and abroad.

Figure 93. Experiment indicates that Polywater isn't real

Polywater became the subject of a huge scientific controversy in the late 60s and very early 70s as the scientific community tried to reproduce it. Sometimes successfully, and other times not. However, in 1971, some scientists started to seriously doubt that this weird form of water was real. An experiment published in the world-famous journal *Science* (Figure 93), involving a small amount of sweat of a scientist after playing handball, produced a substance with identical properties. This alerted the community to the idea of even a slight contamination of water could produce a false confirmation.

Later, when experiments that had initially produced polywater were repeated with thoroughly cleaned glassware, the anomalous properties of the resulting water vanished. At this point, even the scientists who had originally advanced the case for polywater agreed it did not exist. The Soviets published a letter in Nature – the other world's leading scientific journal – in August 1973 stating "these [anomalous] properties should be attributed to impurities rather than to the existence of polymeric water molecules".

So, poorly controlled scientific experiments lead to the false confirmation of a weird form of water. We also see the critical importance of a scientific community here. Only when scientists from around the world started seriously working on the problem was the issue finally sorted out – and it took several years to do so. Remember, not all amazing initial reports of some fancy phenomenon are real. We need the community to look into it and give their stamp of approval, or otherwise.

8.2.2 4.1.2.2 False Rejection

False rejection is also a serious concern in experimental design. We saw an example of it in the PC troubleshooting in lecture 1. Recall that the first HDMI cable wasn't functioning correctly. If I had believed it was working correctly then I would have concluded that either the graphics card or mother board was at fault. I would have falsely rejected the hypothesis that the monitor display on my laptop was at fault.

Another example from lecture 1 was an ineffective method was initially used to coat the outside of the teabag with water (illustrated in the video). This resulted in a failed test of the hypothesis because the water added to the outside of the teabag failed to properly seal it. If I had accepted the results of this test, believing that I had properly sealed the outside of the teabag, then I would have falsely rejected my hypothesis.

In conclusion, false confirmation and rejection of scientific explanations due to improperly designed experiments is a real concern. We need to carefully think through the experiments when testing scientific hypotheses and theories. And if **you** don't do it, you can rest assured that when you communicate your results to the scientific community, someone else will.

In the next section, we'll discuss how the communication of scientific findings is fundamental to contemporary scientific research. We haven't mentioned anything so far about how contemporary scientific research is conducted – much of which is concerned with testing scientific explanations. How does the scientific method fit into the way modern research is done? We will need to address this before moving onto other considerations of testing scientific explanations.

9 4.2 Contemporary Scientific Research

9.1 4.2.1 More Detailed Illustrations of the Scientific Method than “Observe, Explain, Test”

If you Google the Scientific Method, there are a lot of flow diagrams talking about it (Figure 5). So where does “observe, explain, test” fit into all of this?

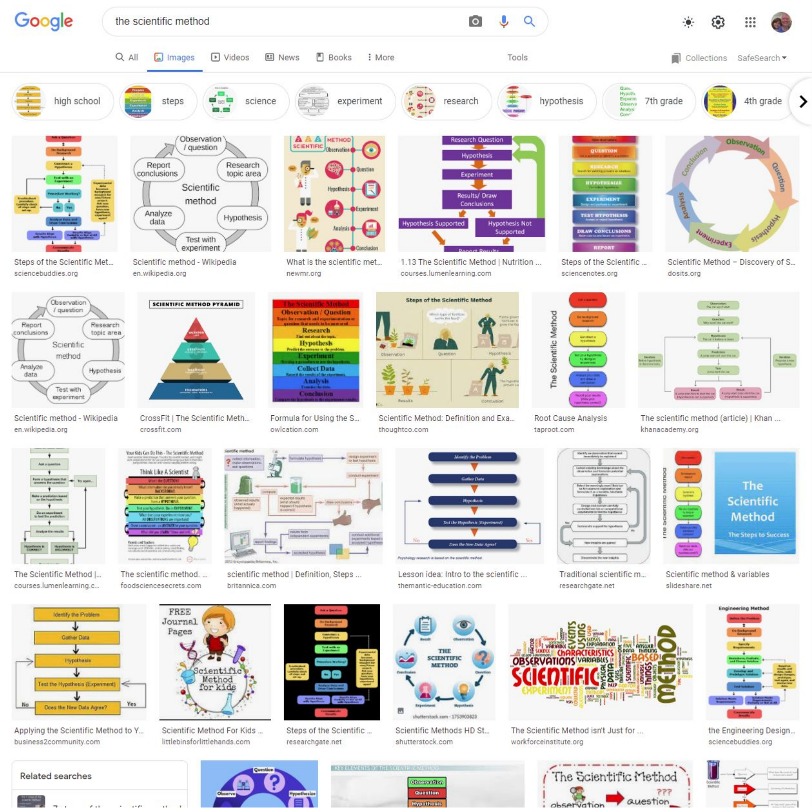


Figure 94. Results of a Google image search on "Scientific Method"

9.1.1 4.2.1.1 Observation/Question

Figure 95 is the diagram we find on Wikipedia. It starts with observation/question, the same as our nutshell description of the scientific method. We observe something puzzling, and we want to find out how or why that something happens or occurs. Maybe we don’t understand what just happened at all, so we want to find out what it is. The question could be almost anything really, but it involves finding out something in nature we currently don’t understand.

9.1.2 4.2.1.2 Research Topic Area

The next step is “research topic area”. In modern science, you always need to do a “literature search”. For this, you’ll need access to a good library, scientific data bases on published research and access to scientific journal publications. This is done since it could just be a phenomenon that *you* don’t know about. Others may be fully aware of it, in which case it isn’t really a mystery at all – it was just a mystery to you personally.

Or perhaps the phenomenon has also been observed by others and they have also tried to figure out what’s going on. Maybe they even have an explanation. But after you’ve considered what these other scientists have done, you might be skeptical of their findings or conclusions, or perhaps they overlooked something, and you’re pretty sure their findings are wrong. Maybe you even have your own alternative explanation.

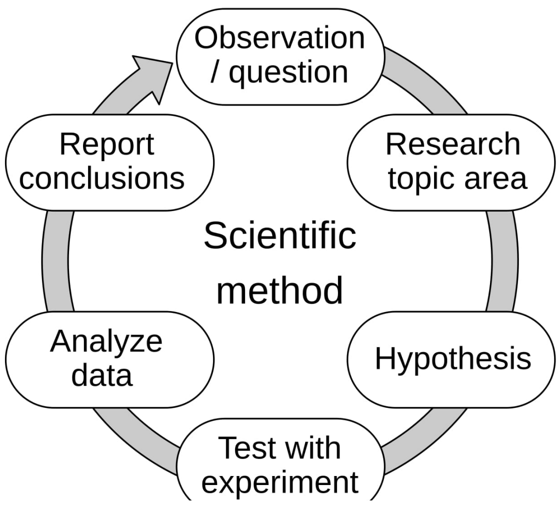


Figure 95. [The Scientific Method as illustrated in Wikipedia](): Efbrazil, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons

You really don't know what you might find published out in the scientific literature until you've done a thorough check. Basically, you need to do your "due diligence" to make sure you've found out everything you can about the phenomenon in question, including any additional observations that may have been made by other researchers. You want to make sure you haven't missed anything. This was one of our concerns of making proper scientific observations we mentioned in the first lecture. This step falls under the "observation" part of the scientific method.

9.1.3 4.2.1.3 Hypothesis

Next on the Wiki chart is "hypothesis", which is a speculative or tentative scientific explanation that must be falsifiable and/or testable. This is the second step in our nutshell version of the scientific method. Of course, the explanation may not necessarily be a hypothesis, it might actually be a theory that already has some supporting evidence. You would know this because you've already done a literature search. It could be that an explanation has already been provided by other scientists, or perhaps it's a brand-new phenomenon, so you're going to have to come up with an explanation yourself, or maybe you just aren't convinced by the current explanation and can imagine better tests of it. Whatever the case maybe, there is some sort of testable explanation that you can check to see if it can be supported by evidence, obtained through experiments or observations, or rejected.

9.1.4 4.2.1.4 Test with Experiment

The next step in the Wiki chart is "test with experiment". Well, last video I explained that it might not be so simple as just testing the explanation based on the hypothesis. We saw last video that we might first have to figure out something that should happen, or maybe shouldn't happen, if the explanation were true. We might even have to produce a scientific model to make a prediction of what should happen if true. In which case, based on what we expect to happen if the explanation were true (or perhaps not happen), we can then carefully design an experiment, making sure we avoid false confirmation or rejection, to test our explanation.

But performing experimental tests of scientific explanations is not free. Doing experiments can be very expensive. Safe labs may need to be purpose built, and precision equipment acquired. Scientists, engineers and technicians need to be employed. Consumables need to be paid for and be available for the work. Sometimes travel can be involved, or perhaps even field work is required, so specialized vehicles may need to be designed and built. All of this funding needs to come from someplace.

Research funding at universities typically comes from grants either from the government or the private sector. If we're talking about corporate research, the companies will need to foot the bill, and often they'll only do so if there's a profit to be seen at the end. Whatever the reason, funding proposals need to be prepared, submitted, reviewed and then funding awarded. If all of that does not happen, then research stops at this point on our chart.

But even if the research is funded, the research team must still answer for what they have achieved with it. The organization or people providing the funding will want to see what their money has bought them. If results are not forthcoming, be it either positive or negative, then the research team may not get funding in the future. It also means that research groups can't just conduct research on whatever they want once funding is awarded. The research money that is awarded is for research on whatever it was awarded for, and not for anything else.

9.1.5 4.2.1.5 Analyze Data

Next on the flow chart is "analyze data". This part of the process corresponds to the "testing" step in our nutshell version of the scientific method. It is mentioned here because sometimes the experiment requires gathering data. Often the data is measurements from instruments, but it could be survey results, or perhaps, they are fragments of historical documents or artifacts, or maybe even camera footage or images. Whatever it is, it will typically require careful analysis. You'll see examples of this later in the course when discussing climate change and sustainability – in fact you will be involved in gathering data and analyzing it from around Singapore yourself.

9.1.6 4.2.1.6 Report Conclusions

The final step of the flow chart is to report the findings of the work. This is always a requirement of the funding bodies. Research conducted, but left unreported, might as well not have been done at all because nobody knows about it. This might seem a trivial and obvious step in conducting contemporary scientific research, but is in fact a crucial part of the science and the weighing of the truth.

9.2 4.2.2 Communicating Scientific Findings in the Primary Literature

The reporting of scientific findings needs to be discussed in detail to properly appreciate just how rigorous this process is. "Getting published" and having the work added to the ever-growing knowledge and understanding of the world requires review of the work by world experts. This then allows for the scrutiny of the results and conclusions to be made by the rest of the scientific community. This is important because scientists are people too, that is, they can make mistakes or draw wrong, or inappropriate conclusions. Having the work studied and checked by all will further validate, or disprove, the work.

But "getting published" in a scientific journal isn't as simple as it sounds. To qualify that statement — getting published in a *reputable* journal isn't as simple as it sounds, and often funding bodies only want their scientists publishing in such journals. Figure 96 shows a flow chart of the process which is described below and in the video.

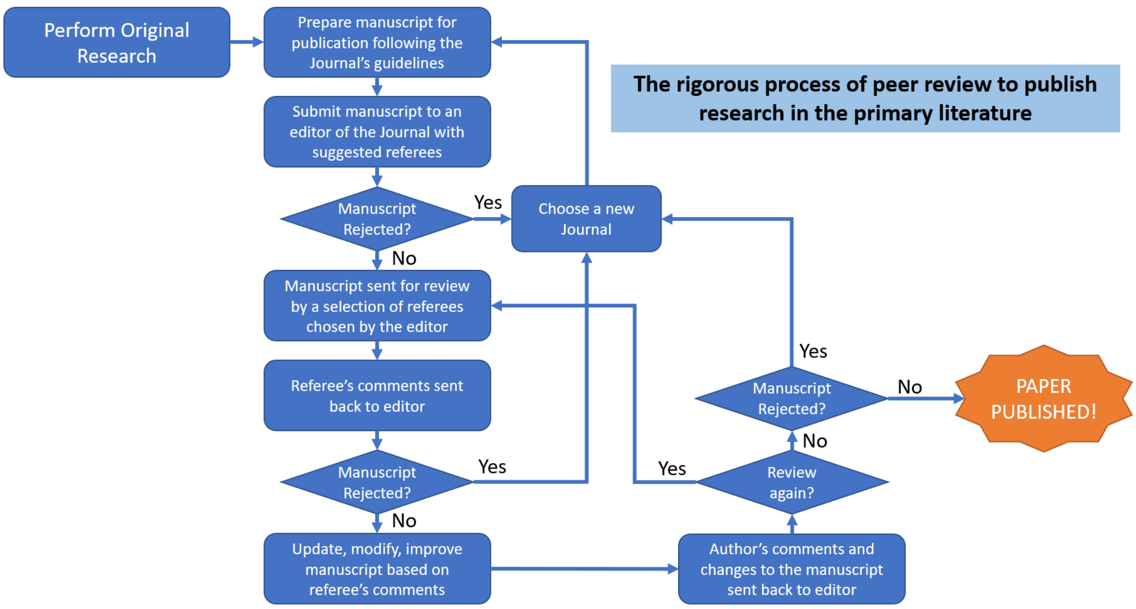


Figure 96. Flow chart for getting scientific research published in the primary literature

Reputable journals have strict guidelines, including ethical guidelines, on how research is conducted and reported. If these aren't followed, then it will be hard, or even impossible, to publish there. There can be word limits, rules for tables, figures, captions, and document templates to follow when writing up the research. Obviously, the language used needs to be concise, clear, understandable, whilst making sure that it is not misunderstood.

For example, here's the requirements for authors trying to publish in either [Science]() or [Nature]() (and the links within). These are the two leading scientific journals in the world.

Once a manuscript has been prepared as per the prescription, it can then be submitted to one of the journal editors. Many journals have several editors who are world experts in particular areas of science. So, when you submit your manuscript to the most suitable editor for your research, you also need to provide several (typically three to five) referees to review your manuscript before it can be published.

At this point the editor will briefly review your manuscript and assess its suitability for the journal you submitted to. Maybe the work isn't really appropriate for the journal, so the editor might reject it and suggest another more appropriate journal. Or, maybe the work isn't as earth shattering as you think it is, so the editor decides it's not exciting enough to be published in their journal. In such a case, the manuscript is rejected, and you'll need to find another journal to submit your work to.

If your manuscript makes it past the editor, it is sent for peer review. This means some of the scientists you suggested to review your manuscript will go thought it thoroughly. Additionally, other referees picked by the editor will also go through your manuscript. All the peer reviewers, i.e., referees, are world experts in the field of your research, and they will be looking for errors, mistakes, things you might have overlooked and suitability of the work for the journal.

The peer reviewers then make a recommendation to the editor on what changes you need to make to the manuscript to allow it to be published in the journal. Or they may outright reject the manuscript because the work isn't exciting enough in their opinion, or its seriously flawed, or there's something else they take serious exception to.

Based on the recommendations of the reviewers, the editor decides whether to reject your manuscript or send it back to you to make the appropriate changes as suggested by the referees. If you agree to make the changes, or have a good reason not to follow what the referees suggest, you can resubmit your revised manuscript and the editor then decides on publishing it or not. Sometimes the editor might submit your revised manuscript again to the referees and the process continues.

Getting your research published is quite a rigorous process and not just a matter to stating anything you like and have it go into print. It's why when considering the source of a claim in science, as mentioned in the Baloney toolkit rule 1, the source must be reputable. If the work hasn't gone through this rigorous peer review process, it can quite literally be something someone simply just made up.

9.3 4.2.3 In Conclusion

This brings us back to the Wiki flow chart (Figure 95), and as we can see, the entire process can continue again now that the research is published and available for the entire scientific community to scrutinize. You can find other slight variations of the scientific method detailed elsewhere, but our nutshell description itself hides a lot of fine details. Nevertheless, it really does capture the basic steps of the scientific method, as illustrated in this section.

In the next section, we'll take a look at accuracy, trueness, precision and uncertainty. These concepts play an important role in experimentation and testing of scientific explanations.

10 4.3 Uncertainty and Precision

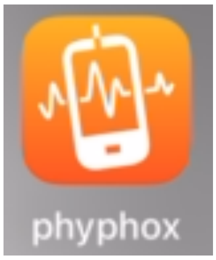
10.14.3.1 Introduction

Figure 97 A lightning strike near Sungei Ulu Pandan along Commonwealth Avenue West

The video begins with a lightning strike somewhere near Sungei Ulu Pandan along Commonwealth Avenue West. Thunder is heard very soon afterwards. Based on the time taken between the strike and thunder it is possible to determine the distance the strike is away from the listener. However, this can only be deduced if one knows the speed of sound. In this video we will illustrate the concepts of uncertainty and precision by performing an experiment that measures the speed of sound.

10.2 4.3.2 Measurement of the Speed of Sound

One way I can measure the speed of sound is measure how long sound takes to travel a known distance. So, if it takes sound 1 second to travel 300 meters then it must be travelling at 300 m/s. So how could I measure this?



Well, I could use this app "phyphox" – available for free on both the iOS and Android – and use the *Acoustic Stopwatch* inside the application. This stopwatch is pretty basic, it simply starts when the phone's mic picks up a loud noise, and stops again when it picks up a second loud noise – that's it. We can utilize this functionality to measure the speed of sound.

All Measurements Possess Uncertainty

Every measurement you make or read or hear has an uncertainty associated with it, and by this we mean there is a "±" on the number – it isn't exactly the number you see.

For example, consider nutrition labels on food, or lab results from your doctor on the cholesterol in your blood. Measurements of weight, like that of marbles, possess uncertainty. Volume measurements as well, like the volume of water and its density which you looked at in Explo X, or even the heights of trees which you'll do in your field trip – all measurements have uncertainty in their value.

Sometimes, though, you might get the impression that this isn't true. I mean, if you take, say, a cupcake, and place it on a kitchen scale, it might read 38.4g. You repeat the measurement, and it still weighs 38.4g. You can do this any number of times and it reads the same, so where's the uncertainty?

The uncertainty is in the additional decimal places that aren't shown. We don't know what the weight is in the second decimal place – it is completely uncertain. Using a more precise instrument, i.e., one that reads reproducibly to more decimals, we can remove some of the uncertainty from the weight measurement.

With two phones running the acoustic stopwatch placed a carefully measured distance apart, 20m in our experiment (Figure 98), we can measure the speed of sound. We also need two people, each standing close to each phone so they can successively make a short, sharp, loud noise, like the sharp click of two sticks hitting each other.

Figure 98 Speed of Sound Measurement Setup. Measurements were taken at 30 ^{0}C and in 65% humidity.

Using this setup, we can measure how long sound takes to travel 20m, which we'll represent with the symbol T. It works like this. The first clack of the sticks by the person standing next to phone 1 immediately starts the acoustic stopwatch app on it. We call this timer 1. The sound of this clack then travels the 20m to the second phone and when it arrives T milliseconds (ms) later, it activates phone 2's acoustic stopwatch, i.e., timer 2 starts. We note that timer 2 starts after timer 1. The delay in its commencement is solely due to the time taken for sound to travel 20m, i.e., T ms. Next, the person standing at phone 2 clacks their sticks together near phone 2 which immediately stops timer 2. Again, the clack sound travels 20m to phone 1 and when it arrives a time T later timer 1 then stops also.

If we compare timer 1 and timer 2 to each other, we notice that they are different. Timer 1 reads a longer time than timer 2. The difference between these two times is equal to $2T$. Timer 1 reads a longer time than timer 2 because it started on time but ended late by T. Timer 2 reads a shorter time than timer 1 because it started late by time T and ended on time. So, if c is the time between the two clacks, then timer 1 would read a time $c + T$ and timer 2 would read a time $c - T$. Taking the difference: timer 1 minus timer 2 we get $2T$[1]. Dividing the difference by two we get T. Now because speed is just distance traveled divided by the time taken to travel it, we can determine the speed of sound in meters per second by dividing the 20m by our measured T.

10.34.3.3 Uncertainty, Margin of Error, Confidence Levels, and Intervals

We repeated these individual measurements of $2T$, i.e., time differences between timer 1 and 2, ten times because we don't expect the difference in readings to be exactly the same each time. Of course, the speed of sound isn't changing each time, nor is the distance between the phones. What is changing is, (a) the effectiveness of the phones in being able to detect immediately when the clack sound reaches them as well as, (b) our ability at being able to repeatably produce a "clack" that is short, loud, and sharp enough for the phone's software to know exactly when to start and stop the timers.

[1] What measurement do we obtain if we take the *sum* of the readings on the two timers instead of the difference?

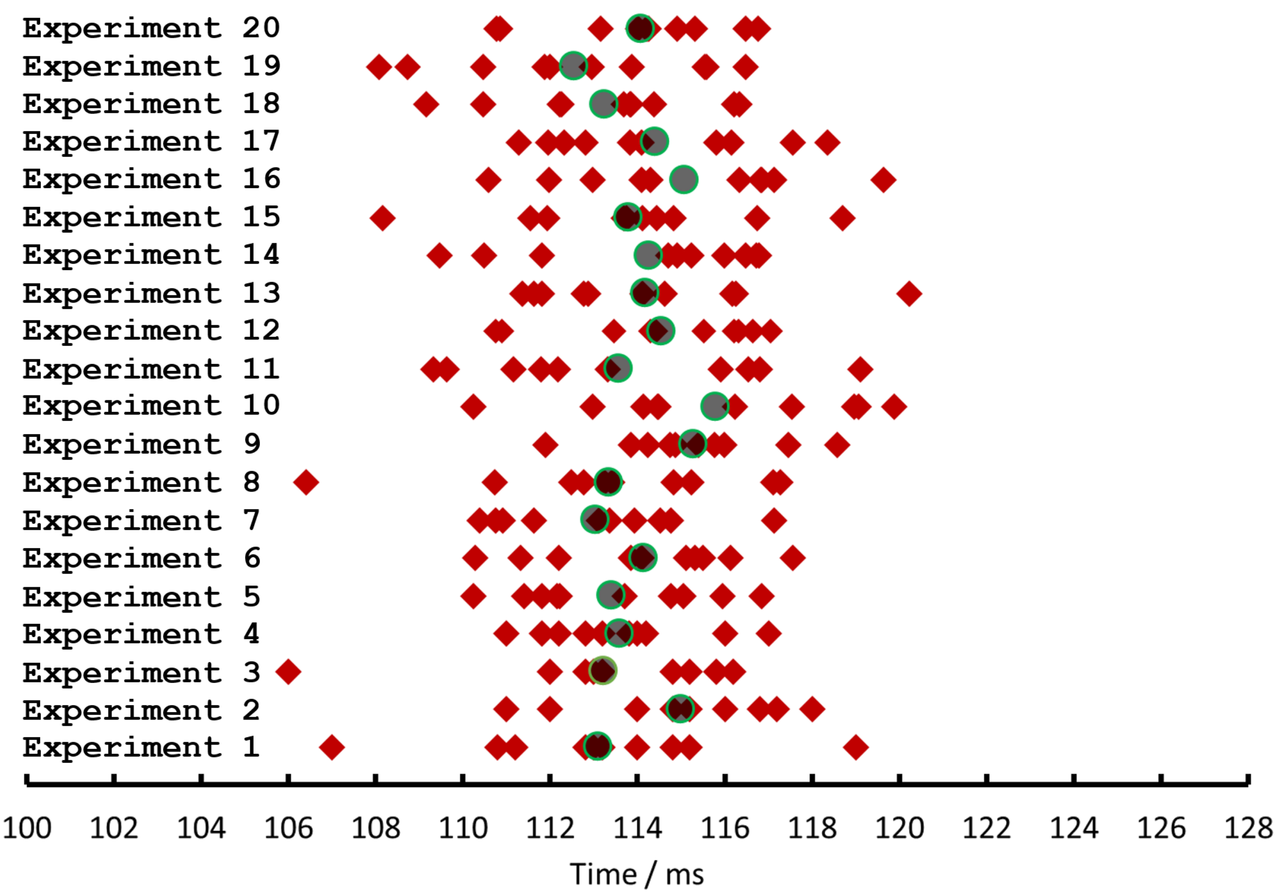


Figure 99 Measured timer differences (2T) in milliseconds (ms) for 20 experiments. Each experiment constitutes 10 individual timer difference measurements (red-filled boxes). The grey-filled green circles represent averages of the ten individual measurements that constitutes each experiment.

We shall call a set of 10 individual measurements an "experiment". In fact, we ended up performing quite a few such experiments (which took *a lot* of time under the hot sun!). Figure 99 shows 20 such experiments. Examination of Figure 99 shows that individual measurements can be spread out over a fairly large range compared to how much the averages shift about. This is indicated in Figure 100 by the red braces for the individual measurements and the grey braces for the averages.

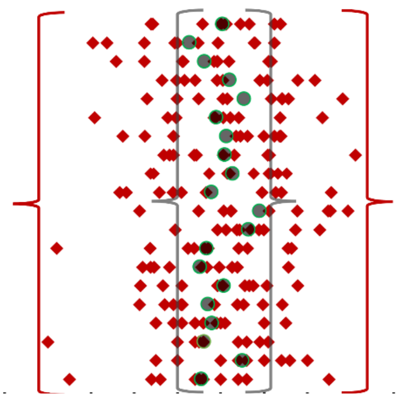


Figure 100 The spread of individual measurements in our 20 experiments (red braces) compared to the spread in the average values (grey braces).

Any time we make an individual measurement we are uncertain about where exactly that measurement might be. As seen in Figure 100, any individual measurement could occur within the red braces, although there seems to be a clustering of red boxes in the middle. We observe that we have an *uncertainty* associated with an individual reading. That is, how much the reading shifts about if we were to take more individual readings. This uncertainty can be characterized with a ± on the reading – a so called "margin of error" for an individual reading.

We also note from Figure 100 we have a shifting about of the average as well, but it is much less than how much the individual measurements shift about. Thus, we also have an *uncertainty* associated with an average value. Again, we can characterize this uncertainty in the average with a ± on it. This ± is also a "margin of error", but this time it is an error margin on the average value.

Now if we are using the average as an estimate of our true value of $2T$, as we are doing here, then the relevant margin of error we need to know is the uncertainty in the average. It is possible to calculate just what this is, but for HSI1000, we don't need to know how this is done. Nevertheless, in a course like GEA1000, you will do such things. Interested students can refer to the opposite blue box for details.

However, to get an actual number to put after the ± we need to first specify a *confidence level*. The confidence level refers to how confident we are that the value we are trying to determine, i.e., the true value, would be somewhere within our ± range. The range of values covered by our ± is called the *confidence interval*.

As an example, if we consider experiment 1, (refer to Figure 99) we have an average value of 113.1ms obtained from our ten measurements. If we specify a 95% confidence level, then it's possible to calculate from our measurements a margin of error of ±1.6ms on this average[2]. These two pieces of information allows us to now determine the 95% confidence interval (or CI). The 95% CI is from $113.1 - 1.6 = 111.5$ to $113.1 + 1.6 = 114.7$.

So, what does our average and 95% margin of error of 113.1 ± 1.6 ms or our 95% CI of 111.5 – 114.7ms tell us? Referring to Figure 101, we can see experiment 1 labelled, and the average value indicated with a filled circle. We can also see the 95% CI shown with a blue line. Also shown in this figure are the averages and CIs for the remaining 19 experiments as well. Highlighted with a yellow line is the *true value* for twice the time it takes sound to travel 20m at 30 ^{0}C and 65% humidity.

We can see from Figure 101 that the true value lies somewhere inside its CI. In fact, we can be 95% sure that experiment 1 will capture the

For those interested students, we can determine the uncertainty in our individual readings and average using mathematics. We can estimate the uncertainty in our individual readings from the *standard deviation* of our individual readings. The more readings we make, the better we will know the true standard deviation and true average value of our measurements.

We can estimate the uncertainty in our estimated average by taking the standard deviation *and dividing by* the square-root of the number of individual measurements we made to estimate the average. So, in our example here, we made 10 measurements for each experiment, therefore the standard deviation from our 10 measurements would be divided $\sqrt{10}$. The uncertainty in the average is smaller than the uncertainty for the individual readings and gets smaller and smaller the more readings we make. This is because we know the average value better and better. The uncertainty in the average is always smaller than the uncertainty in the individual readings because the average shifts about a lot less.

When we divide the standard deviation by the square-root of the number of measurements we end up with a number called the *standard error*. Thus, the standard deviation is a measure of the uncertainty of individual measurements

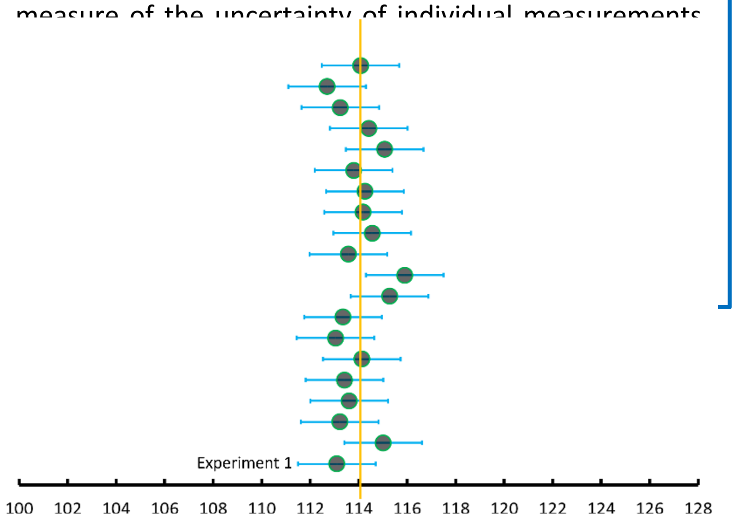


Figure 101 Average values and associated confidence intervals of our 20 experiments to measure 2T.

[2] Interested students can refer to the blue box on the next page to see where this number comes from. This material will be covered in GEA1000. Again, knowing how to do the maths for this not examinable for HSI1000.

true value within its CI. This is the meaning of confidence level. It is telling us how sure we are that the experiment we did will contain the true value within its CI.

For those interested students, we can obtain the margin of error in the average value for experiment 1 from the standard error. To determine the standard error, we need to know the standard deviation (σ) (cf. GEA1000) of our individual measurements and the number of measurements we made. For experiment 1, $\sigma = 2.6$ms, so the standard error is $\frac{\sigma}{\sqrt{N}} = \frac{2.6}{\sqrt{10}} = 0.822$ms. When we specify a 95% confidence level, we need to multiply the standard error by 2 (1.96 actually, but 2 is good enough). This number comes from the bell curve, or normal distribution. Thus, our margin of error on the average is ±1.6ms at the 95% confidence level.

If we only wanted to be 68% confident then we could just use the standard error directly as our margin of error, but normally scientists use the 95% confidence level as a default. This is about twice the standard error if it's an average we're interested in, or twice the standard deviation if it's the individual variation in measurements we're more interested in.

If we examine the remaining 19 other experiments, because we have chosen the 95% confidence level, we find that 95% of them capture the true value somewhere within their CIs. Why? Because a 95% chance of finding the true value within the CIs means a 5% chance of **not** finding the true value within the CIs. 5% is 1 in 20, so if we look carefully, we observe one experiment about half-way up (experiment 10) that *doesn't* have the true value within its 95% CI. Nevertheless, experiment 10 doesn't miss the true value by much.

10.4 4.3.4 Summary of Uncertainty, Margin of Error, Confidence Levels, and Intervals

Let's summarize this for any kind of measurement. Any time you see, read, or hear a number that's some kind of measurement, there's an uncertainty associated with it. Sometimes this uncertainty is shown, often it isn't, but the fact is there's an uncertainty always present, that is, a ± on it, which can also be called the margin of error.

This uncertainty also has attached to it a confidence level, usually that's 95%, but sometimes it can be less like 68%, say, or more, like 99.7%. The uncertainty, or margin of error, can be used to figure out the confidence interval, that is, a range of values, not a single number.

What the confidence level is telling you is how sure you are that your confidence interval you've figured out contains the true value you're interested in knowing. So, if it's a 95% confidence interval, then you're 95% sure your range of values contains the true value. However, there's still a 1 in 20 chance that this range of values doesn't include the true value, but if it doesn't it's probably not too far off anyway.

10.54.3.5 Uncertainty in Measurements and Averages

Here's something else important we saw. There is an uncertainty associated with individual readings, and a smaller uncertainty associated with the average of individual readings. We have two different uncertainties, and it is critical you know which one you are talking about or interested in.

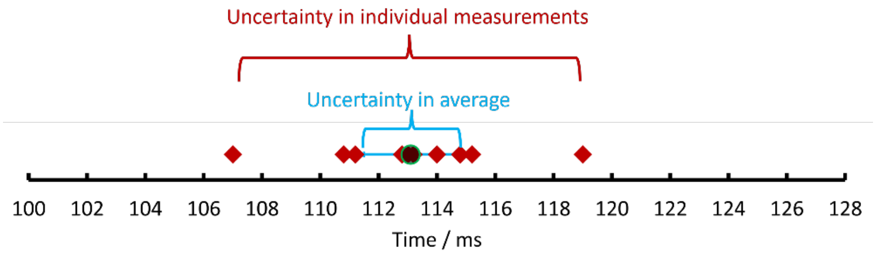


Figure 102 The two difference uncertainties discussed roughly indicated by the red and blue braces.

If you're interested in a specific number, like the speed of sound, or nutritional content in food, or cholesterol in your blood, then you're interested in the uncertainty of the average of a number of measurements. This is because the average is a much better estimate of the number you want, than any individual measurement might be. But what if you only made one measurement? If that's the case, then the uncertainty in the number you got must be associated with the uncertainty in the individual readings because we don't have more than one measurement to average.

Sometimes we specifically are *not* interested in the average, and only want to know about how much our individual readings vary. Maybe we want to make a doorway that can accommodate 95% of males passing through it without them having to duck down. To know how high our doorway must be, we don't care about the average height of males. What we need to know is the range of male heights, then make sure we build it high enough to accommodate 95% of them (Figure 103).

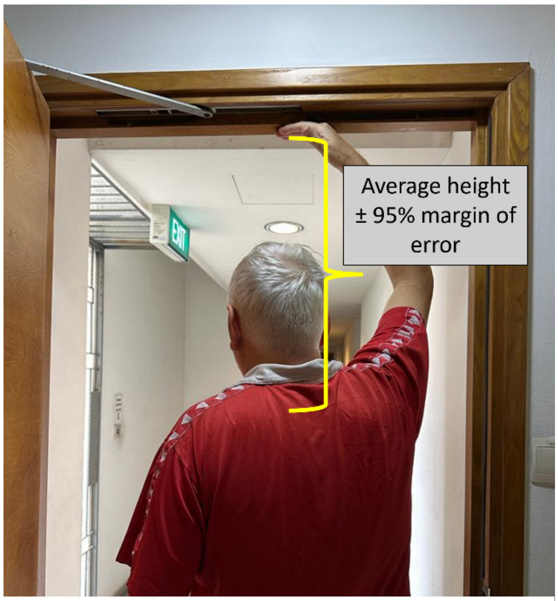


Figure 103 Illustrating that to accommodate 95% of males through a doorway without ducking down we want to know the margin of error on individual measurements (individual heights in this case).

You will hear more about this later in the course when Prof Lee talks about climate model predictions. There, we have quite a number of different model predictions, all of which are equally credible with no individual model expected to be more reliable than any other. In the situation you'll come across later in the course it will be clear that we aren't interested in the average prediction of all these models at all. You'll see that what's of interest is the variation in those predictions, that is, the uncertainty in model predictions. Here each individual climate model prediction is equivalent to an individual "measurement".

10.64.3.6 Precision

OK, now that we have an idea of what uncertainty is, it's time to talk about the term "precision", which is closely related to uncertainty. Basically, the smaller the uncertainty, the higher the precision. A highly precise number will be one with a tiny uncertainty, and vice versa. Let's look at an example using the scales you used in Explo X.

Figure 104 shows a low-quality kitchen balance which can measure mass to 0.1 grams. When used, it reads around 5.4 or 5.3 grams most of the time for the exact same marble. The uncertainty associated with the individual readings works out to be about ±0.2 grams. However, Figure 105 is a more precise balance and can read to 3 decimal places. Making a number of readings of the same marble shows us it weighs about 5.41 grams almost all of the time with an uncertainty of around ±0.009 grams for any individual reading. The second balance is a much more precise instrument than the kitchen scales because we have a much lower uncertainty of ±0.009 grams in an individual reading compared to the kitchen scales of ±0.2 grams.

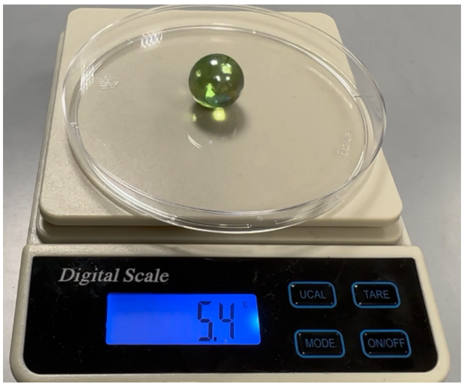


Figure 104 Kitchen balance from Explo X

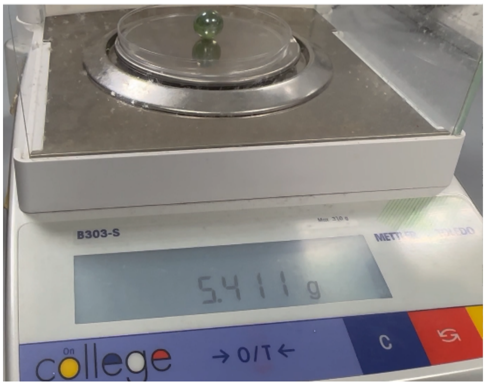


Figure 105 More precise balance from Explo X

The term precision is a relative term, for example we could get a more precise average of the time taken for sound to travel 20 meters by taking more care at producing reproducible sharp, short, loud noises to start and stop our audio stop clocks. This more precise average would mean we would have a smaller uncertainty in our time-differences.

There really is not much more to the term "precision" in science than that. A highly precise measurement is one with many digits that can be reliably reproduced. That is, a measurement with many significant figures. A low precision reading only has a few reliable digits, or significant figures. It's the digit where the uncertainty is, that tells you the number of significant figures you have. So, 20±1 has two significant digits, which is a more precise number than 20±10 which has only 1 significant figure. However, 20±1 is less precise than 20.0±0.1, which has 3 significant figures. High precision means lots of significant figures and a small uncertainty.

10.74.3.7 Concurring with the Literature on the Speed of Sound

OK, after all this what did we measure as the speed of sound, and how does it compare with the literature? Well, combining all our measurements and halving the result gives us the time it takes sound to travel 20 meters. That number is 57.0 ± 0.2 ms at the 95% confidence level. So, we have 3 significant figures in our time. Taking account of the 20m distance between the phones, this works out to be a 351 ± 1 m/s.

This means that the 95% confidence interval is 350 – 352 m/s. The literature says the speed of sound at 30 ^{0}C and 65% humidity is 350.5 m/s. Well, that looks pretty good, so we must concur with the literature as our results are completely consistent with this value within the margin of error.

Now 351 meters is roughly one-third of a kilometre, so sound travels about a third of a kilometre in a second. So now we know. One-third of the number of seconds that pass between a lightning flash and the thunder is about the distance in kilometres away the lightning was from you. And this lightning flash (Figure 97), then thunder, was only 25 frames apart in the video, which means the time taken for the thunder to travel to me was only about 830 ms. The lightening was only 290 meters away!

11 4.4 Accuracy

11.14.4.1 Introduction

Now that we have explored the concepts of uncertainty and precision in scientific measurements, which are crucial for testing explanations, let us delve into the topic of accuracy. In this section, we will first discuss the common definition of accuracy, followed by an introduction to the ISO 5725 definition.

To illustrate the concept of accuracy, we will conduct a practical exercise near the NUS Oval grandstand. Our objective is to measure the height of a tree. This activity is significant because, in a later field trip to a Nature Park and Reserve, you will be required to perform similar measurements. By doing so, you will have the opportunity to apply the knowledge acquired during this part of the course. While undertaking these measurements, we will also reinforce the key concepts previously covered on uncertainty and precision in scientific measurements.

11.2L04.4.2 Obtaining the "True" Height of the Tree

Figure 106 The target tree that will be used for the height measurement.

Figure 106 shows the tree that we will use for the height measurement. It's located near the grandstand at the NUS oval near the University Hall end. The height is defined as the vertical distance from where the trunk enters the ground to the highest part of the plant, which here is a leaf right at the very top.

Unlike the speed of sound measurement, we don't have any literature value to consult to find the true height of this tree. To obtain its true height we used a device called a *hypsometer* (Figure 107) to measure its height. Such a device isn't as accurate as using a tape measure, but it's the next best thing.

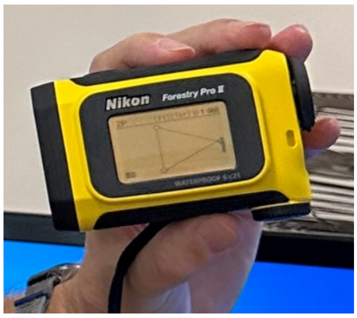


Figure 107 Nikon Forestry Pro 2, a hypsometer

A hypsometer includes a laser range finder, which accurately tells you how far away objects are that are illuminated by a laser. It also includes a clinometer, which accurately measures angles to objects. Your smartphone has one, which we'll be using in a later section.

11.2.1 L04.4.2.1 Validation of the Hypsometer

Now in science, when using an instrument for the first time, or after a while, you need to first check its accuracy. *Now by accuracy we mean how far off an experimentally determined value is from the true value.* If you don't check your instrument's accuracy, then how can you be sure your readings are correct? Thus, checking your measurements against known values is called *validation*. Sometimes you may need to even do a *calibration*, i.e. adjust your instrument so it reads the correct values, but calibration isn't necessary here. Nevertheless, we validated the readings from the hypsometer by using it to measure the heights to the tops of railings (Figure 108 – Figure 110) in University Hall we had previously measured with a tape measure.

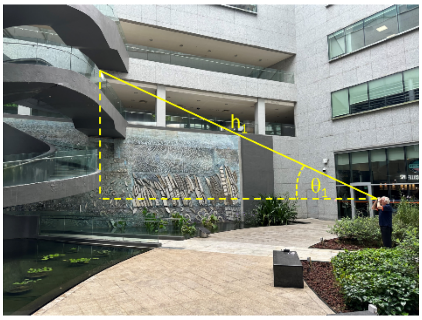


Figure 108 Use the hypsometer to sight to the highest point. The hypsometer stores the hypothenuse and angle.

Figure 109 Use the hypsometer to sight to the lowest point. The hypsometer stores the hypothenuse and angle.

Figure 110 From the two angles and hypothenuses one can obtain the vertical height.

Figure 108 – Figure 110 illustrate how the hypsometer obtains the vertical height. The method is called the "sine method", for obvious reasons. The beauty of the sine method is that both points need not be directly above each other to obtain the vertical height.

After making a lot of readings from different places near the stairs, we found we could get agreement between the average readings from the hypsometer and the tape measure to within 15 cm. So, it seems we should be able to measure our tree height with the hypsometer to within 15 cm or so. This number is telling us the accuracy of our hypsometer method. It isn't the uncertainty in our average, which can be quite small if you make a lot of measurements, but instead it tells us how far off averaging a lot of readings is from the true value using this instrument and our approach. This is the meaning of accuracy.

11.2.2 L04.4.2.2 Measuring the Actual Tree Height

Figure 111 Measuring the tree height with the hypsometer.

We used the hypsometer to measure the height of the tree (Figure 111). We made about 10 readings at different locations and averaged the result. We found the tree to be 11.49 ± .15 m. Plus-or-minus 15 cm, is our margin of error on the average to the 95% confidence level. This uncertainty just so happens to coincide with the accuracy of our hypsometer we already established from the University Hall validation. Thus, we will consider other methods for measuring tree height to be quite accurate if they can reproduce this same height to within 15 cm.

11.3L04.4.3 Tree Height: Photographic Method

Figure 112 Photographic method used to measure the tree height. Dr Ng Yee Hong is in the photo at the base of the tree whose height is known.

The first method we'll consider measuring the tree height is one many students have used in their field trip later in this course. It's called the photographic method. Basically, you take a picture of someone you know the height of standing at the base of the tree (Figure 112). Later, you analyse the photo and count how many of that person you can stack to estimate the height, as illustrated in Figure 113. Here we did it 5 times in total, each time starting again as if making the measurement for the first time. This gives us an estimate of the uncertainty. From the measurements using Ryanne Rae Ang Pei we obtained a tree height of 9.62 meters. The margin of error at the 95% confidence level was ±0.15 meters. As a double check of these measurements, we did the same thing but with Dr Ng Yee Hong as the subject and got very similar results. Figure 114 compares our measurements with the 95% CIs in the average using the photographic method to the actual tree height.

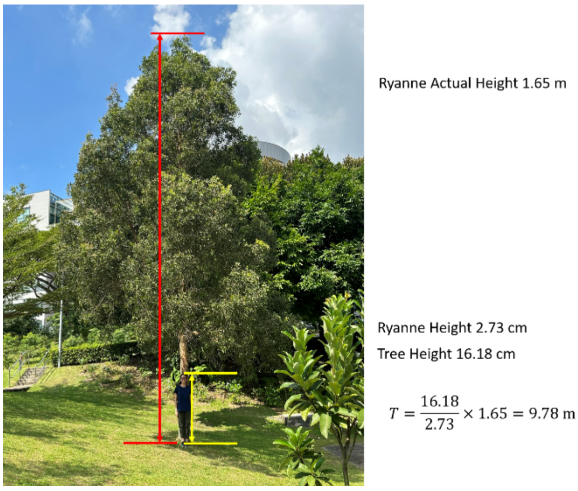


Figure 113 Analyzing the photo to obtain the tree height. Here Ryanne Rae Ang Pei is the subject in the photo.

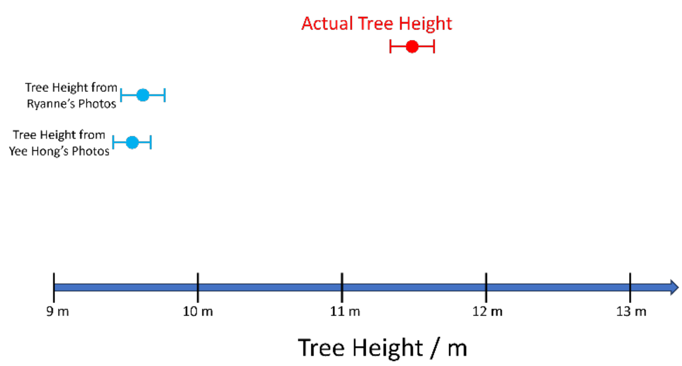


Figure 114 Comparison of tree heights using the photographic method to the true tree height.

11.3.1 L04.4.3.1 Uncertainty vs Accuracy

Evidently, there's something really wrong with our photographic method for measuring tree heights. Figure 114 shows the key difference between accuracy and uncertainty. The uncertainty is illustrated with the confidence intervals on the photographic method. We can make measurements, and get fairly repeatable results leading to an uncertainty in our average or individual readings. However, if the method or instrument we are using is inaccurate, then our margin of error tells us nothing about where the true value we are trying to measure is. Using an inaccurate instrument or method you can be quite far out from the true value as seen here, with the margins of error giving a false impression of what you're trying to find. This is why it is absolutely critical to validate and/or calibrate your method first.

11.3.2 L04.4.3.2 Investigation of Inaccuracy

To discover the reason for the inaccuracy, we apply the scientific method. We have an observation that the photographic method gives way too short heights – the method is totally inaccurate. Next, we need an explanation and referring to Figure 95 we find that we may get some assistance with the explanation by referring to the literature. By checking the literature, it was soon discovered the issue is with something called "tilt distortion". Close examination of Figure 116 reveals that this is exactly what's happening. Doing this makes tall objects appear shorter. If you just hold the camera at right angles to the ground, then you should get a much better estimate of the tree height. For interested students, *Figure 115* shows how tilt distortion happens.

Figure 116 Tilting the camera when taking a picture leads to "tilt distortion".

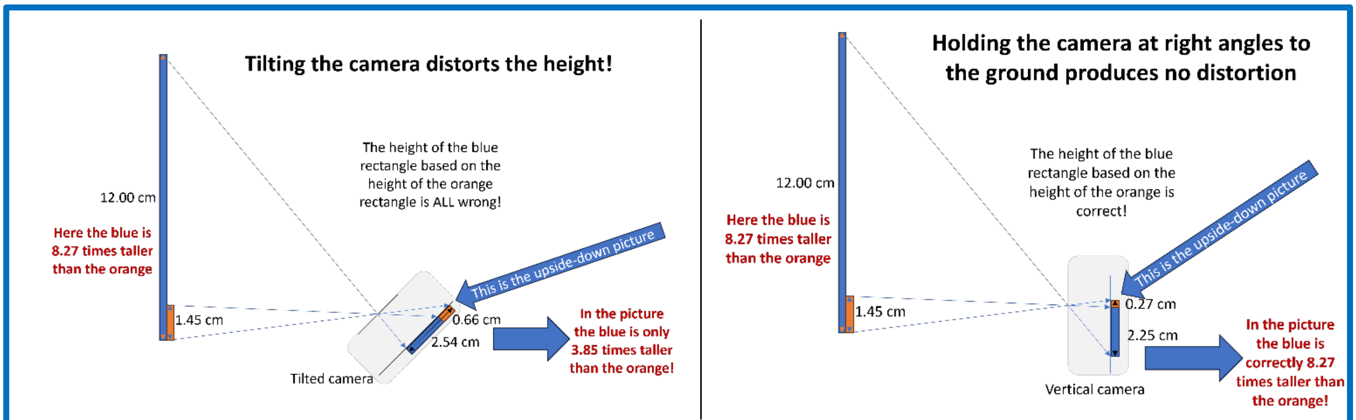


Figure 115 Illustrating how tilt distortion can produce a misleading impression of the height of an object

Continuing with the scientific method, we now have an explanation for the inaccuracy, so to test this we repeated the measurements. However, this time we ensured that the camera was vertical by using a level, as seen in Figure 117. We can compare the tilted camera picture to that taken with the camera held vertically – the difference is truly striking (Figure 118). The results after analyzing the new data can be seen in Figure 119.

Figure 117 Ensuring the camera is absolutely level while taking the picture of the subject under the tree.

Figure 118 Vertical camera image (left) vs tilted camera image (right) of the same tree with Ryanne Rae Ang Pei in both pictures.

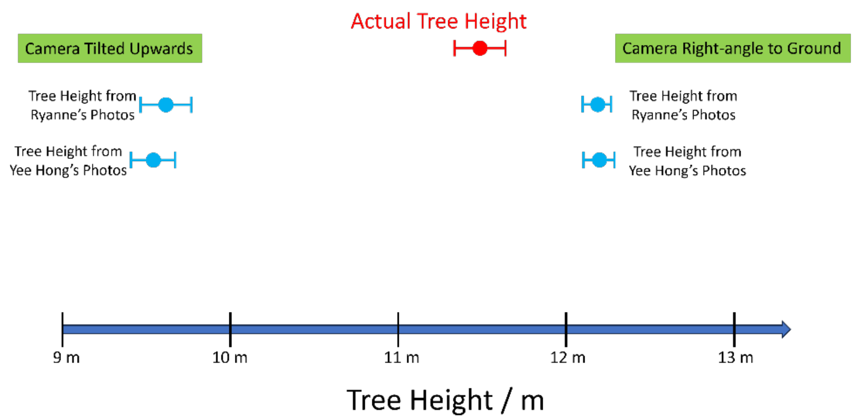


Figure 119 Results for the tree height estimated using the photographic method.

Examination of Figure 119 shows the 95% CIs are significantly smaller for the camera held vertically compared to the CIs for the tilted camera. The uncertainties are lower now because we are controlling a parameter, that is camera tilt, that greatly effects the results. However, the results are still off the true value, not as bad as before, but nevertheless the results are still inaccurate.

I can think of two reasons for this. Firstly, if the subject is standing at the tree-trunk, and the highest point of the tree **isn't** directly over this point, then the subject can appear taller or shorter in the photo then they should be. Secondly, the small camera in the smart phone can distort the photo somewhat.

Ultimately Ryanne and I went to quite some effort to verify this by doing the validation of the photographic method, which we should have done in the first place. And it is indeed true. For tall objects the heights can be distorted by a few percent due to any number of the reasons given below.

Reasons for images being distorted by a smart phone camera:

a. The phone camera has a small sensor.
b. Wide lenses are often used for phone cameras – there will be a barrel distortion effect (edges are stretched out).
c. The phone's software often tries to correct for barrel distortion when generating images.
d. Automatic image stabilisation features (in iPhones) means there is a small motor/mechanism in the phone lens that automatically tilts the camera within the hardware.

To summarize (a) science definitely works at figuring stuff out. (b) Always validate a method you're using to measure something. (c) Don't tilt your camera if you want to get a rough height of something tall. (d) However, don't expect your results to be super accurate if you're using a smart phone, that is, the true value probably won't be within your confidence interval.

11.4L04.4.4 Tree Height: Tangent Method

The second method commonly used by students to measure tree height uses trigonometry and is often referred to as the "tangent method". The person making the measurement stands a measured distance away from the tree trunk and uses a clinometer to sight to the highest point on the tree. Smart phones typically possess a clinometer, which on the iPhone is found in the "measure" app. The app is basically a "level" and measures angles of inclination in whole degrees.

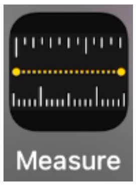


Figure 120 Using the "level" app in a smart phone as a clinometer.

The measurement can be made by sighting along the top edge of the phone to the top of the tree (Figure 120) and take note of the angle – you'll need someone to read that for you. To obtain the height of the tree you also need to know how far your eye is from the ground. With these two distances and an angle you can obtain an estimate for the height of the tree as shown in Figure 121, which is a *conceptual model* coupled with a *mathematical model*.

As with the photo method, we repeated this whole process, including measuring out the distance to the tree, four more times to get an idea of the uncertainty. The results of these measurements are graphically illustrated in Figure 122.

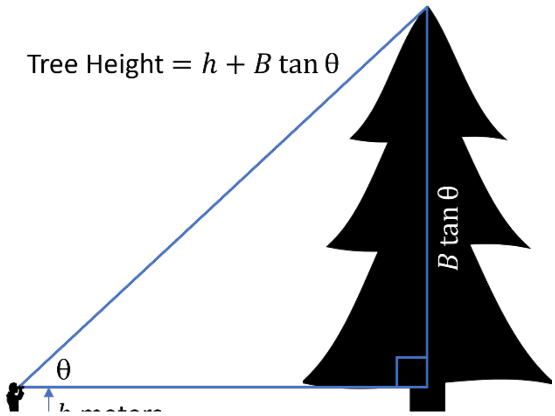
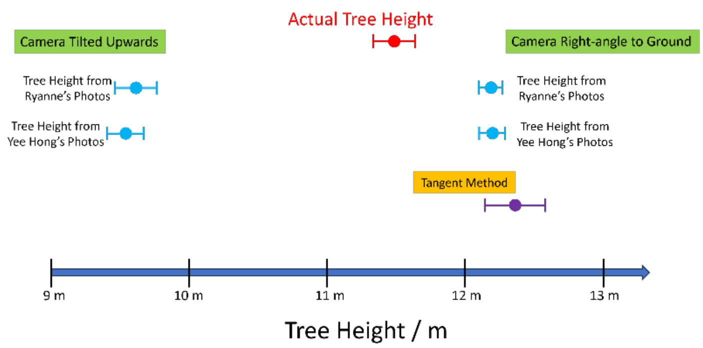


Figure 121 The tangent method for measuring tree height. You need to measure the distances B and h and the angle θ, with your smart phone.



Notice that the 95% confidence interval (purple) in Figure 122 is much larger than our other methods. This is because the clinometer in the smart phone only measures to whole degrees. That is, the instrument's *precision* isn't quite good enough. A decimal place on the angle would be a considerable improvement, for instance, the hypsometer measures angles accurately to one decimal place. With just one decimal place in the measured angle, we would reduce the uncertainty. Nevertheless, we can see here that this method is inaccurate also, but not as bad as a tilted camera. The method is inaccurate because there is still a marked difference between the confidence interval obtained from it and the actual tree height.

What is responsible for this inaccuracy? Again, we apply a scientific approach to figure this out. We have an observation, i.e., our tangent method is inaccurate, so now we need an explanation to work with to see if we can improve our method. Our method is inaccurate, so let's consider the method by considering our model, Figure 121. How close does the real world reflect this idealization of reality? We can see from the figure that our tangent method relies on two assumptions about the real world. (i) The ground is horizontal to the trunk, which is the base of the triangle, and (ii) the tallest point of the tree is directly above the point on the ground you measured to, which in this case is the tree trunk.

Figure 122 Results of the tangent method (purple) compared to other methods and the actual tree height.

Figure 123 Viewing the tree from a different angle shows the tree is tilted somewhat.

For our measurement, the ground seemed reasonably flat, but when we examine the tree from a different angle, we can immediately see that it is tilted (Figure 123) towards the location 11m away from the trunk where we took the measurements. This is definitely a source of inaccuracy, which will give rise to a tree height measurement that's too high, as shown in Figure 124.

We now have an explanation for a contributing inaccuracy in our measurements. We can test this explanation by measuring the distance from the observer to that point on the ground directly below the tallest point on the tree, instead of measuring to the tree trunk. Locating such a point on the ground can be done with any weighty object attached to a string. For this purpose, we used a ball on a string from the Explo (Figure 125).

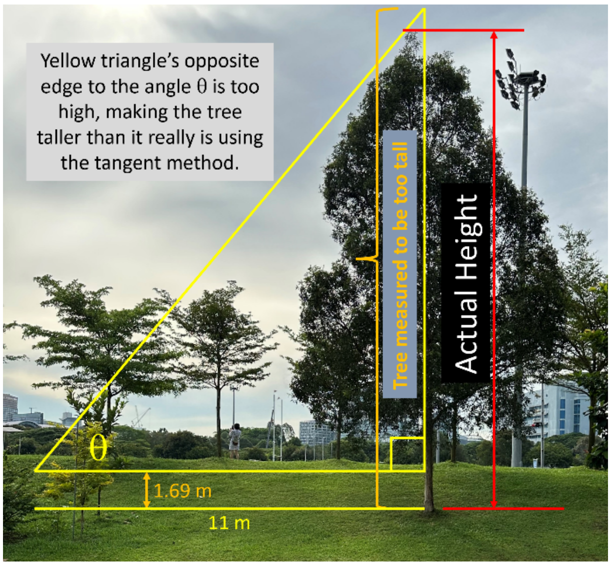


Figure 124 The tallest point not being directly above the point measured to on the ground for the base of the triangle leads to inaccuracy in the tree height measurement.

You can find the point on the ground directly below the tallest point on the tree by first lining a person up in profile (Figure 125) and then face-on.

After doing this we obtained the results shown in Figure 126. Our corrected height is even closer to the true value.

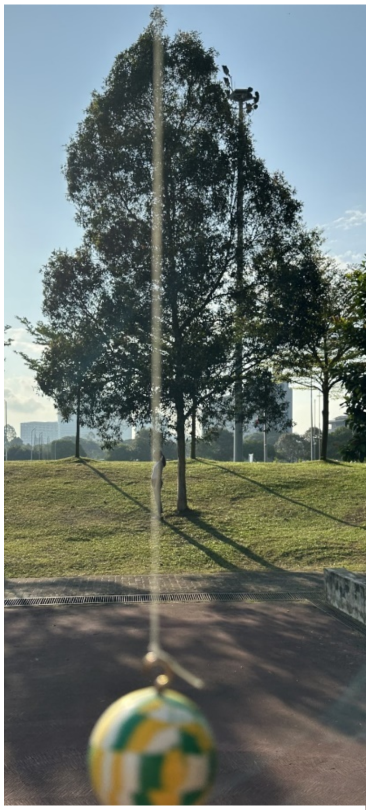


Figure 125 Finding the spot on the ground directly under the highest point on the tree. Look carefully and you will see Ryanne in the photo near the tree trunk lined up with the tallest point on the tree.

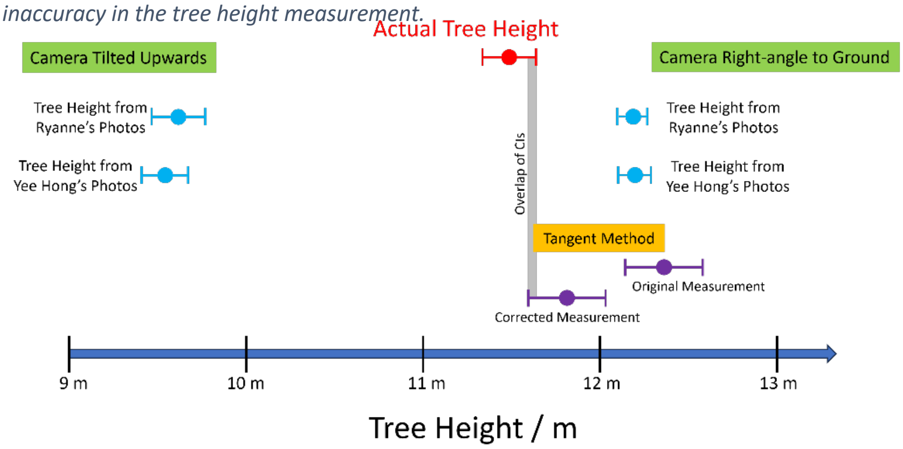


Figure 126 Results of the original tangent method, then the corrected version (purple) compared with other methods and the actual tree height.

Examining Figure 126 we notice that the CI for the actual tree height overlaps slightly with how well we know the true tree height. However, as we'll see in the next section, this overlap isn't very much, so there probably is still a slight problem with the accuracy of the corrected tangent method, which is maybe due to the ground not being perfectly flat.

11.5L04.4.5 Summary of the Common Definition of Accuracy

By now it should be clear that accuracy relates to the closeness of an average of a bunch of measurements to the true value. If the average is quite close to the true value, then the result is quite accurate. If it is far from the true value, as we just saw in our various attempts at measuring the tree height, then we have an inaccurate result.

How far away an average of many measurements is from the true value is given a special name, and that name is "*systematic error*". Systematic errors in measurements can occur for all sorts of reasons, like failing to calibrate an instrument, or using a faulty instrument, or simply not using it properly, and many more.

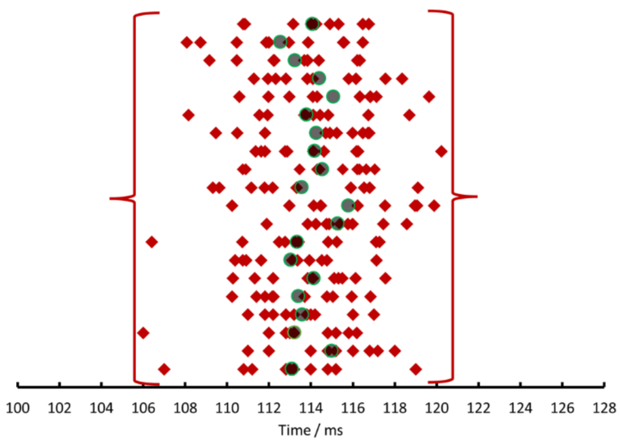


Figure 127 Individual measurements (red) of twice the time taken for sound to travel 20m. The circles are averages of 10 individual measurements. This was studied in chapter 4.3.

Uncertainty in our individual measurements doesn't include the systematic errors. Think about the randomness we observe in taking individual readings, like our measurements of twice the time taken for sound to travel the length of the pitch in the previous chapter (Figure 127), or the variation in our individual measurements of tree heights in this video. This uncertainty has nothing to do with the errors causing all the readings to be shifted, or biased, away in a specific direction from the true value. For example, tilting the phone up to take pictures introduces a large shift to smaller values in all our measured tree heights. This big shift to shorter measured tree heights is a big *systematic error*.

Variations in individual readings contribute to our margin of error in the *average*. Referring to Figure 128, we can see that the margin of error, which gives us the CIs shown, doesn't at all account for the huge systematic error. Thus, a result of 9.54 ± 0.13m doesn't account for the systematic error of about -2m, which is how far off this measurement is from the true value. The ± 0.13m only accounts for the random variation we would expect to get in taking another average of five tilted photo measurements.

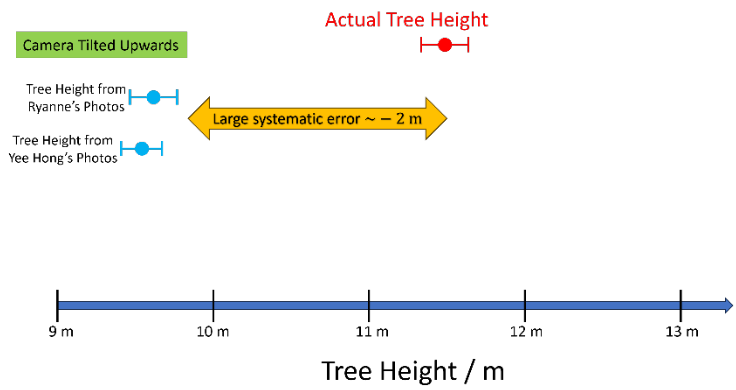


Figure 128 A large systematic error resulting from tilting the camera.

Substantial systematic errors make results inaccurate, and if they are so large as to exceed the uncertainty in the average, then this pretty much renders the uncertainty meaningless because it no longer can tell us anything about where the true value is. Eliminating systematic errors in scientific measurements is paramount. Doing so means that your measurements will be accurate, if not you can fall prey to false conformation or rejection of hypotheses, which I'm sure you can appreciate is always a bad thing.

11.6L04.4.6 ISO 5725 Definition of Accuracy

Here we will briefly mention an alternative definition of accuracy. That definition has been given by the International Organization for Standardization, or the ISO. Checking Wikipedia (Figure 129), you'll see the common definition of accuracy mentioned, as well as the ISO 5725 definition of accuracy. Further down the page you can see a more complete description of the ISO's definition.

We won't be discussing the ISO's definition of accuracy any further. Throughout this course we'll stick to the common definition, as this definition is still mostly used throughout the scientific community today. Nevertheless, you should be aware that there is an alternative definition of accuracy, which is different and stricter than the common definition. If you're interested to find out more, you're quite welcome to check the Wikipedia page here.

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Accuracy and precision

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From Wikipedia, the free encyclopedia

Accuracy and precision are two measures of *observational error*. ***Accuracy*** is how close a given set of measurements (observations or readings) are to their *true value*, while ***precision*** is how close the measurements are to each other.

In other words, *precision* is a description of *random errors*, a measure of statistical variability. *Accuracy* has two definitions:

1. More commonly, it is a description of only *systematic errors*, a measure of statistical bias of a given measure of central tendency; low accuracy causes a difference between a result and a true value; ISO calls this ***trueness***.
2. Alternatively, ISO defines[1] accuracy as describing a combination of both types of observational error (random and systematic), so high accuracy requires both high precision and high trueness.

In the first, more common definition of "accuracy" above, the concept is independent of "precision", so a particular set of data can be said to be accurate, precise, both, or neither.

In simpler terms, given a statistical sample or set of data points from repeated measurements of the same quantity, the sample or set can be said to be *accurate* if their average is close to the true value of the quantity being measured, while the set can be said to be *precise* if their standard deviation is relatively small.

Figure 129 Wikipedia on Accuracy and Precision (https://en.wikipedia.org/wiki/Accuracy_and_precision).

11.7L04.4.7 Conclusion

In chapter 4.4 we found that accuracy, using the common definition of it, relates to how close the average of a very large number of measurements is from the true value. In the common definition, it is independent of the precision and uncertainty associated with the measurements. An accurate measurement would possess zero systematic error, because systematic error is responsible for consistently shifting an average away from the true value.

We also found that validating a method, or calibrating an instrument used for measurements is important in science to help eliminate inaccuracies. We applied the scientific method to assist us in tracking down any inaccuracies we discovered while making measurements.

When it came to measuring tree heights, we found that the photographic method required the camera to be held vertically to the ground, but nevertheless still possessed some inaccuracy, which we discussed. Consequently, the corrected tangent method was probably more accurate.

12 L04.5 Testing Causal Explanations in the Health Sciences

12.1L04.5.1 Introduction

We've heard about making scientific measurements with devices and instruments and seen that accuracy and uncertainty definitely plays a role when it comes to testing scientific explanations. But there are other areas of science where there are no devices, or machines, we can use to test hypotheses. We've also heard that correlation doesn't necessarily imply causation, so if we have a causal explanation for something, say in the field of medicine, how might we go about establishing a causal link?

Figure 130 Dr Yau Wai Ping, Department of Pharmacy, NUS.

For example, say we have an herbal medicine that is hypothesized, or claimed, to counter the effects of depression, or maybe there is a liquid extract, that if drunk, is claimed to cause you to score better in exams. How can we test these hypotheses? There is no machine we can use to make measurements here to help us out. Well, it turns out that there is an excellent method we have at our disposal that involves studying groups of test subjects. This is what we shall be talking about in this chapter, with the help of Dr Yau Wai Ping from the Department of Pharmacy here at NUS.

12.2 L04.5.2 Interview with Wai Ping

Key: RP in green is Ryan Bettens, WP in blue is Yau Wai Ping.

12.2.1 L04.5.2.1 Overview

RB: Let's start with an example, because I think it's easier to talk about. Let's say I have some medicine that is hypothesized to cause people to get better if they are sick, or perhaps improve their health in some way. Is there some method considered, say as the "gold standard", for establishing such a causal link?

WP: Yes, there is. When we want to establish whether there is a cause-effect relationship between, for example, taking the medicine and getting better, the "gold standard" method to test this is the Randomized Controlled Trial, also known as RCT in short. The RCT is a clinical experimental method, meaning that it is a form of scientific experiment involving human participants. Individuals who fulfil eligibility criteria for inclusion into the RCT are invited to participate. Those who agree to participate in the RCT are then randomly assigned to two or more groups. In the simplest design, participants are randomly assigned to an intervention group (also known as experimental group) or a control group. For those assigned to the intervention group, they receive the medicine of interest, i.e. the medicine that we are testing in the RCT. For those assigned to the control group, they do not receive the medicine of interest; instead, they receive standard of care or a placebo. Typically, the study participants are blinded to which treatment they receive. Both intervention and control groups are followed for a specified duration of time or until the occurrence of the outcome of interest which for example is recovery from the illness. When the RCT is completed, the two groups are compared to assess if there is any difference in the outcome of interest, for example if there is any difference in the proportion of individuals in each group who have recovered from the illness within the duration of the RCT.

12.2.2 L04.5.2.2 Why is there a Control Group?

RB: OK, let's unpack all that. Let's start with the control group. Why is there one?

WP: Just like in any scientific experiment, a control group is needed in a RCT to serve as a baseline or comparison for the intervention group.

12.2.3 L04.5.2.3 Why use random selection?

WP: Randomization is the cornerstone of RCT. Firstly, by randomly assigning participants to either the intervention group or the control group, all participants have the same chance of being assigned to each of the groups. The assignment of participants is purely by the play of chance and not selected by the investigators or the participants. Hence, this helps to eliminate selection bias.

Secondly, randomization ensures that all baseline characteristics (for example age, sex, race or ethnic group, and even characteristics that are unknown or unmeasured, such as genetics) are, on average, distributed equally among the randomized groups. This helps to eliminate confounding.

Therefore, randomization establishes the basis for testing the statistical significance of differences between the groups in the measured outcome. Any significant differences between randomized groups in the measured outcome can be attributed to the intervention and not to some other factors.

12.2.4 L04.5.2.4 Interlude: Introducing Table 5.1 from Chapter 5 of the Textbook

TABLE 5.1

Sample Size	Approximate Margin of Error(%)*
25	+/–22
50	+/–14
100	+/–10
250	+/–6
500	+/–4
1000	+/–3
1500	+/–2.5
2000	+/–2

*The interval surrounding the actual sample outcome containing 95% of all possible sample outcomes.

NB to ½ MoE, need 4 x's as many subjects.

Same goes for our MoE on our average (L4.3)

Used with the three rules of thumb to help establish a causal link.

Sample size is the number of subjects in the control group or experimental group.

Margin of error is a ± percentage.

Numbers for 95% confidence level, are calculated using statistics (binomial distribution).

Can only apply table when subjects are assigned *randomly* to groups.

Only exact when result is 50%, e.g., control group size 100, result found to be 50%, Table 5.1 says: 50% ± 10%.

Numbers can still be used as a *guide* when different from 50%.

To see that the numbers in Table 5.1 are a guide when the "success" rate is not 50% let's look at a quick example. Say we did a trial with 50 in the experimental group, and let's also say that the number of subjects that improved after the intervention occurred was 90%. When we use Table 5.1, we see that the margin of error is ±14%. Thinking about this we realize that this can't be so because we can't get a value for the CI that's greater than 100%. The upper value for the CI here would be 90%+14% = 104%, which is impossible. In reality, the margin of error in this case is about ±8.5% at the 95% confidence level. The same holds true if the success rate is near 0%, i.e., using Table 5.1 would give a negative percentage if the success rate was low enough. To obtain accurate margins of error one needs to do a bunch of statistics, which is outside the scope of this course. Nevertheless, since we're just applying "rules of thumb" for statistical significance (we'll see how later), we can still use Table 5.1's numbers as a general guide.

12.2.5 L04.5.2.5 Continuing the interview: Does sample size matter?

WP: Yes, sample size does matter in whether we are able to detect a statistically significant difference between randomized groups in the measured outcome.

In RCT, we are not able to study everybody with a particular illness. Instead, the participants included in an RCT are a sample of the population with the illness. If the sample size is not large enough, we may not be able to conclude whether the medicine leads to recovery from the illness in the larger population, as the difference observed between the groups in the measured outcome could be due to chance variation often found in small samples.

Say, for example, we have 100 participants in the intervention group and 100 in the control group. 27% of those in the intervention group recovered, while 19% in the control group recovered. This translates to an 8% difference in the proportion of participants who recovered between the two groups. This magnitude of difference in the outcome between the two groups is known as the *effect size*. Is this effect size enough for us to conclude that the medicine leads to recovery from the illness based on the number of participants?

TABLE 5.1

Sample Size	Approximate Margin of Error(%)*
25	+/–22
50	+/–14
100	+/–10
250	+/–6
500	+/–4
1000	+/–3
1500	+/–2.5
2000	+/–2

*The interval surrounding the actual sample outcome containing 95% of all possible sample outcomes.

Let's take a look at Table 5.1 of the textbook which provides the approximate margin of error at 95% confidence level for each sample size. For a sample size of 100, there is a +/-10% margin of error at 95% confidence level. This means that in the experimental group whereby 27% recovered, there is a 95% chance that in the population from which the sample was taken, somewhere between 17% and 37% would improve. In the control group whereby 19% recovered, somewhere between 9% and 29% would improve. Diagrammatically, Figure 131 illustrates the CIs for the control and experimental groups.

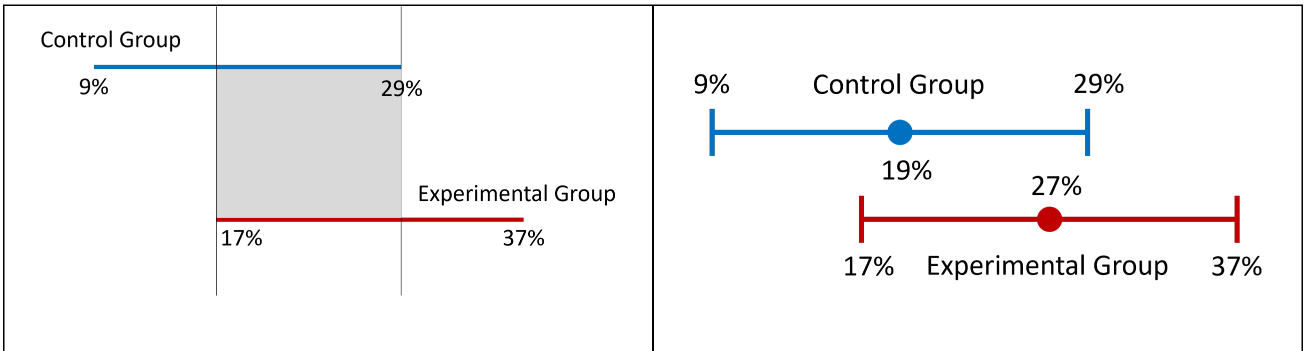


Figure 131 (Left) A properly proportioned version of Figure 5.1 from the textbook. (Right) An alternative representation of the same thing.

Here there is considerable overlap between these two intervals – which is more than one-third of all values. This means that chances are quite high that the observed difference between the groups is due to random statistical fluctuations in the sampling process. We are not able to conclude whether the medicine leads to recovery from illness in the larger population. Maybe it does, but the effect size of 8% is too small to be detected as a statistically significant difference using groups with 100 participants each.

What if we had larger sample sizes? Say, for example, we now have 1000 participants in the intervention group and 1000 in the control group. Let's look at Table 5.1 of the textbook again. For a sample size of 1000, there is a +/-3% margin of error at 95% confidence level. This means that in the experimental group whereby 27% recovered, there is a 95% chance that in the population from which the sample was taken, somewhere between 24% and 30% would improve. In the control group whereby 19% recovered, somewhere between 16% and 22% would improve. Diagrammatically, this is represented in Figure 132.

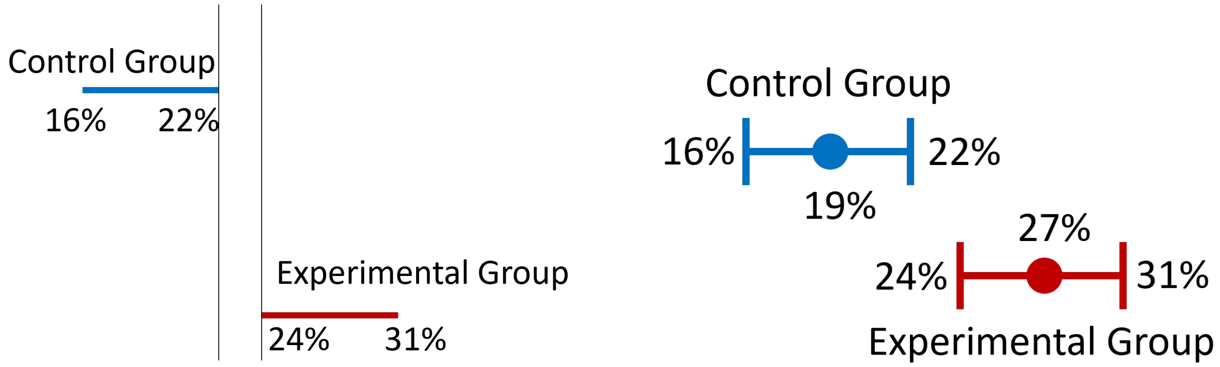


Figure 132 (Left) A properly proportioned version of Figure 5.2 from the textbook. (Right) An alternative representation of the same thing.

As you can see, there is now no overlap between these two intervals, allowing us to conclude that there is a statistically significant difference at the 95% confidence level based on the same effect size of 8%, but using larger groups with 1000 participants each. We can therefore conclude that there is at least a 95% chance that there is a causal link between the medicine tested and recovery from illness. Actually, in this particular example, because there's clearly a gap between the control and intervention groups, we can be even more confident than just 95% that we do have a causal link, i.e., the medicine works.

In summary, yes, sample size matters. RCTs with too few participants may not produce conclusive results. Hence, estimating the sample size needed is one of the most important early parts of planning an RCT.

12.2.6 L04.5.2.6 Blinding in RCT

RB: You mentioned that study participants are typically "blinded". Do you mean they're blindfolded?

WP: No, it has nothing to do with blindfolds. Blinding refers to withholding information about the assigned interventions from people involved in the RCT who may potentially be influenced by this knowledge. These include the study participants receiving the treatment, the clinical staff administering the treatment, the doctor assessing the treatment, and the team analysing and interpreting the results. Very often, you may see that RCTs are described as "double-blind". It means that neither the participants nor the research team know who is receiving which treatment.

12.2.7 L04.5.2.7 Why double blind?

If participants are not blinded, they are more likely to have biased psychological or physical responses to the treatment they are receiving. For example, participants in the control group who receive placebo may report no improvement in or worsening of illness, while those in the intervention group who receive the medicine may report better outcomes.

If the research team is not blinded, the doctor assessing the treatment is more likely to have biases that may affect his outcome assessment. For example, the doctor may give extra attention to participants receiving the medicine and may be tempted to look more carefully for outcomes in the intervention group. Hence, blinding is an important aspect of RCT to minimize the risk of conscious or unconscious bias in the different parties involved in the RCT, so as to ensure objectivity.

12.2.8 L04.5.2.8 Is it always possible to be double blind?

No, not always. In some cases, blinding is difficult or impossible, either for technical or ethical reasons. For example, surgical interventions often cannot be blinded because it is unethical to perform sham surgery in the control group. Hence, some RCTs may be unblinded (also known as open label), meaning that all parties are aware of who is receiving which treatment. Some RCTs may be single blind, where only participants are blinded.

12.2.9 L04.5.2.9 Is it always possible to be RCT?

No, RCTs are not always feasible due to ethical reasons. It is ethical to perform RCT only when clinical equipoise exists, i.e., when the overall benefit or harm offered by the treatment over another is uncertain and there is no good basis for which is a "better" treatment. This then justifies random assignment of participants to different treatment groups.

If RCTs are not feasible, there are other clinical research methods, known as observational studies, that can be considered. For students who would like to gain a deeper appreciation of scientific inquiry in the context of health sciences, I welcome you to sign up for the SI2 course that I am teaching, which is HSI2001 *Scientific Inquiry & Health: Good Science, Bad Science*.

1.1.1 L04.5.2.10 What is your SI2 (HSI2001) about?

In HSI2001 *Scientific Inquiry & Health: Good Science, Bad Science*, students will learn how the ba
principles of scientific inquiry are applied in the context of health sciences. Topics include science vers
pseudoscience, animal experimentation, RCTs, observational studies, systematic review and me
analysis, and statistical pitfalls. This course aims to develop students' scientific thinking capacity and criti
thinking skills to distinguish good science from bad science using interesting authentic case studies a
everyday examples on selected health topics. Students will learn how to critically appraise the strengt
and weaknesses of RCTs and observational studies that impact the credibility of study findings; ident
potential statistical pitfalls that result in misleading conclusions in health sciences literature; and be ab
to make informed decisions based on well-grounded evidence in the context of health sciences. At the e
of the course, students should be empowered to be critical consumers of health information.

12.2.10

12.3L04.5.3 The Three Rules of Thumb

In the previous interview with Prof Yau, we saw a specific example taken from the textbook that applied the rules of thumb. These rules (below, and page 85 of the textbook) are used to establish if we have a statistically significant difference between a control and experimental groups.

(1) If there's no overlap in the CIs, then the difference is statistically significant at the 95% confidence level.
(2) If the overlap is less than one-third of the range covered by the two CIs, then the difference could be statistically significant. But the greater the overlap, the less confident we are that the difference is real.
(3) If the overlap is more than one-third of the range covered by the two CIs, the difference is probably not statistically significant.

We might have a hypothesis or claim that doing something, or eating or drinking something, improves a person. Maybe this something makes them better if they are sick, or perhaps the something, whatever it might be, somehow improves your grades at university. Whatever the situation might be, there is a procedure we can follow in science that can help us find out if the something causes us to improve. That is, there is a way to establish a causal link between the cause, this "something", and the effect, the improvement.

This procedure is the randomized controlled double-blind trial. Now if we can conduct such a trial properly then we can apply the rules of thumb found in our textbook to see if it's really true that the "something", or the "intervention" it is sometimes called, has any effect. Of course, we can never ever be 100% certain of the outcome, but we can at least be 95% sure that the effect is real, which is pretty darn sure.

Students have asked what is the point of the control group? Why not just use the experimental group? Surely if people improve in the experimental group then that means the intervention works, right? Actually, no, because sometimes people can improve without any intervention at all. If we don't use a control group, then we can't gauge whether the intervention was really responsible for the improvement. If the intervention works, then there should be a big *effect size* between the control and experimental groups.

As an aside, remember our list of 5 things we must watch out for when making proper scientific observations? One of those was "Have we considered any necessary comparative information?" Making sure you have a control group is just one example of doing this.

The three rules of thumb we apply tells us whether there really is a statistically significant difference between the two groups. To apply the rules of thumb we need the confidence intervals for our two groups. To find the confidence intervals we look up the margin of error for whatever sample size was used in the trial. This we find from Table 5.1 in out textbook. With our margins of error, we can figure out the confidence intervals of the two groups. Now rule one says if there's no overlap between the two CIs then there is indeed a statistically significant difference between the two groups at the 95% confidence level, so we are pretty sure that we have established a causal link. However, once there's overlap between these two CIs we become less and less confident that there is a statistically significant difference between these groups. This is where rules (2) and (3) come in, and we'll use them next in the worked example.

12.4L04.5.4 Worked Example in Applying the Rules of Thumb

The following was part of a test question for previous HSI1000 students:

A radio announcer during a morning show quoted a recent article from a well-regarded newspaper. The announcer said that according to the paper a recent study by a well-respected university found that well over half the students involved reported improved attention span and were able to remember more facts if they studied while consuming a special type of caffeine-free tea. The announcer summed up the study by stating, "There you have it folks, and I always thought it was true myself because as a student I also drank the special tea, and I swear by it; it totally works and finally they have proven it! So good luck students! Oh, and parents, make sure your kids get some of this tea in them while they study!"

Question:
You managed to track down the scientific study. The work was indeed conducted at a highly prestigious and well-regarded university, with the work being published in a well-respected peer review journal. You check the work and find that it was a randomized controlled double-blind trial involving 50 students in each of the control and experimental groups. You also find that 60% of students in the experimental group said that the special tea did indeed improve their attention span and helped them remember more facts – a percentage well over half, just as the radio announcer said. However, he neglected to report that 50% of the students in the control group also reported experiencing the exact same thing. Does this study show at the 95% confidence level that it is the *special tea* that causes the students to improve their attention span and helped them remember more facts?

a) Maybe, as there is overlap of the range covered by the two CIs, but it is less than one-third.
b) Yes, as there is no overlap of the range covered by the two CIs.
c) No, as there is overlap of more than one-third of the range covered by the two CIs.
d) Yes, as it's clear that well over half (60%!) of the students in the experimental group reported that the special tea did improve their attention span and helped them remember more facts, just as the radio announcer said.
e) Yes, because the experimental group's percentage (60%) is greater than the control group's percentage (50%).

The trial is a legitimate double-blind RCT. The sample size is 50 for the control group and 50 for the experimental group. Referring to Table 5.1, we find the margin of error to be ±14% for both groups as they are both the same size. The experimental group had a success rate of 60% ± 14%, while the control was 50% ± 14%. This corresponds to CIs of 46% - 74% for the experimental group and 36% - 64% for the control group.

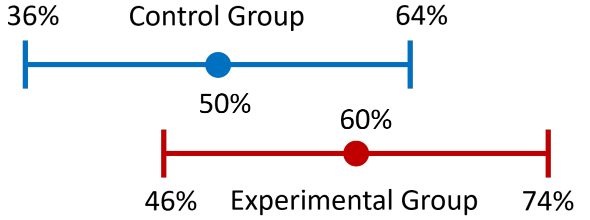


Figure 133 The CIs for the control and experimental groups for the worked example.

There is overlap of these two CIs as illustrated in Figure 133. Rules (2) and (3) mention the range covered by the two CIs. Here that is from 36% to 74%, which is a range of 74% - 36% = 38%. The overlap is from 46% to 64%, which is worth 64% - 46% = 18%.

An overlap of 18% is 18/38=47% of the range covered by the two CIs. According to rule (3), this difference is not statistically significant at the 95% confidence level. This means that option (c) in the MCQ as the correct answer.

An easier way to do this question is to consider the effect size. The effect size is 10% = 60% - 50%. This is the effect we observed on the experimental group that was over and above the control group. If there is more than a third overlap between the two CIs then the margin of error will be greater than the effect size. Here the margin of error is ± 14%, and our effect size is only 10%, so there will be greater than a third overlap between the CIs, as we already deduced.

12.5L04.5.5 Conclusion

In this chapter we saw that a randomized controlled double-blind trial is the "gold standard" in the Health Sciences (and elsewhere where appropriate) for establishing causal links. We heard why a control group is necessary, why the subjects must be selected at random to go into either of these groups, why sample size matters, and why double blinding is necessary. We also discovered that it's not always possible to conduct such trials, so some other approach must be adopted in an attempt to scientifically establish a causal link in these cases. Given that a double-blind RCT has be conducted we learned how we can determine for ourselves if a causal link has been found, given we have the relevant data (i.e., success rates and sample sizes). We saw that we can be 95% confident, or not, in a causal link by applying the three rules of thumb to the confidence intervals for the control and experimental groups.

13 The Science of Climate Change

Intended Learning Outcomes for Lecture 5

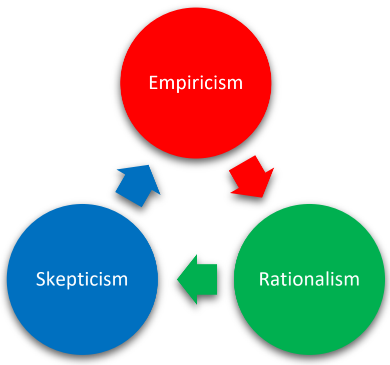
By the end of this lecture, you should be able to:

(1) *Describe* the historical development of our understanding as to the nature of the atmosphere;
(2) *Discuss* the discovery of the greenhouse effect and greenhouse gases;
(3) *Recount* the discovery of oxygen and its importance in the emergence of chemistry as a distinct science;
(4) *Explain* the greenhouse effect by reference to the absorption of radiation by greenhouse gases; and,
(5) *Estimate* the greenhouse effect using the single-layer atmosphere model.

13.1Epistemic Responsibiliy

13.1.1 Empiricism, Rationalism, Scepticism

Scientific inquiry is simply a way of interrogating the world in which we live, of elucidating an understanding with which we can have confidence. This confidence in the reliability of the scientific method depends on the correctness of three philosophies that science uses: empiricism, rationalism and scepticism.[3] Empirical evidence is used to propose hypotheses which logically explain natural causes by predicting natural effects; because explanations might be fallacious, hypotheses are sceptically tested by additional empirical observations or experiments to see if their predictions are fulfilled; if so, the corroborated hypotheses are used to construct logical theories that explain the universe. This is the observe, explain, test hendiatris[4] introduced by Professor Bettens to summarise the scientific method.



This method of knowing can be described as ***critical thinking***. It has the power to complement your own rational and sceptical faculties so that you have confidence in the knowledge that you possess.

The ability to reason, in which we manifest these faculties, is what makes us human. Faustian Bargain

[3] Schafersman, S. D. (1997). Naturalism is an essential part of science and critical inquiry. Paper presented at the Conference on Naturalism, Theism, and the Scientific Enterprise in Austin, Texas.
[4] Hendiatris, or tripartite motto, is a figure of speech in which three words are used to express one idea.

Some look at the world today, with its environmental degradation, and consider science to be somewhat of a Faustian bargain that has condemned us to a dystopian future. However, it was Johann Wolfgang von Goethe himself who put forward perhaps the greatest defence of science is his greatest literary work. The true dystopia that would arise in the absence of science is described when the demon Mephistopheles continues to beguile and further persuade Faust to reject reason:

Figure 134: Illustration by Harry Clarke for a 1925 edition of Goethe's Faust (public domain).

"Have but contempt for reason and for science,
Man's noblest force spurn with defiance,
Subscribe to magic and illusion,
The Lord of Lies aids your confusion,
And, pact or no, I hold you tight."[5]

This course will equip you with the skills to see through such illusions, to dampen your confusion, and to value your ability to reason.

13.1.2 Mea Culpa

In this second block, we will attempt to unpack the elements of scientific inquiry within the context of climate change. I have been studying and teaching atmospheric science and climate change for over 25 years. In 2004, I stood in front of a class of NUS students for the first time and delivered my first lecture. In that lecture, I described climate change as without a doubt the greatest threat to humankind. I am deeply saddened that in the course of the last 25 years next to nothing has improved with regard to how humanity has addressed this issue. It is with great regret that the responsibility to mitigate this threat will belong to your generation. I very much hope that you will not have to share your sadness about a lack of action of your generation with the next. You do not deserve to shoulder this responsibility, but it is yours, nonetheless.

Why are we studying climate change? Well partly it is because if you are to burden the responsibility for combatting climate change it is important that you understand the nature of climate change. But further, understanding the history of the last 25 years with respect to climate change will help illustrate many of the concerns discussed earlier in the course. Climate change has become the focus of certain anti-scientific positions. The fossil fuel industry has waged 'war' to undermine the science behind climate change. It thus provides an unparalleled source of examples to discuss and illustrate pseudoscientific thinking.

Sufficient Evidence

Beyond these reasons, I think it is important for you all to realise that taking an anti-climate change position is not only scientifically incorrect, but that it is also morally wrong. I believe that every citizen has an ***epistemic responsibility*** to base their beliefs on sufficient evidence. This position was first articulated in the essay, The Ethics of Belief, by the English mathematician and philosopher, William Kingdon Clifford:

[5] von Goethe, J. W. (1808). Faust Part I, lines 1851–1855.

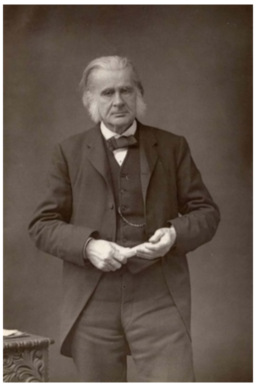


Figure 136: Photograph of Thomas Henry Huxley by John Edwards in c. 1890 (public domain).

"[I]t is wrong always, everywhere, and for anyone, to believe anything upon insufficient evidence."[6]

Figure 135: Portrait of William Kingdon Clifford by John Collier in 1899 (National Portrait Gallery, London, public domain).

A similar position was taken by the English biologist and anthropologist, Thomas Henry Huxley, who wrote:

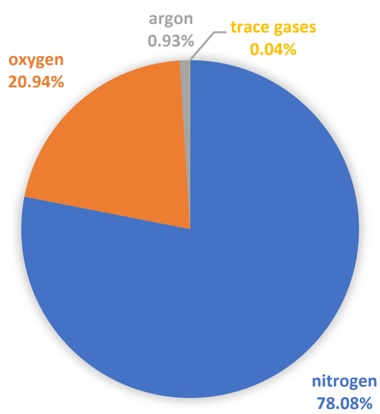
"[I]t is wrong for a man to say that he is certain of the objective truth of any proposition unless he can produce evidence which logically justifies that certainty."[7]

I believe that epistemic responsibility is a driving force behind scientific inquiry, and I would ask that you justify your beliefs with evidence. This is fundamental to responsible scientific inquiry. Having positive evidence to support a claim is also recognised in the third element of the Baloney Detection Toolkit as discussed by Professor Bettens.

13.2 Nature of the Atmosphere

I think most people know that climate change is mainly due to the increasing presence of carbon dioxide in the atmosphere. I think that most people know that this increasing presence of carbon dioxide is due to the burning of fossil fuels. And I think that most people know that during the combustion of fossil fuels, the carbon in the fossil fuels reacts with oxygen in the atmosphere to form carbon dioxide. But how do we know that there is oxygen in the atmosphere? And how do we know that combustion involves oxygen?

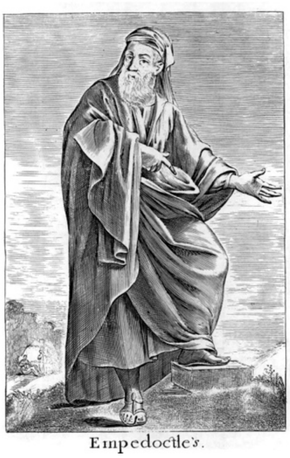
13.2.1 Atmospheric Composition



To address the first question, let's talk about the composition of the atmosphere. Our knowledge of its composition has reached a stunning level of fidelity. As I am sure you are aware, the broad composition is approximately 78% nitrogen, 21% oxygen, and 1% argon. In addition, there are trace gases present. Among these trace gases are carbon dioxide, methane, and nitrous oxide. These are the greenhouse gases whose increasing presence in atmosphere is the cause of climate change. Carbon dioxide is currently measured at levels of around 420 parts per million by volume, or ppmv, also simply referred to as ppm. Four hundred and twenty parts per million means that for every million air molecules, four hundred and twenty of those million are carbon dioxide molecules. Methane is currently measured at levels of around 1900 parts per billion, or ppb. And nitrous oxide, also known as laughing gas, is currently measured at levels of around 335 ppb.

We have not always known that the atmosphere is made up of different gases. I want to take a journey through the history of our discovery of the nature of the atmosphere. Before I start that journey though, I want to allay some fears you might have. In this historical account, I am going to give you lots of names and dates. Do not focus on the marginalia. I will not test you on these things in closed-book settings. Focus on the context and relevance to scientific inquiry.

[6] Clifford, W. K. (1877). The ethics of belief, *Contemporary Review*, **29:** 289.
[7] Huxley, T. H. (1889). IX Agnosticism and Christianity. In *Christianity and Agnosticism: A controversy*. New York, NY: The Humboldt Publishing Co.



This history is important to our understanding of scientific inquiry. This history will celebrate the work of experimental scientists in describing the nature of the atmosphere. Their observations were critical to the advancement of our understanding of the importance of the atmosphere. Such work is critical in all areas of science.

The earliest references to atmosphere were as the element air in the classical cosmogonies of ancient Greece, Egypt, Persia, Babylonia, Japan, Tibet, and India.

In ancient Greece, Empedocles of Agrigentum introduced the idea that all matter is made up of four universal elements—fire, air, water, and earth—although it was Plato who later coined the term 'element'. Empedocles proposed that these four elements could be mixed in different proportions and thus produce the changing complex substances that one finds in the world. They were combined by Love and separated by Strife. He described the process, thus

"And these things never cease their continuous exchange of position, at one time all coming together into one through Love, at another again being borne away from each other by Strife's repulsion."[8]

There is a cycle: when elements have been thoroughly mixed by Love, Strife gradually sorts them out again; when Strife has separated them, Love gradually reunites them. Thus, every compound substance is temporary; only the elements are everlasting. We can imagine that biogeochemical cycles, such as the carbon cycle so important in understanding climate change, could have their origins in such descriptive verse. If we remove the poetic language, we can recognise Love as an attractive force and Strife as a repulsive force. In so doing, we witness language that sounds a little more scientific.

Figure 137: Engraving of Empedocles in The History of Philosophy (1655) by Henry Stanley (public domain).

I know that I am a little off topic, but I do want to pause a moment and discuss this a little more deeply. We have an important question!

Is Empedocles' cosmogony a scientific theory? Certainly, this theory is obsolete, but is it scientific? Professor Bettens argued that a scientific theory is a well-substantiated explanation of some aspect of the natural world that is based on an expansive body of evidence, is often rigorously tested, and is widely accepted within the scientific community. I think that Empedocles would argue that his theory provided a conceptual framework to explain the appearance of all the different forms of matter seen in nature. It has explanatory power. It not only accounts for observed data, but it also offers insights into the underlying mechanisms, processes, and relationships involved. As to its wide acceptance, it was a theory that was standard dogma for some two thousand years. But was it rigorously tested. It is certainly testable. The ancient Greeks, however, were loathe to perform experiments. Why this aversion? Aristotle explained that in an experiment, we intervene in nature. The result, thus, would either be artificial, reflecting merely the results of our own agency, or would do violence to nature by forcing bodies to behave contrary to their nature. Scientific inquiry to the ancient Greeks required them to stand back and observe the natures of things to reveal themselves.

[8] Empedocles, Fragment 17, 6–7.

That said, it was Aristotle, ironically, who performed an early experiment that tested Empedocles' cosmogony. Aristotle argued that although seawater seemed the natural state of water, that it was in fact a compound of other more primitive elements. To show this, he performed an experiment to separate salt from seawater, namely a distillation. He both admits and describes his experiment as follows:

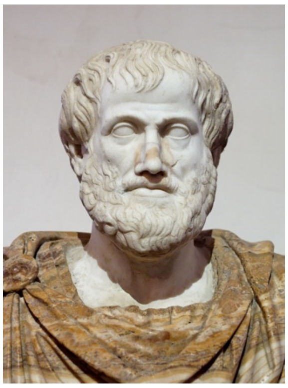


Figure 138: Roman copy of a bust of Aristotle by Lysippos from 330 BCE (public domain).

> *"I have proved by experiment that saltwater, when evaporated, forms fresh water, and the vapour does not, when it condenses, condense into seawater again."*[9]

The purest form of water, then, is fresh water. This result was also confirmed by distilling wine and other liquids; they too were revealed to be compounds of water and earth because, when distilled, they too condensed back to fresh water, leaving a separate earthy compound as a residue.

It isn't perfect, but this historical account articulates an application of the observe, explain, and test description of the scientific method.

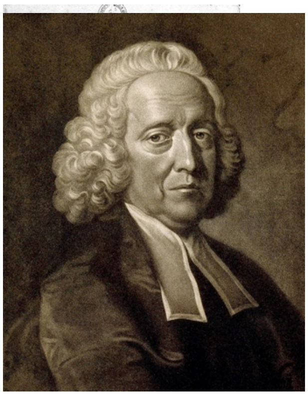
Let's return to the atmosphere. To the ancient Greeks, air was a single element. They would also argue that a pure atmosphere was this element air. The atmosphere could certainly intermingle with other elements to form compound substances. Aristotle describes this in his account of the water cycle in which he discusses the evaporation of water into the atmosphere and its subsequent condensation as clouds and its return to Earth as rain. This water cycle was the first time that a biogeochemical cycle had been described and is a successful application of Empedocles' four elements theory. This is an important part of scientific theories, that they are able to successfully integrate new information or observations. It implies consistency and coherence.

The first suggestion that the atmosphere might be something other than a single substance came from the Italian polymath, Leonardo da Vinci, after observing that air is not completely consumed during combustion and respiration. The English chemist and physiologist, John Mayow, showed that combustion and respiration require only a part of air that he called *spiritus nitroaereus*. Mayow was able to show this during experiments in which he placed either a lit candle or a mouse in a closed container over water caused the water to rise and replace one-fourteenth of the air's volume before extinguishing the subjects. The part of the atmosphere that da Vinci and Mayow had identified is of course oxygen.

Figure 6: Portrait of Leonardo da Vinci by Francesco Melzi in c. 1515–1518 (public domain).

Figure 7: Engraving of John Mayow in Medico-physical Works (public domain).

[9] Aristotle, Meteorologica II, ch. 3, p. 358, 16–18.

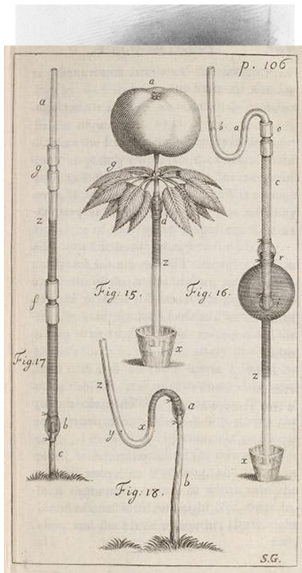


In around 1630, the Flemish scientist, Jan Baptist van Helmont, recognised that many reactions produce substances that are *"far more subtle or fine…than a vapour, mist, or distilled oiliness, although…many times thicker than air"*. In an experiment in which he was burning charcoal, he called the vapours given off *gas sylvestre*, which means 'wood gas', and thus coined the term 'gas'. Today, of course, this gas is known as carbon dioxide. He further recognised that carbon dioxide was produced in other processes, such as the fermentation of wine.

Figure 141: Portrait of Jan Baptist van Helmont (CC by 4.0).

In 1756, the Scottish physician, Joseph Black, in searching for a cure for gallstones found that magnesium carbonate gave off a gas when heated. He called this gas, the same gas discovered by van Helmont, 'fixed air'. Further experiments showed that the gas turned lime water milky and did not support life or combustion. He proved that the gas is naturally present in the atmosphere, confirming that the atmosphere is not a single substance. Black further identified that carbon dioxide is present in exhaled breath. The fact that respiration and combustion return carbon from the biosphere to the atmosphere is critical to understanding the carbon cycle and ultimately understanding climate change. Black never discovered a cure for gallstones.

Figure 140: Alembics owned by Joseph Black in the National Museum of Scotland (CC by 4.0).



So then, who discovered the mechanism by which carbon returns from the atmosphere to the biosphere? The first to suggest that the atmosphere may play a role in the growth of plants is due to the Reverend Stephen Hales. In 1727, Hales published his work on plant transpiration, that is the loss of water from the leaves of plants. This work, entitled *Vegetable Staticks*, noted that "*plants very probably draw through their leaves some part of their nourishment from the air"*. That this nourishment is carbon dioxide was finally recognised by the Dutch scientist, Jan Ingenhousz, in 1796.

These discoveries identified the importance of carbon dioxide and the mechanisms by which carbon moves between the atmosphere and the biosphere, but also recognised that respiration is just another form of combustion.

Figure 142: Mezzotint of Reverend Stephen Hales by J. McArdell (public domain).

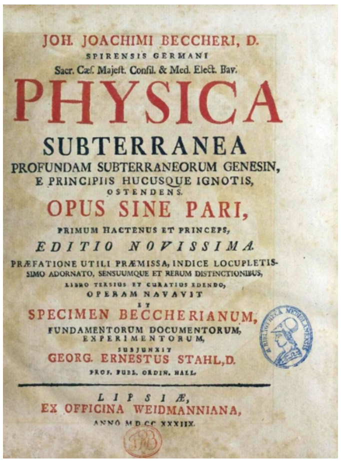
Figure 143: Experiments on an apple tree in Vegetable Staticks (1727) (CC by 4.0).

13.2.2 Problem of Combustion

I have mentioned combustion several times, but what is combustion? The problem of combustion challenged many of the scientists of the 17th and 18th centuries. The solution required the discovery of oxygen and an understanding of the role of oxygen in combustion.

Combustion was completely misunderstood by the alchemists and early chemists. As we have just discussed, it was known that air was needed to sustain combustion and to sustain life. A French physician, Jean Rey, discovered that when the metals lead and tin are heated, they changed and gained weight. Rey attributed this to the incorporation of air into the metal. This was an insightful explanation, but it was completely ignored by his contemporaries.

Figure 13: Engraving of Johann Joachim Becher (public domain).



JOH. JOACHIMI BECCHERI, D.
SPIRENSIS GERMANI
Sacr. Cæs. Majest. Consil. & Med. Elect. Bav.
PHYSICA
SUBTERRANEA
PROFUNDAM SUBTERRANEORUM GENESIN,
E PRINCIPIIS HUCUSQUE IGNOTIS,
OSTENDENS.
OPUS SINE PARI,
PRIMUM HACTENUS ET PRINCEPS,
EDITIO NOVISSIMA.
PRÆFATIONE UTILI PRÆMISSA, INDICE LOCUPLETISSIMO ADORNATO, SENSUUMQUE ET RERUM DISTINCTIONIBUS,
OPERAM NAVAVIT
ET
SPECIMEN BECCHERIANUM,
FUNDAMENTORUM DOCUMENTORUM, EXPERIMENTORUM,
SUBJUNXIT
GEORG. ERNESTUS STAHL, D.
PROF. PUBL. ORDIN. HALL.
LIPSIÆ,
EX OFFICINA WEIDMANNIANA,
ANNO MDCCXXXIIX.

Figure 14: Physica subterranea, 1738 edition (public domain).

Figure 15: Engraving of Georg Ernst Stahl in 1715 (CC by 4.0).

One of the most famous attempts to explain combustion is due to two Germans: an alchemist by the name of Johann Joachim Becher,[10] and a chemist by the name of Georg Ernst Stahl. They are credited with establishing the phlogiston theory for combustion.

Phlogiston theory states that all combustible materials were made of two parts. One part, called phlogiston, was given off when a substance containing it was burnt—consistent with the observation of smoke, *i.e.*, the substance loses something during combustion. The remaining part, the dephlogisticated part, was thought to be the substance's true form, or calx. If something gave off a lot of heat, it was thought to be rich in phlogiston—consistent with the observation that some things are easier to burn than others. Soot was considered to be almost pure phlogiston—consistent with the observation that a metal calx heated with soot transforms the calx back into the metal, *i.e.*, returning phlogiston to the metal calx reveals the metal.

This theory has two problems. First, it was known that combustion could only take place in air, but air has no role in phlogiston theory. Second, the increase in weight of a metal after combustion implies that phlogiston has negative mass. Both of these observations were known prior to the development of this theory by Becher and Stahl. These should have been devastating to the survival of phlogiston theory. Instead, phlogiston theory was modified. Johann Heinrich Pott, a student of Stahl, argued that air was needed because air attracts phlogiston. For many advocates of phlogiston theory, including the celebrated Anglo-Irish scientist, Robert Boyle, the negative mass of phlogiston was not a deal breaker. Phlogiston theory remained the prevailing theory through much of the 18th century.

For a complete understanding of combustion, the discovery of oxygen was ultimately critical. It has been recognised that many scientists of the 17th century, such as the English scientist, Robert Hooke, the Dutch scientist, Ole Borch, the Russian scientist, Mikhail Lomonosov, and the French scientist, Pierre Bayen, produced oxygen in a variety experiments, but failed to realise that this gas was a chemical element. The

[10] Becher's standing as an alchemist cannot be overstated. The title of his first lecture at the University of Mainz was titled *'About the reality of the lapis philosophorum or the philosopher's stone'*.

reason for this failure was due to the widespread acceptance of the phlogiston theory. Importantly, when it comes to crediting someone with discovery, they did not isolate this gas.

So, who did discover oxygen? On this many are credited, but who should be given priority?

Figure 144: Painting of Michael Sendivogius demonstrating alchemy to King Sigismund III of Poland by Jan Matejko (1867) (public domain).

In 1604, the Polish alchemist, Michael Sendivogius, described a substance contained in air which he called *cibus vitae* or 'food of life'. In experiments he performed between 1598 and 1604, he recognised that this substance is the same as the gas released when saltpetre, known today as potassium nitrate, is heated. His experiments into this food of life required large amounts of saltpetre. Normally saltpetre was collected by alchemists from cave walls and was identified as tasting cool to the tongue and being highly explosive. Without access to suitable caves, Sendivogius had to collect his saltpetre from public urinals. History does not record how he identified this saltpetre.

The secretive Dutch engineer and scientist, Cornelis Jacobszoon Drebbel, performed similar experiments, possibly after instruction from Sendivogius himself, and purified what he called the *"spiritous part of it that makes it fit for respiration"*. In 1621, Drebbel demonstrated to King James I, who took a keen interest in science, that his 'liquor', presumably oxygen, could sustain up to twelve men in a submarine for 1–3 hours as they rowed some seven miles from Westminster to Greenwich down the River Thames in London, England.

Figure 145: Painting of the first navigable submarine (public domain).

Figure 146: Portrait of the Carl Wilhelm Scheele (public domain).

A third challenger to the title of discoverer of oxygen is the Swedish pharmacist, Carl Wilhelm Scheele. He produced oxygen by heating mercury oxide and various nitrates in experiments between 1771 and 1772. Scheele called this gas 'fire-air', partly because a candle burnt more brightly in its presence. He wrote his account of this discovery in a manuscript titled *Treatise on Air and Fire*, which he sent to his publisher in 1775. This manuscript was finally published in 1777. The delay in publication was due to an inability to understand the new gas using phlogiston theory and also because the publisher wanted to replicate the findings. Replication and publication are considered important elements of how science works, and delays in publication have lost scientists the rights to claim priority in discovery. It can be critical to choose your publisher carefully. This seems to be the moral of the story for Scheele.

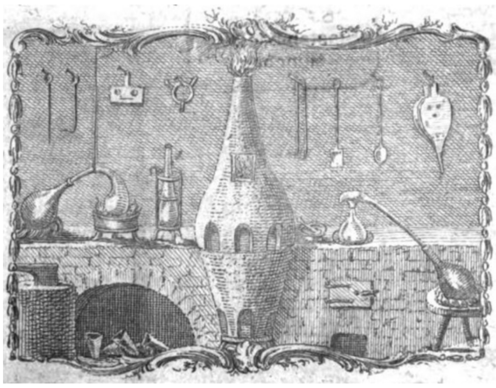


Figure 147: Engraving on the title page of Scheele's Chemical Treatise on Air and Fire (1777) (public domain).

Figure 20: portrait of Priestley commissioned by Henry Fuseli (c. 1783) (public domain).

Perhaps the person most frequently associated with the discovery of oxygen is the English theologian, Joseph Priestley. On 1 August 1774, Priestley conducted an experiment in which he focussed sunlight on mercury oxide in a glass tube which liberated a gas he called 'dephlogisticated air', because it supported combustion and was totally consumed. He noted that candles burned brighter in this gas and mice were more active and lived longer breathing this gas. Priestley published his findings in 1775 in a paper entitled *An Account of Further Discoveries in Air*. Priestley also added to the story of carbon dioxide. In his investigations of how the solubility of carbon dioxide varies with pressure, he discovered carbonation. He called his fizzy drink 'windy water'. So, not only do we have Priestley to thank for soda water, but this work on solubility explains the acidification of the ocean in the presence of increasing concentrations of carbon dioxide in the atmosphere.

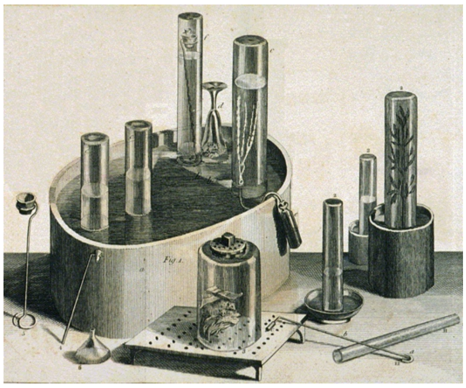


Figure 21: Engraving on the title page of Priestley's Experiments and Observations on Different Kinds of Air (1774) (public domain).

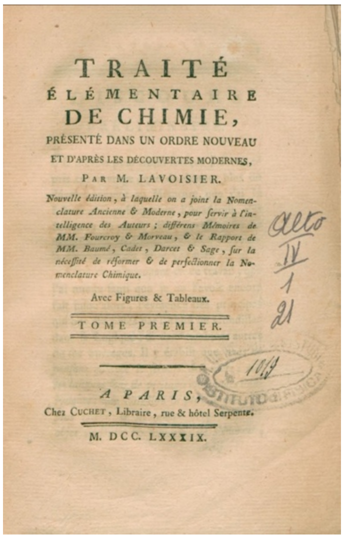
The final challenger most frequently given a right to the claim of discoverer of oxygen is the French chemist, Antoine-Laurent Lavoisier. His claim, though, is not without controversy. In October 1774, Priestley visited the Lavoisiers in Paris and related his studies into his dephlogisticated air. Furthermore, Scheele sent a letter to Lavoisier dated 1 September 1774 in which he described his own discovery and detailed his experimental method. Despite these events, Lavoisier claimed later to have discovered oxygen independently. A gas he called 'vital air'. The Scheele letter remained a mystery until it was finally revealed in a donation by the Lavoisier family to the French Académie des Sciences in 1993. The Lavoisier family had hidden this letter for 219 years because it proved that Lavoisier used Scheele's methods without acknowledgement, proving him guilty of plagiarism.

13.2.3 Birth of Chemistry

There is one final twist to this story. Despite having 'discovered' oxygen, Lavoisier struggled to prove whether oxygen was a new element or a compound. For eight years, he struggled. He doubted whether phlogiston theory could explain oxygen, but he was also unable to disprove phlogiston theory. The final piece of evidence needed to explain combustion, and the role of oxygen, came from an English scientist by the name of Henry Cavendish. In 1766, Henry Cavendish noted that when a gas that he called 'inflammable air' was burnt dew formed on the glass walls. He proved that this dew was pure water. The scientific community was incredulous. This seemed to make no sense. Since ancient times, it had been accepted that water was an element and not a compound. And this is where Lavoisier comes in. On 24 June 1783, Lavoisier invited eight chemists to watch him prove that Cavendish was wrong. When water appeared, Lavoisier was stunned! He suddenly realised that the Cavendish observation had revealed a universally accepted error. He declared, *"Water is not an element, but a compound made of inflammable air and vital air"*. Lavoisier then named inflammable air 'hydrogen' and vital air 'oxygen'. Professor Bettens discussed the Scientific Revolution within the framework provided by Thomas Kuhn. He mentioned that such paradigm shifts had occurred in specific scientific disciplines. Lavoisier's insight

Figure 148: Portrait of Antoine-Laurent Lavoisier and his wife, Marie-Anne, by Jacques-Louis David in 1788 (public domain).

created the greatest Kuhnian paradigm shift in the history of chemistry. It led to his great chemical revolution and Cavendish had provided the key. Over the next six years, Lavoisier demolished phlogiston theory and revised all chemical theory.



TRAITÉ
ÉLÉMENTAIRE
DE CHIMIE,
PRÉSENTÉ DANS UN ORDRE NOUVEAU
ET D'APRÈS LES DÉCOUVERTES MODERNES,
Par M. LAVOISIER.
Nouvelle édition, à laquelle on a joint la Nomenclature Ancienne & Moderne, pour servir à l'intelligence des Auteurs; différens Mémoires de MM. Fourcroy & Morveau, & le Rapport de MM. Baumé, Cadet, Darcet & Sage, sur la nécessité de réformer & de perfectionner la Nomenclature Chimique.
Avec Figures & Tableaux.
TOME PREMIER.
A PARIS,
Chez Cuchet, Libraire, rue & hôtel Serpente.
M. DCC. LXXXIX.

Figure 149: Title page of Lavoisier's Traité Élémentaire de Chimie (1789) (public domain).

He stated that combustion is always and only to do with oxygen, which combines with other substances during combustion. It was also Lavoisier, in a collaboration with Pierre-Simon de Laplace, who proved that animal respiration is a slow form of combustion with the consumption of oxygen and the release of carbon dioxide. In noting that the weight gained by a substance in combustion is lost by the air, he established the Law of Conservation of Mass upon which all modern chemistry is founded. In all of science, only phlogiston possessed negative mass. Lavoisier wielded Occam's razor and cleaved this ontological belief from the body of science. It has never returned.

It is thus that the study of gases such as carbon dioxide and oxygen, and the solving of the problem of combustion, is linked inextricably to the emergence of chemistry as a distinct and rational science. Lavoisier incorporated his foundational ideas in the publication of the first modern chemistry textbook, *Traité élémentaire de chimie*. We celebrate Lavoisier because he was able to see clearly and recognise that combustion is solely about the reaction with oxygen. Many celebrated scientists did not see as clearly, blinded as they were to their adherence to the phlogiston theory. Lavoisier's story ended during the French Revolution. On 8 May 1794, at the height of the Reign of Terror, the Revolutionary Tribunal tried, convicted, and beheaded Lavoisier, the Father of Modern Chemistry.

13.2.4 A Question of Priority

So, who discovered oxygen? As this discovery has been described as the most important discovery in the history of science, it is not without some cachet. The three most frequently credited are Scheele, Priestley, and Lavoisier. The attribution of priority is often decided by national bias. For the Scandinavians, it is Scheele, for the British it is Priestley, and for the French it is Lavoisier. Of these three, Scheele was the first to isolate this gas, Priestley was the first to publish, but it was Lavoisier who was first to understand the discovery.

Perhaps Occam's razor, the principle of parsimony, should be brought to bear again. If Occam's razor is applied to the question of whether Scheele, Priestley, or Lavoisier, or possibly all three, should be credited with the discovery of oxygen, the result is quite clear—none of them; oxygen was discovered and isolated more than a century before their births. Sendivogius isolated oxygen and correctly associated it with that part of the atmosphere required for life. This is sufficient to give priority for the discovery of oxygen to Sendivogius. Well, that is my opinion, others disagree, but I would be interested in whom you believe should be credited with the discovery of oxygen.

13.2.5 Conclusion

This historical discussion not only gives insight into our discovery of the nature of the atmosphere, but also into the development of scientific inquiry and the early application of the scientific method. In the next part of this lecture, I want to discuss the role the atmosphere plays in keeping the Earth surface warm.

13.3 Earth's Blanket

We have just learnt about the composition of the atmosphere. We also learnt how carbon moves between the biosphere and the atmosphere. Its presence in the atmosphere, as carbon dioxide, is critical to understanding how the atmosphere keeps the Earth's surface warm.

So, let's learn how our knowledge of the processes that explain the Earth's surface temperature developed. Once again this narrative will be historical and once again this discussion will help exemplify the principles of scientific inquiry.

13.3.1 Discovering the Greenhouse Effect

The first person to establish that the atmosphere plays a role in controlling the climate was a French mathematician, Jean-Baptiste Joseph Fourier. The same Fourier who has confounded students with his mathematical techniques, but also for his development of an analytical theory of heat transfer.[11]

Figure 150: Portrait of Fourier by Claude Gautherot, c. 1806 (public domain).

It was in his contemplations of heat flow that he came to consider the Earth's temperature. His approach was similar to one I will present later. Initially, as others had done before, he considered the Earth receiving energy from the Sun. Such a model though leads to an Earth that gets hotter and hotter and hotter. He realised that the Earth itself must radiate, although at wavelengths we cannot see. He called this radiation, radiant heat, what we now call infra-red radiation.

Fourier made very precise measurements of this radiant heat, and together with the radiation from the Sun, calculated that the Earth's temperature should be −18 °C, way below the some 15 °C we observe and certainly not conducive for life as we know it.

Something was missing, and in 1824, Fourier realised that this missing something was the atmosphere. The atmosphere, he surmised, must act as an insulator preventing some of this radiant heat from escaping to space and returning that radiant heat to further warm the Earth's surface. In 1824, Fourier pronounced that,

> *"the temperature [of the Earth] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat."*[12]

This was the first formulation of what we now call the greenhouse effect and marks the discovery of this phenomenon. However, for historical completeness, we should note that Fourier did not coin that term. The term 'greenhouse effect' first appeared in the work of the Swedish meteorologist, Nils Gustaf Ekholm, in around 1900.

This connects nicely with Professor Bettens' 'observe, explain, test' description of the scientific method. Fourier was aware from the careful measurements of others of the *observed* Earth surface temperature. He developed a theoretical *explanation* to account for this temperature, that the energy received from the Sun would be balanced by the radiant heat from the Earth. To *test* this mathematical model, Fourier needed measurements of the radiant heat from the Earth, which he subsequently gathered. Inputting these numbers into his model, however, resulted in a substantial discrepancy that he sought to resolve by inferring that the

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[11] On the first page of his book Analytical Theory of Heat Transfer, Fourier described the relationship between science and nature. He stated, *"Primary causes are unknown to us; but are subject to simple and constant laws, which may be discovered by observation, the study of them being the object of natural philosophy."* Fourier, J. (1822). *Théorie analytique de la chaleur*. Paris: Firmin Didot Père et Fils.

[12] Fourier, J. (1824). Remarques générales sur les temperatures du globe terrestre et des espaces planétaires, *Annales de Chimie et de Physique*, **27:** 136–167.

atmosphere must play a role. He said that, *"the Earth is kept warm because air traps heat, as if under a pane of glass"*.[13]

In this example, we witness the different roles of a scientist. Fourier most closely typifies the role of theoretician, although he was responsible for gathering some of the necessary data. Today, the theoretical scientist and the experimental scientist are most likely separate. The theoretician is someone who develops testable theories. A great deal of the work of a theoretician is putting together mathematical, and indeed, computer models. These models make predictions that can be tested against observations collected by experimental scientists who are particularly skilled in this area.

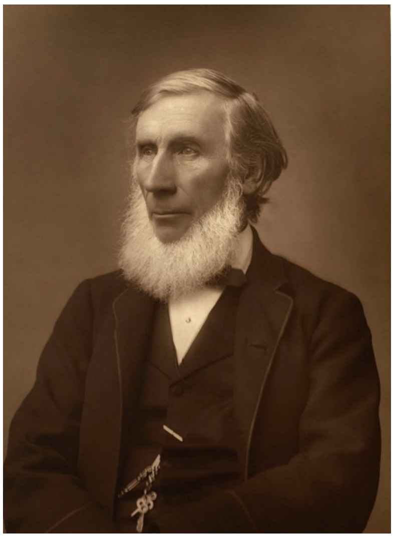

Figure 151: Photograph by John Tyndall, c. 1885 (public domain).

The work of Fourier begs several questions. What role does the atmosphere play in warming the Earth's surface? What is it about the atmosphere that explains this role? What is the underlying process? And who discovered this underlying process?

The Irish physicist, John Tyndall, is commonly credited with explaining the greenhouse effect, which underpins the science of climate change. Starting in 1859, Tyndall published a series of studies on the way a number of gases, including carbon dioxide, absorb radiation. This was an area of investigation that in his words was *"a perfectly unexplored field of inquiry"*. To measure the absorption of radiation by various gases, he had to build his own equipment, in particular, the ratio spectrophotometer.

[13] Fourier, J. (1827). Mémoire sur la température du globe terrestre et des espaces planétaires. In Vol. 7. Mémoires de l'Académie Royale des Sciences. pp. 569–604.

With this instrument he quickly realised the importance of water vapour in the absorption of terrestrial radiation. In 1861, Tyndall wrote,

> *"Remove for a single summer-night the aqueous vapour from the air which overspreads this country, and you would assuredly destroy every plant capable of being destroyed by a freezing temperature. The warmth of our fields and gardens would pour itself unrequited into space, and the sun would rise upon an island held fast in the iron grip of frost."*[14]

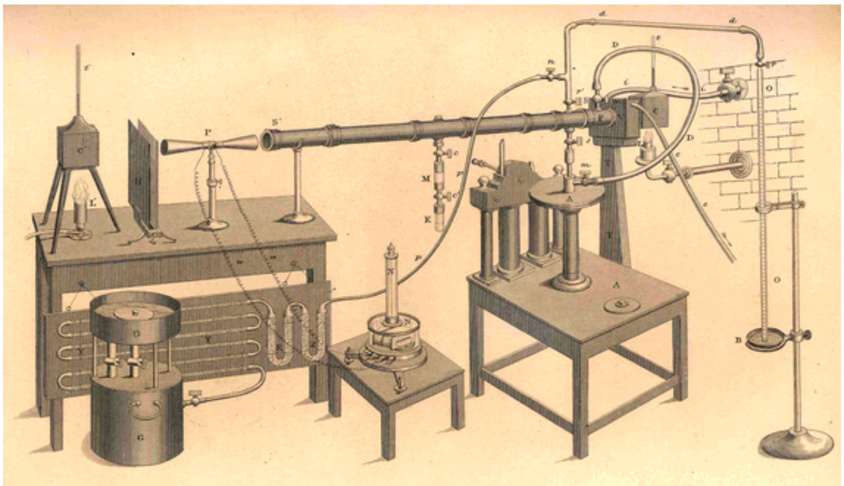

Figure 152: Tyndall's ratio spectrophotometer measured the extent to which infrared radiation was absorbed and emitted by various gases filling its central tube (public domain).

The importance of other gaseous species and the relative effectiveness of each in absorbing infra-red radiation was reported in a paper published in 1862. Following very careful measurements, Tyndall determined that carbon dioxide is 90 times more effective at absorbing infra-red radiation than air. He determined methane as being 403 times more effective. He later determined water vapour to be some 16,000 times more effective at absorbing infra-red radiation than pure air.

The implications were clear. In 1862, Tyndall wrote,

> *"As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth's surface."*[15]

This describes the key to climate change. Tyndall had discovered in his laboratory that certain gases, including water vapor and carbon dioxide, are opaque to radiant heat. He understood that such gases high in the atmosphere help keep our planet warm by interfering with escaping radiation. Words like 'transparent' and 'opaque' are used deliberately in this context. They acknowledge that the atmosphere allows radiation to pass through unhindered at some wavelengths, that is the atmosphere is transparent at these wavelengths; and, the atmosphere absorbs strongly at some wavelengths preventing such radiation from passing through, that is the atmosphere is opaque at these wavelengths.

We know the nature of the discovery, but should Tyndall be given priority in this discovery?

I query this, for an 1856 presentation delivered before the American Association on behalf of the American scientist, Eunice Newton Foote, describes experiments in which she filled glass jars with water vapour, carbon dioxide and air, and comparing how much they were heated up in the Sun.

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[14] Tyndall, J. (1861) I. The Bakerian Lecture.—On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction, *Phil. Trans. R. Soc*. **151:** 1–36.

[15] Tyndall, J. (1863) XXVII. On radiation through the earth's atmosphere, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, **25(167):** 200–206.

She wrote, *"The highest effect of the sun's rays I have found to be in carbonic acid gas"*.[16] Carbonic acid gas was the contemporary term for carbon dioxide. She further wrote, *"The receiver containing the gas became itself much heated—very sensibly more so than the other—and on being removed, it was many times as long in cooling."*

Figure 153: Photograph of Eunice Newton Foote by Ida Hinman in the Washington Sketch Book (public domain).

However, it is the discussion that followed that particularly warrants attention. Foote speculated that the concentrations of carbon dioxide in the air could influence global temperatures:

> *"An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted."*

Eunice Foote identified carbon dioxide as a greenhouse gas a few years before Tyndall, and also noted its importance in controlling the Earth's surface temperature. Foote's contribution to the science of climate change needs to be more widely acknowledged given how marginalised female scientists are in the history of science.

So, with the work of Eunice Foote and John Tyndall, we now have the underlying process that explains the greenhouse effect. The greenhouse effect is due to the absorption of terrestrial infra-red radiation by gases in the atmosphere, primarily water vapour and carbon dioxide.

Before we move on to the next part of the story, I want to highlight the importance of instrumentation in this discovery. In his first lecture, Professor Bettens spoke about how revolution in science is frequently precipitated by the invention of a new instrument that leads to new discoveries. The example given was the telescope of Galileo. Here, I described the ratio spectrophotometer built by Tyndall. This development was critical in determining the relative importance of different greenhouse gases. I, perhaps, undersold this development. Critical to the importance of this instrument was its ability to determine the absorbance of infra-red radiation due to the different gases, rather than simply the broad absorption of all radiation.

Although I maintain that far more credit needs to be afforded Eunice Foote, this critical element of Tyndall's instrument does perhaps tip the balance as to priority. <u>Tyndall was able to show that the importance of carbon dioxide was its ability to absorb infra-red radiation.</u> Foote's instrument could only show that carbon dioxide absorbed some part of incoming solar radiation. Again, I would be interested in your view as to the priority of this discovery.

The work of Fourier, Foote and Tyndall gave us a working model of the greenhouse effect. It was now time to calculate the magnitude of the greenhouse effect.

13.3.2 Understanding the Greenhouse Effect

In the 1890s, the Swedish geologist, Arvid Högbom, began attempting to quantify the natural sources of emissions of carbon dioxide for the purposes of understanding the global carbon cycle. Högbom found that the estimated carbon production from industrial sources, primarily from the burning of coal, was comparable to the natural sources. He presented these results at a meeting of the Swedish Chemical Society in a paper entitled "On the probability of secular changes in the atmosphere's carbonic acid concentration". After the talk, the possibility that changes in the carbon dioxide concentration could produce changes in the surface

[16] Foote, E. (1856) Circumstances affecting the heat of the sun's rays, *American Journal of Science and Arts*. **22:** 382–383.

temperature came up in discussion. In the audience was Svante August Arrhenius, the Swedish chemist who would later win the third Nobel Prize in chemistry.

Figure 154: Photograph of Svante Arrhenius in 1909 (public domain).

This discussion prompted Arrhenius to consider the effect of changing amounts of carbon dioxide in the atmosphere. Using a simple mathematical model similar to one we shall use later, Arrhenius calculated that a doubling of atmospheric carbon dioxide would raise average global temperatures by 5–6 °C. That estimate made in 1896 is not so very different from most modern attempts to calculate the temperature change due to increasing carbon dioxide levels.

The human emissions of carbon dioxide estimated by Högbom, together with his own calculations, led Arrhenius to conclude that such emissions would lead to warming, but he expected the warming would take thousands of years. Indeed, he suggested that such warming might be beneficial to humanity.

So, Arrhenius, having computed the first estimates of global warming, did not believe that anthropogenic climate change would be significant, at least not for thousands of years.

When did concern over global warming begin? The first to suggest that increasing carbon dioxide levels might be having an observed effect was the English engineer and inventor, Guy Stewart Callendar. In 1938, he was the first to demonstrate that Earth's surface temperature had increased over the previous 50 years and argued that this temperature increase was due to rising carbon dioxide concentrations. This work had required Callendar to compile measurements of temperatures from the 19th century on, and correlate these measurements with atmospheric CO_2 concentrations. This link between rising carbon dioxide concentrations in the atmosphere to global temperature is sometimes referred to as the Callendar effect. Like Arrhenius, though, Callendar thought this warming would be beneficial, delaying a "return of the deadly glaciers".

Figure 155: Photograph of Guy Stewart Callendar in 1934 (fair use).

13.3.3 It's Happening Now

Beyond the global temperature, perhaps the most important set of data ever recorded in the history of climate change is the data collected from the Mauna Loa Observatory in Hawaii some 3,000 metres above sea level. In 1958, the American scientist, Charles David Keeling, received funding from the National Science Foundation to collect carbon dioxide samples at this base. By 1961, Keeling produced data showing that carbon dioxide levels were rising steadily in what later became known as the 'Keeling Curve'—a data set that continues to this very day. The data was so concerning that by 1963 the Foundation used Keeling's research in its warning of rapidly increasing amounts of heat-trapping gases.

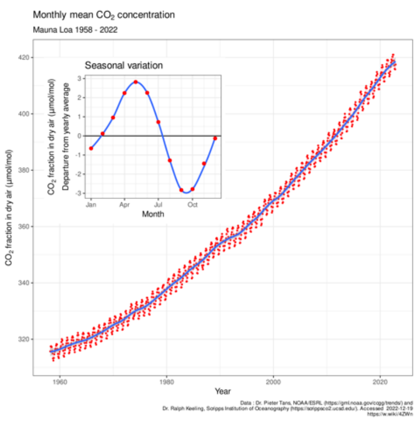


Figure 156: Atmospheric carbon dioxide (CO2) concentrations from 1958 to 2023 (CC by 4.0).

Figure 157: Photograph of Charles Keeling from of the Scripps Institute Oceanography (fair use).

In 1965, U.S. President Lyndon B. Johnson's Science Advisory Committee published their landmark report, 'Restoring the Quality of our Environment'. This report warned of the harmful effects of fossil fuel emissions:

"The part that remains in the atmosphere may have a significant effect on climate; carbon dioxide is nearly transparent to visible light, but it is a strong absorber and back radiator of infrared radiation, particularly in the wavelengths from 12 to 18 microns; consequently, an increase of atmospheric carbon dioxide could act, much like the glass in a greenhouse, to raise the temperature of the lower air."

The committee used the recently available global temperature reconstructions, and carbon dioxide data from Keeling, to reach their conclusions. They declared the rise in levels of atmospheric carbon dioxide to be the direct result of burning fossil fuel. The committee concluded that human activities were sufficiently large to have significant, global impact—beyond the area where the activities took place. In a chilling admission, the committee wrote, *"Man is unwittingly conducting a vast geophysical experiment"*.

Following the advent of computer models, the American scientist, James Hansen, published a study in *Science* in 1981 in which he and his colleagues reported,

"that the anthropogenic carbon dioxide warming should emerge from the noise level of natural climate variability by the end of the century, and there is a high probability of warming in the 1980s. Potential effects on climate in the 21st century include the creation of drought-prone regions in North America and central Asia as part of a shifting of climatic zones, erosion of the West Antarctic ice sheet with a consequent worldwide rise in sea level, and opening of the fabled Northwest Passage".

Figure 158: Photograph of James Hansen testifying to the US Congress by Dennis Cook/AP (fair use).

In 1988, the same James Hansen, now Director of the NASA Goddard Institute for Space Studies, was called before the U.S. Congress to give testimony. Hansen told the congressional committee that it was **99% certain** that the warming trend was not a natural variation but caused by a build-up of carbon dioxide and other artificial gases in the atmosphere. Hansen told the hearing, "Global warming has reached a level that we can ascribe with a high degree of confidence a cause-and-effect relationship between the greenhouse effect and observed warming". He added, *"It is already happening now"*.

Two things stand out from Hansen's statement to the U.S. Congress. First, he states that he is 99% certain that the warming trend is not natural. This number isn't a rhetorical device used to emphasise his testimony. It is grounded in statistics. I will return to this number in the next lecture. Second, he ascribes to the build-up of carbon dioxide, and the observed warming trend, a cause-and-effect relationship. In his third lecture, Professor Bettens discussed causal mechanisms and some of the complications establishing them. This idea of a causal mechanism is clearly important in science. It is also something that is intuitively understood by the public. It was the reason why James Hansen at the Senate hearing in 1988 wanted to state that a cause-and-effect relationship existed. These words bluntly recognised that global warming was happening, and it was human caused.

13.3.4 On Metaphors

But what is the difference between the greenhouse effect and global warming?

This can be confusing, so let's define these terms. First, the 'greenhouse effect' and 'global warming' are not the same thing. Later, we will calculate the magnitude of the greenhouse effect, but in the meantime, it should be noted that without the greenhouse effect we would all be dead.

The greenhouse effect is the name given to the process that causes the surface to be warmer than it would have been in the absence of an atmosphere. Global warming is the name given to an expected increase in the magnitude of the greenhouse effect, whereby the surface of the Earth will be inevitably hotter than it is now.

Earlier we narrated the history of Foote and Tyndall discovering that the greenhouse effect was due to gases that absorbed terrestrial infra-red radiation. A common metaphor for the greenhouse effect is that the atmosphere acts like a blanket. Blankets do not behave in the same way as greenhouse gases though. Blankets keep us warm because they suppress convection. Heat from your bodies is not able to escape because of the blanket. The atmosphere enables convection. The metaphor works because more blankets means warmer person; more greenhouse gases means warmer planet. Unfortunately, there are other emissions to the atmosphere that do not follow this metaphor. If we increased the emissions of sulphate aerosols, say through volcanic eruptions, the planet would cool not warm. This was observed following the eruption of Mount Pinatubo, in the Philippines, in 1991. It is ironic that we call the effect by which the Earth is warmed by the presence of gases like water vapour and carbon dioxide in the atmosphere the greenhouse effect. The reason why is because greenhouses behave in exactly the same way as blankets, the glass inhibits convection and prevents the exchange of air between inside and outside.

It is important that we recognise that there are limits to the usefulness of metaphors, or indeed models, when trying to explain phenomena. Metaphors are certainly important in communicating scientific ideas. However, the reduction of ideas to metaphor does come at the cost of precision. In using metaphors, scientists consider the audience they are addressing.

A word of warning. Metaphors are also used by the unscrupulous to peddle their pseudoscientific nonsense. During the COVID-19 pandemic, vaccine denialists argued that not taking a vaccine was akin to not wearing a seat belt while driving. The implication being that they are only putting themselves at risk. When a person chooses to avoid vaccines, they choose not only to potentially harm themselves, they also choose to potentially harm all those they come in contact with, and all the people that those people come in contact with, and so on. The metaphor is flawed and does not pass close scrutiny. The loss in precision in forming the metaphor leads people to take away a message that is contrary to the science.

13.3.5 A Correct Explanation

Returning then to the greenhouse effect. What is the correct explanation for why the Earth's surface is warmer in the presence of its atmosphere? <u>The surface of the Earth is warmer than it would be in the absence of an atmosphere because it receives energy from two sources: the Sun and the atmosphere.</u> To understand this statement better, we need to build a scientific model for the greenhouse effect. And that will be the subject of the final part of this lecture.

13.4Model Building

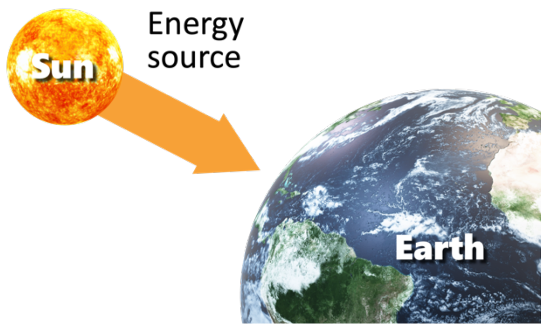
In the final part of this lecture, I want to build a mathematical model to estimate the magnitude of the greenhouse effect. How do scientists go about this?

13.4.1 The Model of Fourier

The first thing we need to define here is what we mean by the magnitude of the greenhouse effect. It seems sensible to follow the approach of Fourier. He recognised that the atmosphere was responsible for keeping the Earth warm and conducive to life. So, we need to build a model that allows us to determine the effect of the atmosphere.

We will do this in a piecemeal fashion. We can start by repeating the calculation of Fourier that predicted the temperature of the Earth's surface in the absence of an atmosphere. We can then modify the model to include an atmosphere.

As I take you through this, focus on the ideas and concepts of model building, not on the derivation itself. Being able to derive the model is not the purpose of this course.

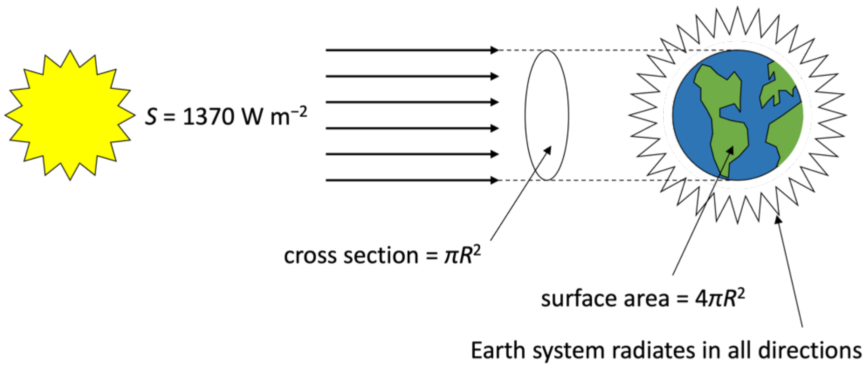


So, let's start. Where does the Earth get its energy? I think most of us would be unsurprised to learn that the most significant source of energy is the Sun. Are there other sources though? Well, we could also consider the energy emanating from the Earth's core. That energy is due to the radioactive decay of fissile material accreted into the Earth system at the birth of the Solar System. The addition of this second energy source seems to be already creating complications. Let's ignore the internal source of energy and only consider solar energy. Careful measurements of the energy emanating from the Earth's core support this simplification: the amount is several orders of magnitude smaller than that received from the Sun. Remember, models are always simplifications of real systems. They will always introduce errors due to simplification. Scientists use the type of scale analysis I have just mentioned to decide which elements of a system to include and which to neglect.

We also know that the Earth is emitting radiation back to space. If the amount of energy entering and being absorbed by the Earth was different from the amount of energy being emitted and leaving the Earth, then the Earth system would be getting hotter or colder depending on the direction of the imbalance. This makes intuitive sense.

It is also a matter of everyday experience that hotter objects emit more radiation, or energy, than colder objects. Scientists have managed to quantify this relationship. The relationship between the temperature of an object and the amount of emitted energy is known as the Stefan–Boltzmann law. This relationship states that the emitted energy from an idealised object is proportional to the fourth power of the absolute temperature, that is the temperature measured in Kelvin in which the scale starts at absolute zero—the coldest possible temperature. This relationship was deduced by Josef Stefan using data provided by the careful measurements of Tyndall, but it was determined theoretically by Ludwig Boltzmann. I said that this relationship holds for an idealised object. This is a common device in theoretical science. Theoreticians make assumptions that never fully hold in nature in order to be able to provide deep insight into the structure of nature. These assumptions *idealise* the situation. For the Stefan–Boltzmann law, the assumption is that the emitting object can be treated as a black-body. Despite its name, this doesn't mean the object is literally black and the exact assumptions do not matter for our purposes. Importantly for our purposes though, the emission of radiation from the Earth, and for that matter the Sun, both to a good approximation follow the Stefan–Boltzmann law.

We are now in a position to calculate the temperature of the Earth in the absence of an atmosphere. To do this, we will need to assume that the temperature of the Earth is constant. This is not really true; the Earth is in fact warmest during the northern summer and coldest during the southern summer. The range in temperature is about 4 °C. If we wanted to build a model that could account for this variation we would need to account for the elliptical orbit of the Earth around the Sun and the tilt of the Earth's axis, as well as the distribution of land and ocean over the Earth's surface. These are complications we don't need. Instead, let's consider that there are no seasons and that we can use an average of the amount of solar radiation the Earth receives over the course of a year.



We can only have a constant Earth surface temperature if the amount of energy being absorbed by the Earth system is the same as the amount that is being emitted by the Earth system. Careful measurements by satellites outside of the Earth's atmosphere tell us that the energy from the Sun reaching the top of the atmosphere, the 'solar constant' which is given the symbol, S, is 1370 W m^{-2}—this is the energy per square metre arriving every second. What is the total amount of solar energy being absorbed by the Earth every second? Well, we need to multiply this solar constant by an area. But what area? Well, if we think of the solar rays arriving at the Earth, we can see that it would be the cross-sectional area of the Earth facing the Sun. If we take the radius of the Earth to be R, the Earth absorbs solar energy over an area πR^2. However, the Earth is emitting energy from its entire surface. The formula for the surface area of a sphere is $4\pi R^2$.

We can equate the amount of energy being absorbed by the Earth system, this will be $S \times \pi R^2$ or $1370 \times \pi R^2$, to the energy being emitted by the Earth system, which will be given by the Stefan–Boltzmann law $\times\ 4\pi R^2$ or $\sigma T_E^4 \times 4\pi R^2$. The sigma symbol is the Stefan–Boltzmann constant which has a value of 5.67×10^{-8} W m^{-2} K^{-4}.

$$\text{energy into the Earth system} = \text{energy out of the Earth system}$$
$$1370 \times \pi R^2 = \sigma T_E^4 \times 4\pi R^2$$

If we rearrange this expression, then T_E^4 is equal to $1370 \times \pi R^2$ all over $5.67 \times 10^{-8} \times 4\pi R^2$.

$$T_E^4 = \frac{1370 \times \pi R^2}{\sigma \times 4\pi R^2} = \frac{1370}{5.67 \times 10^{-8} \times 4} = 6.04 \times 10^9$$

The πR^2 terms cancel, which leaves us to solve for the temperature. Initially we find that the fourth power of the temperature is approximately 6.04×10^9. If we take the fourth root we can find the temperature. The fourth root can be calculated directly on most calculators, but it can also be calculated by taking the square root twice.

$$T_E = \sqrt[4]{6.04 \times 10^9} = \sqrt{\sqrt{6.04 \times 10^9}} = 279\ \text{K}$$

Ultimately this results in a calculation of the Earth's surface temperature of 279 K. Well, that doesn't seem too bad. In degrees Celsius, 279 K is 6 °C. A bit chilly, but liveable.

But wait a moment, that's not the temperature that Fourier calculated. And you're right. We unwittingly made an approximation for which we need to correct. We assumed that all the solar radiation incident on the Earth's surface is absorbed. But in fact, some 30% of the incoming solar radiation will be reflected either by the Earth's surface, clouds or indeed the atmosphere itself. Only the remaining fraction of 70% is absorbed and acts to heat the Earth. The fraction of incoming solar radiation that is reflected is often referred to as the Earth's albedo, and is denoted by the symbol A.

We can easily include this information about the Earth's albedo to calculate a new temperature for the Earth's surface in the absence of an atmosphere. We simply need to multiply the solar constant by $(1 - A)$. When we do this, we find that the temperature of the Earth's surface is 255 K. This is equivalent to −18 °C. The same temperature calculated by Fourier. As noted earlier, this would make the Earth an uninhabitable environment. The planet would be a snowball.

$$T_E^4 = \frac{1370 \times (1 - A) \times \pi R^2}{\sigma \times 4\pi R^2} = \frac{1370 \times (1 - 0.3)}{5.67 \times 10^{-8} \times 4} = 4.23 \times 10^9$$

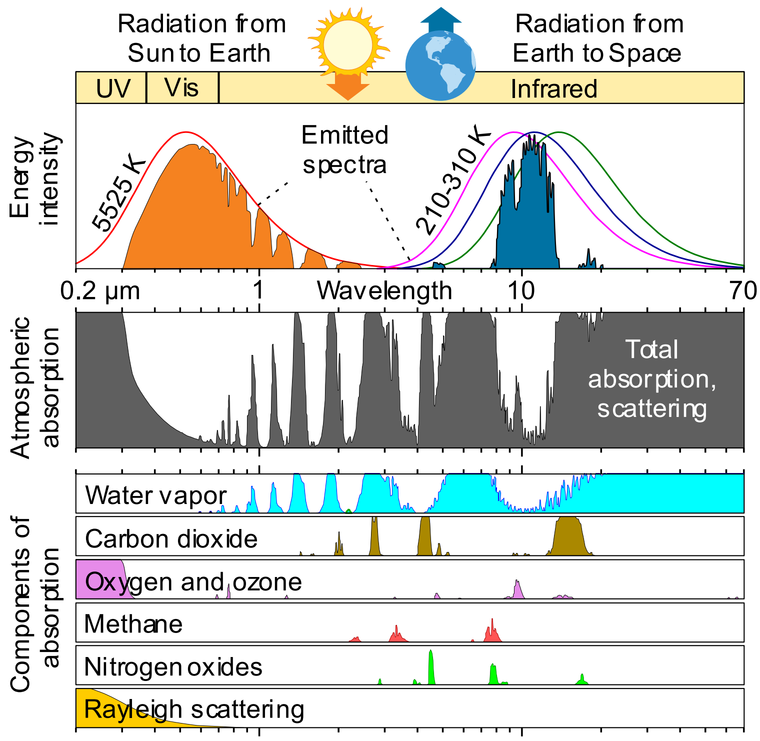
$$T_E = \sqrt[4]{4.23 \times 10^9} = 255\ \text{K}$$

As noted by Fourier, we need to account for the effect of the atmosphere, but note that if we were to point an infra-red thermometer at the Earth from space then this temperature of −18 °C would be the average temperature measured. This is referred to as the planet's effective temperature.

13.4.2 Accounting for the Atmosphere

How can we modify our mathematical model to account for the effect of an atmosphere? What is it about the atmosphere that we need to include? And can we calculate the magnitude of the greenhouse effect?

In answer to the second question, we need to allow the atmosphere to absorb and emit radiation. Let's look at the absorption of radiation by the atmosphere in a bit more detail. In particular, we need to know how radiation from the Sun and the Earth interacts with the atmosphere.



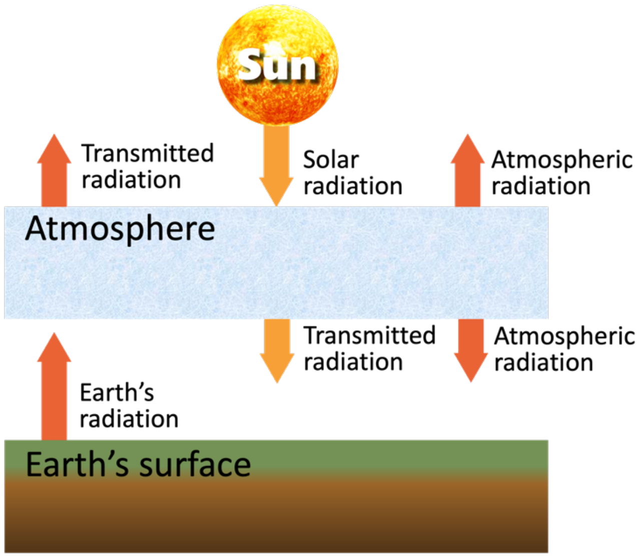
The top panel in the figure[17] above shows this. In orange, we have the radiation from the Sun. The orange line indicates the solar radiation before entering the Earth system—it is the emitted solar spectrum. Note that this solar spectrum peaks in the visible. There is also significant solar radiation present in the ultraviolet and near infra-red. The wavelengths are given on the horizontal axis in microns. Radiation on the left is far more energetic than radiation on the right. It is the ultraviolet radiation, particularly the UV-B radiation between 280 nm and 315 nm (that would be 0.28 microns and 0.315 microns), that leads to skin melanoma. The solid orange area shows how much solar radiation at any wavelength reaches the Earth's surface. The difference between the orange line and the solid orange area indicates how much solar radiation is absorbed or scattered by the atmosphere. The scattering of solar radiation is part of the 30% reflectivity, or albedo, of the Earth system. Approximately 20% of solar radiation is absorbed by the atmosphere. In blue, we have the radiation from the Earth. The blue line indicates the terrestrial radiation emitted by the Earth surface. This radiation is in the infra-red. Note that solar radiation and terrestrial radiation are emitted in different parts of the electromagnetic spectrum. This is because the hotter the object the more the object emits at shorter, and more energetic, wavelengths. The solid blue shows how much terrestrial radiation passes through the atmosphere to reach space. The difference between the blue line and the solid blue area indicates how much terrestrial radiation is absorbed by the atmosphere. This is approximately 90%. The reason why more terrestrial radiation is absorbed by the atmosphere than solar radiation is because of the absorption characteristics of molecules present in the atmosphere. As we can see in the lower panels, water, carbon dioxide, methane, and nitrous oxide can all absorb infra-red radiation over a very broad range. However, the only molecules that can absorb ultraviolet or visible radiation are ozone and oxygen, and only below 315 nm. This leads to the preferential absorption of terrestrial radiation over solar radiation by the atmosphere.

So, we need a model that is capable of such differential absorption of solar and terrestrial radiation. Representing this differential absorption characteristic will also allow us to represent changing atmospheric concentrations of greenhouse gases by modifying how well the atmosphere absorbs infra-red radiation.

[17] This figure is taken from Wikipedia: https://commons.wikimedia.org/wiki/File:Atmospheric_Transmission.svg

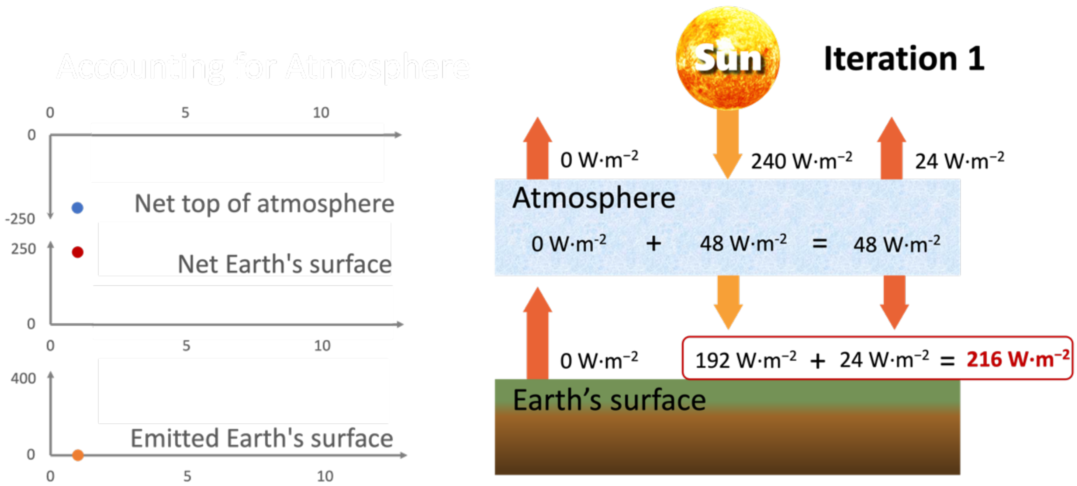
Do we need a model that accounts for the temperature of the atmosphere? Should the model account for how the temperature varies with altitude? This would require us to include a great deal of radiative theory that would greatly complicate our model build. It also seems unnecessary. We're not interested in the temperature of the atmosphere; we're only interested in the temperature of the Earth's surface.

Right then. Let's include two parameters: one that accounts for the absorption of solar radiation; and, one that accounts for the absorption of terrestrial radiation.

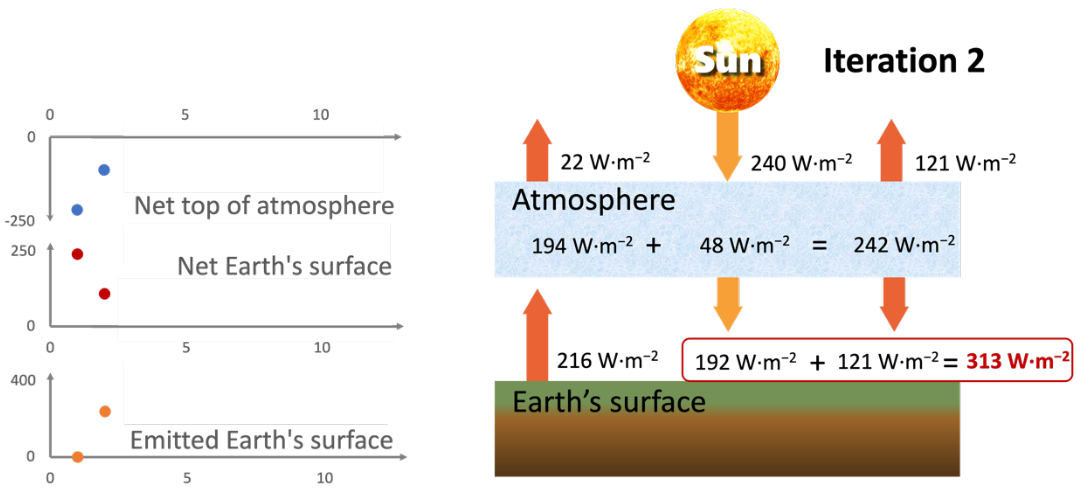


A simple model might look like the figure shown above. For simplicity, we will assume that radiation is directed either up or down. Solar radiation hits the top of the atmosphere, and a portion gets absorbed with the remainder passing through to be absorbed by the Earth's surface, *i.e.*, transmitted radiation. The Earth's surface radiates upwards with a portion being absorbed by the atmosphere and the remaining escaping to space. The atmosphere will also radiate. The amount will be equal to the amount that it has absorbed—it doesn't trap radiation. The question is: in which direction does it radiate? The atmosphere doesn't have a preference. It doesn't know which direction is up or which direction is down. And so, it makes sense that in our model for half of the radiation to be directed down towards the Earth's surface and half to be directed up into space.

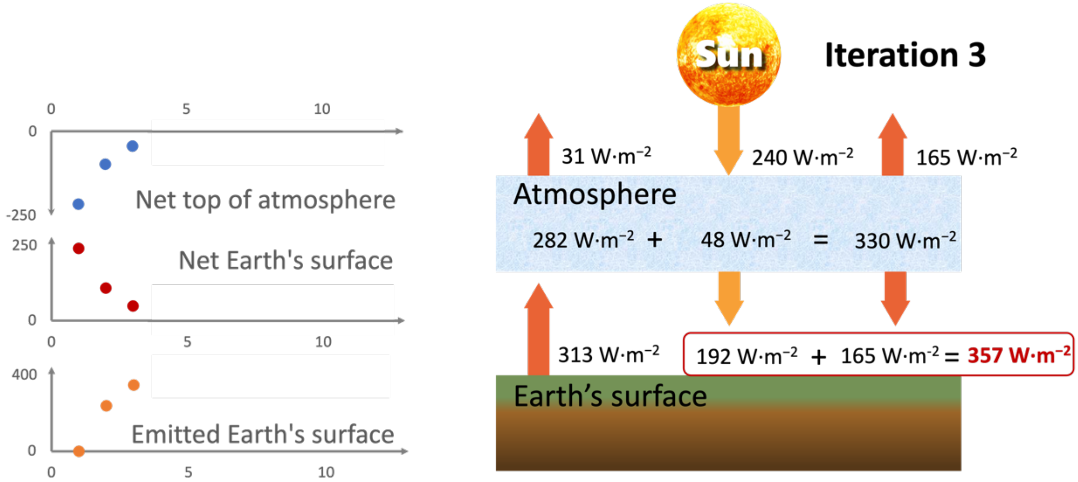
Will this model generate a greenhouse effect? I will later show a simple equation that can be derived using the model we have developed, but I think it would be helpful to think about how the model would evolve in time. We can start this process by assuming that the Earth is cold. Let's assume that it is so cold that it is not emitting any radiation at all. This would be very cold. Objects do not emit any radiation when they are at absolute zero, that is 0 K or −273.15 °C. We also need an estimate for the amount of solar radiation hitting the top of the atmosphere. We can use the numbers in our earlier calculation. Remember the solar constant was 1370 W m^{-2}. As before we want to reduce this number by 30% to account for the amount of solar radiation that is reflected back to space. This radiation is never absorbed by any part of the Earth system and so it cannot affect the Earth's surface temperature. We also need to account for the fact that this number considers the radiation to be absorbed over a flat area, but this is in fact smeared over the entire surface area of the Earth. As the ratio of the area of a sphere to that of a circle of equal radius is 4, we can simply reduce the result by a factor of 4. If we pop in the numbers this means that the effective solar radiation hitting the top of the atmosphere will be approximately 240 W m^{-2}.



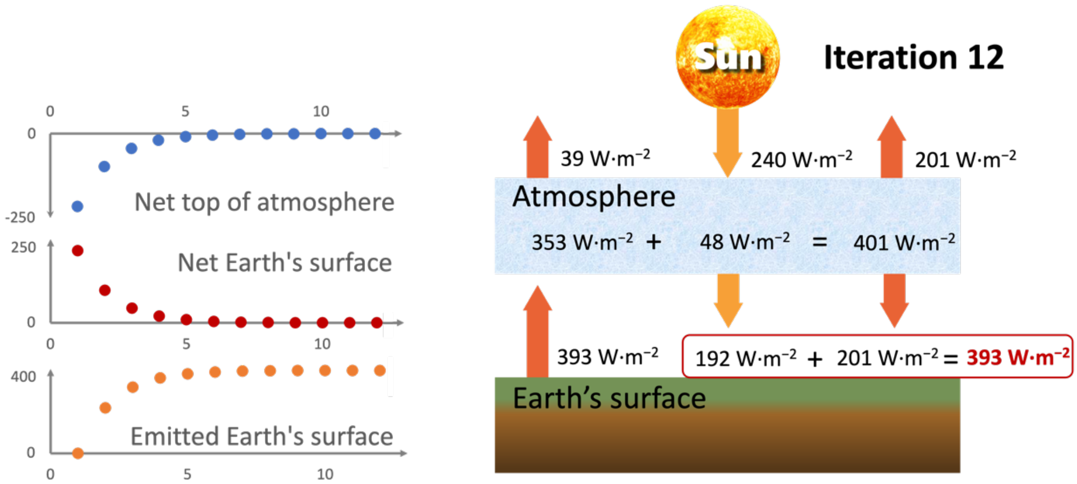
So, let's start our thought experiment. In the first iteration, the Earth emits no radiation. No radiation will be absorbed by the atmosphere of course, as 90% of nothing is still nothing. And no radiation escapes to space, as 10% of nothing is nothing. But the Earth is for the first time bathed in solar radiation to the tune of 240 W m^{-2} at the top of the atmosphere. Twenty percent is absorbed by the atmosphere, this amounts to 48 W m^{-2}, and the remaining 80%, or 192 W m^{-2} passes through the atmosphere. Of the 48 W m^{-2} absorbed by the atmosphere, half, or 24 W m^{-2}, will be emitted upwards into space, and 24 W m^{-2} will be emitted downwards towards the Earth's surface. At the end of the first iteration, we can see that 192 + 24 = 216 W m^{-2} are absorbed by the Earth's surface.



Let's repeat this process. In the second iteration, the Earth will now emit the 216 W m^{-2} it had absorbed at the end of the first iteration. Ninety percent of this, or 194 W m^{-2}, will be absorbed by the atmosphere, and the remaining 10%, or 22 W m^{-2}, will pass through the atmosphere into space. The Sun will still bathe the Earth system in 240 W m^{-2} at the top of the atmosphere. Of which 48 W m^{-2} will be absorbed by the atmosphere and 192 W m^{-2} will pass through. In total, 194 + 48 W m^{-2}, or 242 W m^{-2} will be absorbed by the atmosphere. Again, half of this, or 121 W m^{-2}, will be emitted upwards into space, and 121 W m^{-2} will be emitted downwards towards the Earth's surface. At the end of the second iteration, 192 + 121 = 313 W m^{-2} will be absorbed by the Earth's surface.



In the third iteration, the Earth will now emit the 313 W m^{-2} it had absorbed at the end of the second iteration. Ninety percent of this, or 282 W m^{-2}, will be absorbed by the atmosphere, and the remaining 10%, or 31 W m^{-2}, will pass through the atmosphere into space. The Sun will again bathe the Earth system in 240 W m^{-2} at the top of the atmosphere. Of which 48 W m^{-2} will be absorbed by the atmosphere and 192 W m^{-2} will pass through. In total, 282 + 48 W m^{-2} or 330 W m^{-2} will be absorbed by the atmosphere. Again, half of this, or 165 W m^{-2}, will be emitted upwards into space, and 165 W m^{-2} will be emitted downwards towards the Earth's surface. At the end of the third iteration, 192 + 165 = 357 W m^{-2} will be absorbed by the Earth's surface.



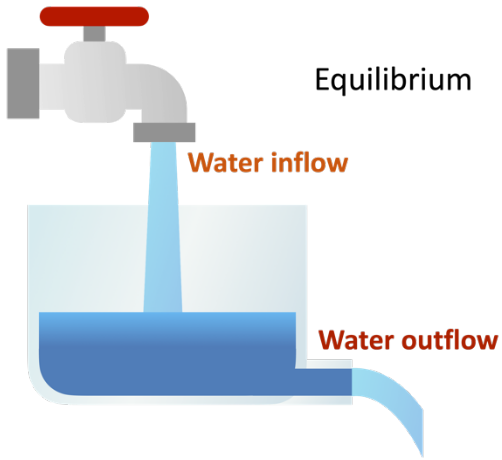
This process will continue. With each iteration, the net amount of radiation leaving the Earth system moves steadily towards zero. Similarly, the net amount of radiation leaving the Earth's surface moves closer and closer to zero. We also see that the total amount of radiation being emitted by the Earth's surface is increasing, but that the increase between steps is getting smaller and smaller. We can see that by the twelfth iteration, the system has reached equilibrium, as indicated by net zero amounts of radiation leaving the Earth system entirely and leaving the Earth's surface in particular. The amount of radiation being emitted by the Earth's surface has also reached a steady value of 393 W m^{-2}.

We can once again use the Stefan–Boltzmann law to determine with what temperature this emitted radiation would be consistent. This temperature is calculated to be 288 K or 15 °C. Given our earlier value for the temperature of the Earth's surface of −18 °C in the absence of an atmosphere, this means that the Earth's surface is 33 °C warmer than it would be without an atmosphere. This is the magnitude of the greenhouse effect.

13.4.3 Scientific Explanation

What have we learnt from this thought experiment?

First, we have seen that solar radiation steadily charges up the atmosphere like a battery. Eventually, the atmosphere becomes a bigger source of radiation to heat the Earth's surface than direct radiation from the Sun. This is what I meant at the end of the last video when I said that the Earth's surface is warmer than it would be in the absence of an atmosphere because it receives energy from two sources: the Sun and the atmosphere.



Second, we also saw how the Earth's system moved towards equilibrium. But why did it move towards equilibrium rather than continue to heat up? It has to do with the fact that the amount of radiation absorbed by the atmosphere is proportional to the amount entering the atmosphere. This establishment of an equilibrium is perhaps more clearly understood by considering the following system. Consider a sink with water in it, a tap that is running into the sink and a hole in the bottom that allows water to empty from the sink. If the water flow into the sink is the same as the water flow out of the sink then the water level in the sink stays constant. The system is at equilibrium. If we turn the tap to increase the flow into the sink, then we would expect that the water level in the sink to increase. But would the sink continue to fill until it overflowed? The answer is no. The reason is because the flow out of the sink depends on the pressure of the water at the bottom of the sink. This pressure depends on the water level in the sink. As the water level increases, the pressure increases, and the flow out of the sink increases. The water level continues to increase until the water flow into the sink is once again equal to the water flow out of the sink. A similar situation would occur if we turned the tap to decrease the water flow into the sink. In this situation, initially the flow into the sink would be less than the flow out of the sink and the water level would drop. But again, as the water level falls, the pressure at the bottom of the sink drops and the flow out of the sink decreases until it eventually equals the new water flow into the sink.

It would be frustrating to go through this iterative process every time we wanted to calculate the temperature of the Earth's surface for a different set of parameters. However, a simple mathematical model can be established on the basis of the single-layer atmosphere model we have been discussing. That mathematical model reduces to the following equation.

$$F_g = F_s \frac{(1+\tau_s)}{(1+\tau_g)}$$

On the left hand-side we have the amount of terrestrial radiation emitted by the Earth's surface. Essentially the flow of radiation from the ground. I have denoted this flow of radiation as F_g. This is equal to this expression. F_s denotes the flow of solar radiation into the Earth's system. Note that this is equal to $S(1 - A)/4$. The other two parameters on the right-hand side are τ_s and τ_g. These are the transmittances through the atmosphere. The transmittance is the fraction of radiation that is not absorbed by the atmosphere. τ_s is the solar transmittance and τ_g is the terrestrial transmittance. I use tau rather than, say, capital T so that we do not confuse transmittance with temperature.

Does this expression make sense? It relates the terrestrial flow of radiation to the solar flow and both the solar and terrestrial transmittances. From the Stefan–Boltzmann law, we know that the terrestrial flow is proportional to the fourth power of the Earth's surface temperature. The greater the terrestrial flow of radiation, the greater the Earth's surface temperature.

$$F_s \uparrow \ \Rightarrow F_g \uparrow \ \Rightarrow T_g \uparrow$$

Okay, what happens in this expression if quantities change? If the solar flow increased, the terrestrial flow would increase, as it is proportional to the solar flow, and so the Earth's surface temperature will be higher. That makes sense.

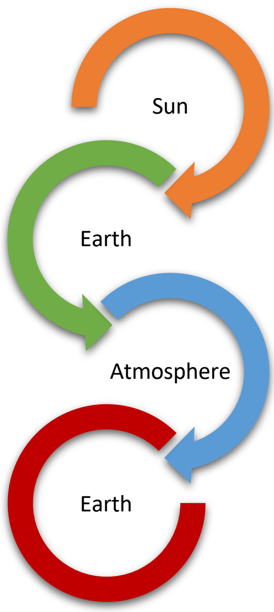
$$\tau_s \uparrow \ \Rightarrow F_g \uparrow \ \Rightarrow T_g \uparrow$$

Similarly, if the solar transmittance increased more solar radiation would impact the Earth increasing the Earth's surface temperature. Again, that makes sense.

$$\tau_g \downarrow \ \Rightarrow F_g \uparrow \ \Rightarrow T_g \uparrow$$

Finally, if we decrease the transmittance of terrestrial radiation, for example if we were to increase the amount of greenhouse gases in the atmosphere, then this expression would lead to an increase in the terrestrial flow of radiation and thus an increase in the Earth's surface temperature. (The denominator on the right-hand side of the expression gets smaller, and so the terrestrial flow, on the left-hand side, will be greater.) So, this single-layer atmosphere model explains how changing the amount of greenhouse gases can lead to global warming. You can check to make sure that it leads to the same Earth's surface temperature as we determined in the iterative thought experiment.

Professor Bettens argued that climate change has causal origins. That the Sun heats the Earth, that then heats the atmosphere, that in turn heats the Earth further. In our discussion here, we have identified the underlying process that explains the greenhouse effect. Underlying processes are an alternative form of scientific explanation. I noted that it was greenhouse gases, such as carbon dioxide, that absorb infra-red radiation from the Earth and prevent that radiation escaping to space. The role of carbon dioxide in absorbing such radiation is an underlying process and was discussed by both John Tyndall and Eunice Foote. This scientific explanation was then incorporated into our mathematical model to better describe the Earth system and to better determine the Earth's surface temperature. Although approximations are still needed, the calculation gives a value for temperature that is consistent with that observed. This model allows us to better understand the Earth system. In particular, it is able to qualitatively predict the effect on temperature of increasing greenhouse gases. I have put together a macro-enabled Excel visualisation of this mathematical model that you will be able to use to calculate the Earth's surface temperature. This will be available for use in any tests.



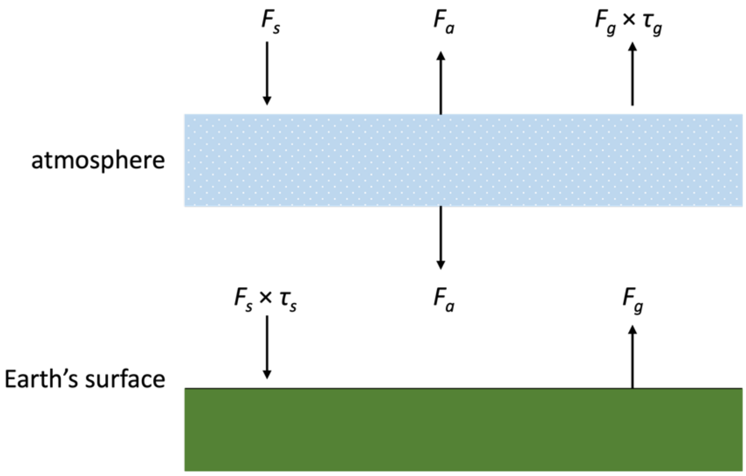
And with that, we have finished our discussion of the science of climate change.

13.4.4 Optional: Macro-enabled Excel Visualisation of the Single-layer Atmosphere Model

If you are unsure how to use the macro-enabled Excel visualisation of the single-layer atmosphere model, then view this screencast presentation on YouTube. The screencast identifies the different elements of the visualisation and shows you how to change the parameters in the model and how these changes will manifest themselves in the graphical representation of the radiative flows and the Earth's surface temperature. You will be allowed to use this Excel visualisation in any tests.

13.4.5 Optional: Derivation of the Single-layer Atmosphere Model

The simplest way to derive our mathematical model is to treat the atmosphere as a single layer of uniform temperature.



In this diagram, we can see the global average solar flow, that is the energy per unit area per unit time, impacting the top of the atmosphere, this is denoted F_s. The flows from the ground and the atmosphere are F_g and F_a respectively.

Note that the total emission from the atmosphere is twice F_a to account for radiation emitted upwards and downwards. To complete this model, we also need to account for the absorption of radiation by the atmosphere. Following the nomenclature used above, we will do this by defining transmittance as the fraction of radiation that isn't absorbed. The solar transmittance is given by τ_s and the terrestrial transmittance is given by τ_g. So, the amount of solar radiation that passes through the atmosphere to be absorbed by the Earth's surface is simply $F_s \times \tau_s$. Similarly, the amount of terrestrial radiation that passes through the atmosphere to space is simply $F_g \times \tau_g$.

If we assume that the temperatures of the Earth's surface and the atmosphere are constant, that is that the system is in equilibrium, then the flows must be in balance both at the top of the atmosphere and at the Earth's surface.

At the Earth's surface, the incoming flow is the sum of $F_s \times \tau_s$ and F_a, this must be equal to the flow leaving the Earth's surface, that is F_g:

$$F_s \times \tau_s + F_a = \mathrm{F_g}$$

At the top of the atmosphere, the incoming solar flow, F_s, must be equal to the flow leaving the top of the atmosphere, that is the sum of $F_g \times \tau_g$ and F_a:

$$F_s = F_g \times \tau_g + \mathrm{F_a}$$

We now have two equations. These can be quickly solved to eliminate F_a to give the expression we saw in the lecture:

$$F_g = F_s \frac{(1 + \tau_s)}{(1 + \tau_g)}$$

This derivation is not examinable and is provided here for those who may be interested.

13.5 What Have You Learnt?

We set ourselves five learning outcomes at the beginning of the lecture. These were that by the end of the lecture, you should be able to:

(1) *Describe* the historical development of our understanding as to the nature of the atmosphere;
(2) *Discuss* the discovery of the greenhouse effect and greenhouse gases;
(3) *Recount* the discovery of oxygen and its importance in the emergence of chemistry as a distinct science;
(4) *Explain* the greenhouse effect by reference to the absorption of radiation by greenhouse gases; and,
(5) *Estimate* the greenhouse effect using the single-layer atmosphere model.

Take out the notes you made at the beginning of the lecture.

Has your understanding changed?

What new ideas or concepts have you learnt?

How does what you have learnt connect with earlier material?

Again jot down your thoughts. Finally, do you remain unsure about your ability to meet any of the learning outcomes? Below I direct you to which section you will need to revisit to find the material you need to meet the learning outcomes.

To achieve **ILO1**, you should be able to describe the discoveries of da Vinci, Mayow, van Helmont, Black, Hales and Ingenhousz. The concept that the atmosphere was a single substance as envisioned by early thinkers, such as Empedocles, unravelled to the realisation that the atmosphere is made up of many gases. You should further be able relate these discoveries to the movement of carbon between the atmosphere and biosphere. If you are unsure, you should review Section 5.2.1.

To achieve **ILO2**, you should be able to discuss the development of Fourier's conception of heat flow in the Earth system and how you need an atmosphere in order to explain the observed surface temperature. The realisation that it was the optical properties of atmospheric gases, that is how gases absorb and emit radiation, that explains surface temperatures is found in the work of Foote and Tyndall. If you are unsure, you should review Sections 5.3.1 and 5.3.2.

To achieve **ILO3**, you should be able to recount the overturning of the phlogiston theory with the theory of combustion described by Lavoisier. You should be able to explain why a scientific theory, like the phlogiston theory, is superseded. You should understand how the accounting of mass in chemical reactions led to the laws that underpin the discipline of chemistry. If you are unsure, you should review Sections 5.2.2, 5.2.3, and 5.2.4.

To achieve **ILO4**, you should be able to explain how the absorption of radiation by gases in the atmosphere affects the Earth surface temperature. You should understand the limitations of metaphors in explaining the greenhouse effect. If you are unsure, you should review Sections 5.4.1, 5.4.2, and 5.4.3.

To achieve **ILO5**, you should be able to calculate the greenhouse effect. The magnitude of the greenhouse effect is defined as the difference in temperature between an Earth system in which gases in the atmosphere absorb and emit radiation, especially infra-red radiation, and an Earth system in which gases let radiation pass unhindered. You should be able to use the single-layer atmosphere mathematical model to do these calculations. If you are unsure, you should review Section 5.4.3.

If you feel comfortable with your ability to meet the learning outcomes, then you are ready to try the quiz. Good luck!

14 Establishing the Scientific Consensus on Climate Change

Intended Learning Outcomes for Lecture 6

By the end of this lecture, you should be able to:

(6) *Describe* the history of the establishment of the scientific consensus on climate change including the role played by the IPCC;
(7) *Articulate* the difference between weather and climate, and between the greenhouse effect and climate change;
(8) *Outline* how proxy methods used in the reconstruction of past temperatures;
(9) *Recognise* the difference between the public perception of the scientific consensus on climate change and that of the scientific community; and,
(10) *Explain* how the scientific consensus on climate change was established.

Scientific Consensus

14.1.1 Defining Climate Change

In lecture 5, I discussed the ***greenhouse effect*** and ***global warming*** and indeed I also gave definitions for what we mean by these terms. Another term that I used was ***climate change***. However, I didn't define what I meant by climate change, and I think it is important that we describe what we mean by this term.

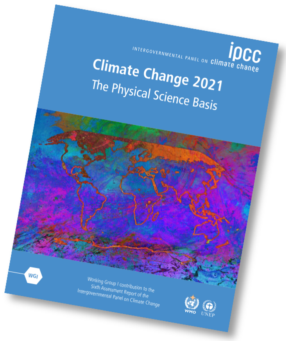
Before we define the term climate change though, we need to know: what is *climate*? In answering this question, it is worth contrasting *climate* with *weather*. Weather can be thought of as a combination of temperature, humidity, precipitation, cloudiness, visibility, and wind, that we might experience at a particular location in the short-term. Weather reflects the short-term conditions of the atmosphere. Climate, on the other hand, describes the typical weather conditions in an entire region for a very long time. One way of thinking about this difference is that climate is what we expect, and weather is what we get.

Climate is what we expect, weather is what we get

Global warming is the cause, climate change is the effect

So, if climate is the average weather in a region over many years, climate change is a shift in those average conditions. In a sense then, climate change includes both the global warming driven by human-induced emissions of greenhouse gases, and the resulting large-scale shifts in weather patterns. However, I believe it is useful to think of global warming as being the *cause*, and climate change as being the *effect*.

14.1.2 Unequivocal, Unprecedented, Irreversible



Today, there is a scientific consensus about climate change. The Intergovernmental Panel on Climate Change, or IPCC, published its Sixth Assessment Report in August 2021.[18] In that report, it is noted that temperatures have risen by more than 1 °C since the 1850–1900 global average, and that it is

> *"unequivocal that human influence has warmed the atmosphere, ocean and land"*[19]

It describes the ways in which Earth's climate has changed due to human activity as *"unprecedented"*[20] in the previous hundreds of thousands of years, with some of the changes as now being inevitable and *"irreversible"*.[21] This is the current scientific consensus.

14.1.3 Appropriate Authority

When I describe the scientific consensus, some of you might be feeling uncomfortable. Am I arguing that you should accept climate change is real because there is a scientific consensus? Is this an argument from authority? It was no less than Galileo Galilei who stated that,

> *"In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual."*[22]

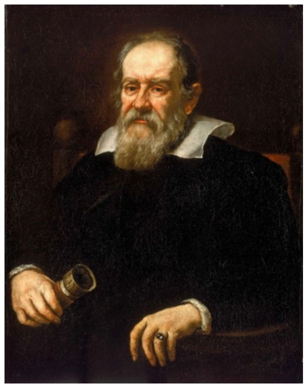
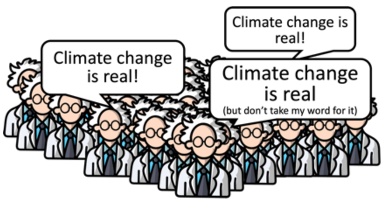


Figure 159: Painting of Galileo Galilei by Justus Suttermans in 1636 (public domain).

Colloquially, when we talk about 'consensus' we mean a general agreement of opinion, but the scientific method argues for an objective framework. In science, facts or observations are explained by a hypothesis, which can then be tested and retested until it is refuted.

As scientists gather more observations, they will build off one explanation and add details to complete the picture. Eventually, a group of hypotheses might be integrated and generalised into a scientific theory, a scientifically acceptable general principle or body of principles offered to explain phenomena.



Scientific consensus is achieved when the great majority of scientists of a given field agree upon a position based on a large amount of evidence. Consensus is not just a general agreement, but is dependent on the expertise of the scientists in question and is based on the accumulation and verification of evidence.

But as Galileo proved, a scientific consensus can shift. Scientists are human and science is a human endeavour.

We are not saying that climate change has happened and is happening because there is a scientific consensus, we are saying that climate change is real because very careful measurements, confirmed by many scientists, have shown that it is happening.

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[18] IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.
[19] *Op. cit.* p. 6
[20] *Op. cit.* p. 8
[21] *Op. cit.* p. 29
[22] Galilei, G. (1632). *Dialogue Concerning the Two Chief World Systems.* Florence: Giovanni Battista Landini.

In his discussion about the Scientific Revolution, Professor Bettens mentioned the importance of the establishment of a scientific community. Here, I am speaking about scientific consensus and its significance. These ideas are inextricably linked—a scientific community is a prerequisite for the emergence of a consensus. The scientific societies that arose during the Scientific Revolution became the model for open and frank discourse that still exists today. It was climate scientists being brought together to evaluate the emerging evidence that led to the consensus position around climate change.

Figure 160: Coat of arms of the Royal Society of London (public domain).

Figure 161: Portrait of Francis Bacon by Paul van Somer I in 1617 (public domain).

Professor Bettens specifically identified the emergence of the Royal Society of London[23] as an example of a scientific community. The Royal Society was greatly influenced by Francis Bacon and his vision of experimental science. When I think about the environment, I am reminded that it was Bacon who stated that the ultimate goal of scientific inquiry was power over nature. I fear this tradition is responsible for the current state of our climate.

I make the point that scientific consensus is not an appeal to authority. That said, there is in many us a cognitive bias to respect authority—the logical fallacy that is the argument from authority has its roots in this cognitive bias. The forfeit of reason to the group comes from the authority of the group and our desire to belong to the group. Appeal to authority becomes fallacious when the authority does not possess the expert knowledge required to make judgment on the subject of discussion. This is about as far removed as is possible from what we mean by scientific consensus.

14.1.4 Realising the Danger

When was this scientific consensus on climate change established?

We touched on the history of climate change research in the last lecture, but this was the work of individual scientists or small groups of scientists. Such judgment does not represent consensus. Rather it represents expert opinion.

Figure 162: Portraits of Joseph Fourier, Svante Arrhenius, Eunice Foote, and John Tyndall (public domain).

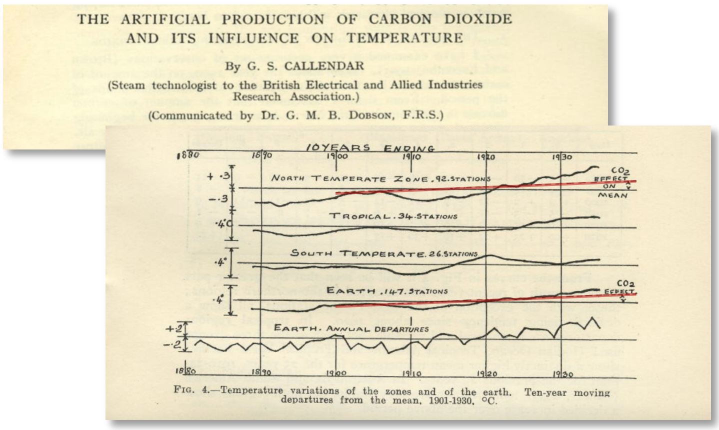
To build a scientific consensus, we need a significant number of scientists working on the problem, making measurements, developing conceptual and mathematical models, verifying each other's work.

You will recall from the last lecture that the first mathematical model to predict the effect on global temperature of increasing carbon dioxide was due to Svante Arrhenius. This had built upon the conceptual work of Joseph Fourier, and the experimental analysis of John Tyndall and Eunice Foote. Arrhenius wasn't concerned about his predictions, perhaps because he was Swedish

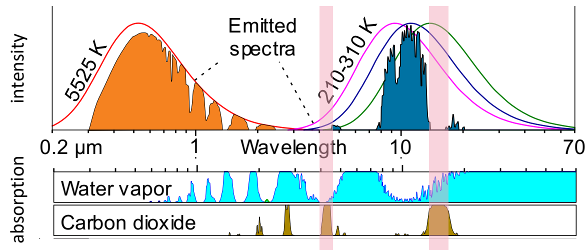
[23] The Latin motto of the Royal Society, *nullius in verba*, means 'take nobody's word for it' and expressed a determination by the Fellows of the Society to verify all statements by an appeal to facts through experiment rather than accept the words of authority.

(Sweden is, after all, a cold country); he viewed the increased temperatures as being a good thing.

Concern about global warming was first voiced by Guy Callendar. By 1938, Callendar was convinced that nearly all carbon dioxide produced by fossil fuel combustion had remained in the atmosphere and suggested that the increase in carbon dioxide may account for the observed slight rise of average temperature in northern latitudes in the previous 50 years.[24] With war breaking out in Europe, Callendar wasn't able to continue his research and little further work was done for some 20 years. One reason why others didn't continue the work of Callendar, even after the war, is because there was an important uncertainty around water vapour. Scientists at the time agreed that carbon dioxide was a greenhouse gas and that if you increased atmospheric concentrations it might affect the climate, but they argued that water vapour is a greenhouse gas and that there is so much more water vapour than carbon dioxide. Scientists were sceptical that small increases in carbon dioxide could have a big effect.



This scepticism is still present today in the arguments proffered by many climate change deniers. However, we can answer this scepticism using a figure we presented in the last lecture. This figure shows the atmospheric absorption due to different gases. You can see that water vapour and carbon dioxide do not absorb at the same wavelengths. Importantly, there are wavelengths at which water vapour absorbs very little, but carbon dioxide absorbs greatly. Increases in carbon dioxide will thus significantly increase the absorption of infra-red radiation at these wavelengths and ultimately affect Earth surface temperatures. So, water vapour will not overwhelm the absorption due to carbon dioxide.



14.1.5 A Need for Measurements

Among the first to recognise that there was a need to return to the work of Callendar were Roger Revelle and Hans Suess. In 1957, they published an influential paper that recognised the importance of studying the Callendar effect, but further acknowledged the inadequacy of current data. They stated that,

> *"Present data on the total amount of CO_2 in the atmosphere, on the rates and mechanisms of exchange, …are inadequate for accurate measurement of future changes in atmospheric CO_2."*

Figure 163: Photograph of Roger Revelle (fair use).

Figure 164: Photograph of Hans Suess (fair use).

They pushed for such measurements to be an integral part of the scientific project for the International Geophysical Year.

[24] Callendar, G. S. (1938). The artificial production of carbon dioxide and its influence on temperature, *Quarterly Journal of the Royal Meteorological Society.* **64(275):** 223–240.

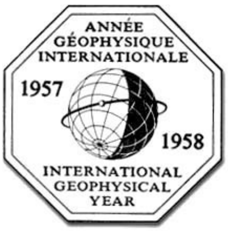
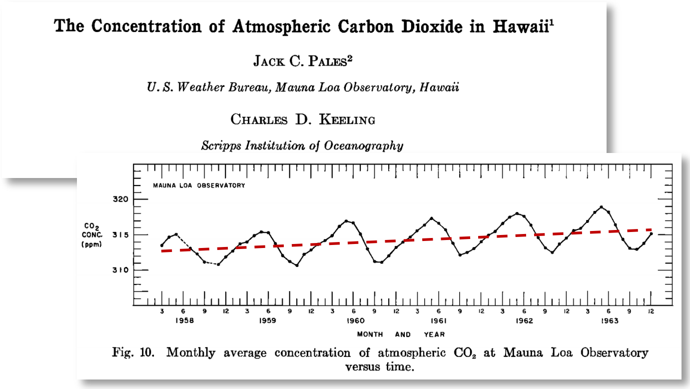


Figure 165: Logo of the International Geophysical Year (public domain).

The International Geophysical Year that lasted from 1 July 1957 until the end of 1958 was crucial in bringing together scientists from across the globe to study many issues of geophysical concern, including climate change. It was as part of the International Geophysical Year that Charles Keeling received the funding, pushed for by Revelle and Suess, to measure carbon dioxide at Mauna Loa in Hawaii.


The Concentration of Atmospheric Carbon Dioxide in Hawaii[1]

JACK C. PALES[2]

U. S. Weather Bureau, Mauna Loa Observatory, Hawaii

CHARLES D. KEELING

Scripps Institution of Oceanography

Fig. 10. Monthly average concentration of atmospheric CO_2 at Mauna Loa Observatory versus time.

The results from Mauna Loa, now referred to as the Keeling curve, showed that instruments had the sensitivity to measure accurately small changes in the CO_2 concentrations in the atmosphere. Keeling's data showed that between 1958 and 1965, CO_2 concentrations had risen by some 1% or 3 parts per million. These data were greatly concerning to the scientific community. Revelle and Keeling were asked to chair the President's Science Advisory Committee that published the report, 'Restoring the Quality of our Environment', that we mentioned in the last lecture. In that report, the authors warned that,

"By the year 2000 there will be about 25% more CO_2 in our atmosphere than at present [and] this will modify the heat balance of the atmosphere to such an extent that marked changes in climate…could occur."[25]

14.1.6 Informing Public Policy

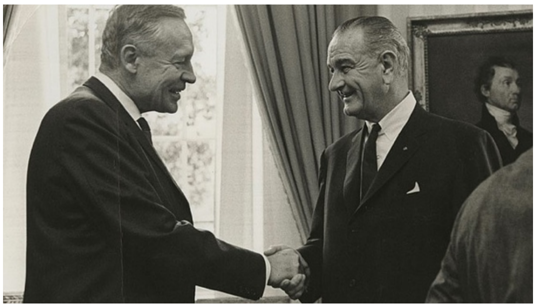


Figure 166: Photograph of Roger Revelle (left) shaking hands with President Lyndon B. Johnson (right) (fair use).

Responding to this report, President Lyndon Johnson declared in a special message to the U.S. Congress, again in 1965, that,

"This generation has altered the composition of the atmosphere on a global scale through … a steady increase in carbon dioxide from the burning of fossil fuels."

Here, the U.S. President was reporting the scientific consensus from his Science Advisory Committee. This is one of the important roles that scientific consensus plays in society; it helps to inform public policy. And indeed, in the 1970s in the U.S. the impact of rising carbon dioxide on climate was informing national policy in terms of energy, national security and the economy.

14.1.7 Achieving Consensus

By the end of the 1970s, in an evaluation of the evidence for CO_2-induced climate change, the [National Academy of Sciences](), the premier science academy in the U.S. whose membership is considered one of the highest professional honours, released a report that stated,

[25] President's Science Advisory Committee (1965). *Restoring the Quality of our Environment*. Washington D.C.: The White House. p. 9.

"A plethora of studies from diverse sources indicates a consensus that climate changes will result from man's combustion of fossil fuels and changes in land use."[26]

The latter primarily due to deforestation and changes in agricultural practice. This was an early description of the state of our understanding of climate change and described this understanding as being the consensus of scientists working in this field. This was a consensus not just of the conceptual understanding by which carbon dioxide influences Earth surface temperature, but it was a consensus of expectation: that if we continue to burn fossil fuels, then climate change, including increased Earth surface temperatures, will result.

So, have we identified when the scientific consensus on climate change was established? Well, yes and no. Yes, we had established a consensus that burning fossil fuels will lead to climate change, but no, in the sense, that there was not a consensus about when this climate change will happen. Identifying this timeline would be crucial and indeed controversial.

The history of the development of scientific consensus over climate change highlights the reliance on scientific societies to inform public policy. This intimate relationship seems to prompt the search for consensus. We saw that the U.S. Government sought expertise from the National Academy of Sciences to establish a scientific consensus with regard to climate change.

I want to reiterate the point I made earlier. There is a danger that scientific consensus can be seen as an argument from authority. This is frequently articulated by climate change deniers. This ignores the fact that scientific consensus is not the general opinion of scientists, it is the position of a community of scientists based on the large amount of verified evidence. Few things in science have been verified more than the position that climate change is happening.

I would also like to reiterate that consensus in science is different from how we use the term colloquially. In science, it isn't just a general agreement of opinion. Rather in science, a consensus is achieved when the great majority of scientists of a given field agree upon a position based on a large amount of verified evidence. The process of verifying evidence is critical. This goes to the heart of what science is, that something can only be science if it is verifiable.

14.2A Question of When

So, the scientific community had established a consensus that burning fossil fuels will lead to climate change, but there was a lack of consensus for when we would see climate change.

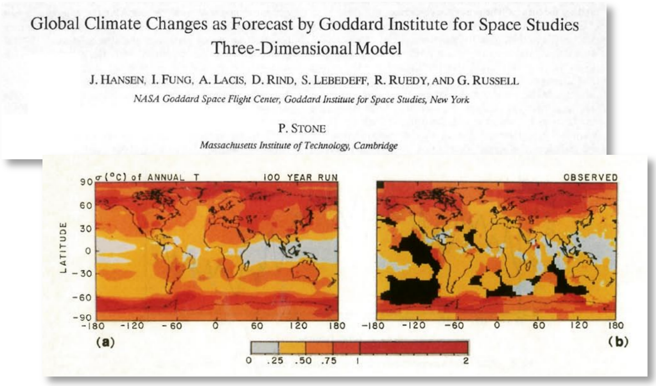
Establishing this consensus, in part to drive public policy to mitigate climate change, was crucial, because the scientific community recognised that the impact on society would be profound. So, scientists set about determining when these changes would be likely to occur. Most scientists at the time thought that changes would not begin to become detectable until the 21st century.

14.2.1 Emergent Recognition

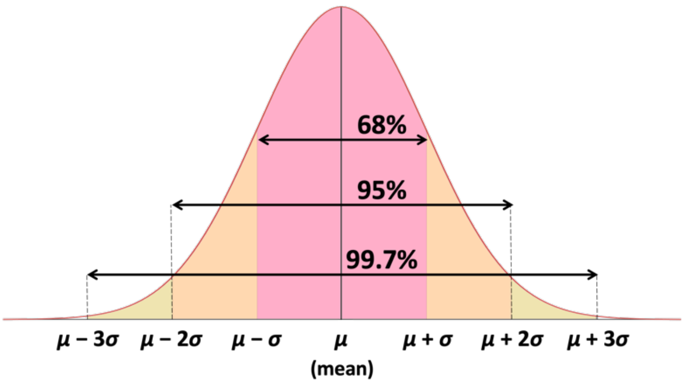
Determining when climate change would be detectable required sophisticated climate models: mathematical descriptions of the climate programmed into computers. These models coupled the atmosphere and oceans, and were forced by changing amounts of greenhouse gases both known and predicted. The predicted changes gave rise to different future scenarios of greenhouse gas emissions. The key to knowing when climate change would be detectable was estimating the natural climate variability. In 1988, James Hansen and co-workers published a seminal paper in which they provided the first estimate of this variability. Hansen used observed

[26] National Academy of Sciences Archive (1979). *An Evaluation of the Evidence for CO_2-induced Climate Change.* Assembly of Mathematical and Physical Sciences, Climate Research Board, Study Group on Carbon Dioxide.

surface temperatures to calculate that this variability in global average temperature was about 0.13 °C, such that an observed rise of about 0.4 °C in the global average would give a 99% confidence that global warming had been observed. He argued that this would *"constitute convincing evidence of a cause and effect relationship, i.e., a 'smoking gun'"*.[27] He further found that his model results showed a similar variability which gave credence to the model's predictions of climate change.

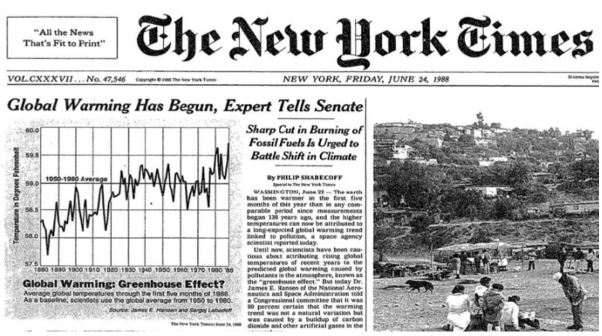


In the last lecture, I mentioned this 99% confidence. I said that it wasn't just a rhetorical device, but was grounded in statistics. This 0.13 °C variability is not the standard deviation of the temperature, but the standard error of the average temperature. Professor Bettens spoke about this in his fourth lecture. The standard deviation of temperature at any point on the Earth's surface would be much larger than this. How does this connect with a rise of 0.4 °C in the global average temperature giving a 99% confidence that global warming was happening?



Statisticians have a rule of thumb, known as the 68–95–99.7 rule—not the most elegantly phrased rule. The 68 refers to the percentage of events that occur within 1 standard deviation from the mean. The 95 refers to the percentage of events that occur within 2 standard deviations from the mean. (Note that in the social sciences, this 2-standard-deviation threshold is used to identify statistical significance—when an event is beyond 2 standard deviations it is considered statistically significant.) And, the 99.7 refers to the percentage of events that occur within 3 standard deviations from the mean. In our case, we are discussing standard errors, but the principle is the same. Three standard errors would be 0.13 °C × 3 = 0.39 °C. This means that only 0.3% of naturally occurring global average temperatures would be expected beyond this limit. Since these numbers are based on annual average temperatures, we would only expect a naturally occurring global annual average temperature beyond this limit once in 370 years. The reference temperature of 0.4 °C that Hansen uses is beyond this threshold. In rounding down to 99%, his statement was in fact conservative.

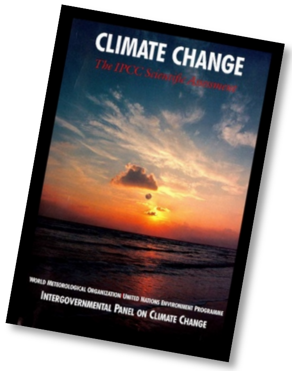
Although Hansen's 1988 paper predicted that this 0.4 °C threshold would likely be witnessed within a few years in the 1990s, Hansen testified before the U.S. Congress that global warming was *"happening now"*. This emergent recognition that climate change was not some abstract phenomenon that might materialise in the 21st century, but an observed fact happening now, at least in the opinion of Hansen, was quickly followed by further studies conducted by other scientists using different



[27] Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., and Russell, G. (1988). Global climate changes as forecast by Goddard Institute for Space Studies, *Journal of Geophysical Research.* **93(D8):** 9341–9364.

climate models. These studies needed to be systematically evaluated, and in 1988, the Intergovernmental Panel on Climate Change, or IPCC, was formed to do exactly that.

14.2.2 The Intergovernmental Panel on Climate Change

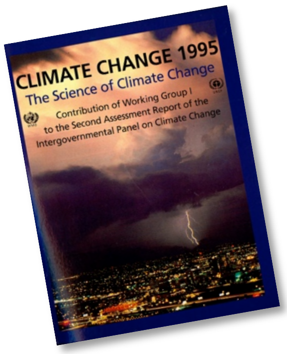


The IPCC is an intergovernmental body of the United Nations mandated to provide objective scientific information relevant to understanding human-induced climate change, its natural, political, and economic impacts and risks, and possible response options. It published its First Assessment Report in June 1990[28] in which they stated,

> *"global mean surface air temperature has increased by 0.3 to 0.6°C over the last 100 years"*[29]

They further noted that,

> *"The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability."*[30]

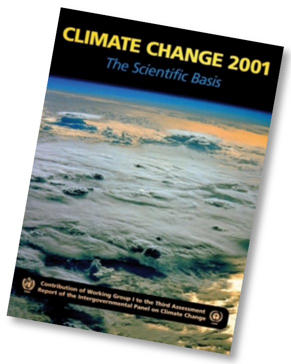


However, in their Second Assessment Report published in February 1995,[31] the IPCC noted that,

> *"The balance of evidence suggests a discernible human impact on global climate."*[32]

In the half decade between the two reports, the scientific consensus had shifted from an understanding that the greenhouse effect is well understood, greenhouse gases are increasing (due largely to human activity), and therefore should lead to significant global warming (though lack of understanding limited specific regional predictions), to a greater understanding (despite continuing uncertainties) that global warming continues and is most likely due to human activity.

In the Third Assessment Report published in January 2001,[33] the IPCC stated that,



> *"Human activities…are modifying the concentrations of atmospheric constituents…that absorb or scatter radiant energy. [M]ost of the observed warming over the last 50 years is likely to have been due to an increase in greenhouse gas concentrations."*[34]

In these assessment reports, the systematic review of the scientific literature revealed that the scientific consensus was that human-induced climate change through burning fossil fuels was being identified in the observational record. It does seem strange that following the Third Assessment Report doubt and

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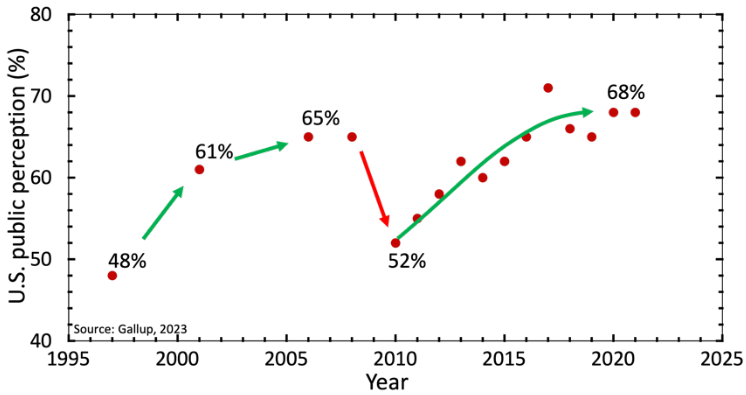
[28] IPCC (1990). *Climate Change: The IPCC Scientific Assessment.* Cambridge: Cambridge University Press.
[29] *Op. cit.*, p. xii.
[30] *Op. cit.*
[31] IPCC (1995). *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.
[32] *Op. cit.*, p. 4.
[33] IPCC (2001) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.
[34] *Op. cit.*, p. 10.

scepticism of this scientific consensus arose in the public arena. How that doubt emerged will be the subject of the next lecture, but let's consider the changing public perception in the U.S.

14.2.3 Public Perception of Consensus



The Gallup environment poll showed that in 1997 only 48% of the U.S. public thought that 'most scientists believe that global warming is occurring'. However, this figure rose sharply such that some 61% of the U.S. public thought this by 2001. This number rose still further to 65% by 2006, but dropped dramatically to 52% by 2010. By 2021, this number rose to 68%, but it seems to stubbornly refuse to rise much higher.

I would argue that this poll is a measure of the U.S. public's perception of the scientific consensus around climate change. Is this reflected in the published, peer-reviewed scientific literature?

	Oreskes (2004)[35]	Cook *et al.* (2013)[36]
papers surveyed	928	11,944
percentage agreed	100%	97.1%
public perception in year of study	64%	62%

The first attempt to determine the level of scientific consensus in the published, peer-reviewed scientific literature was conducted in 2004 by Naomi Oreskes, the co-author of the book *Merchants of Doubt*. Oreskes found that in the 928 papers published in the 10 years between 1993 and 2003 that talked about global warming not one rejected the scientific consensus. Indeed, in a later study of the scientific literature by John Cook and co-authors in 2013, that in a survey of 11,944 abstracts from peer-reviewed journals 97.1% agreed with the scientific consensus that human-induced climate change is real and happening.

There is a disconnect between the public perception of the level of consensus present among scientists studying climate change and the consensus among scientists themselves. This scientific consensus is represented in the reports of the IPCC and is the position of every national and international scientific body.

It is always possible that the scientific consensus might be wrong. If the history of science has taught us anything, it is humility! Many details about climate interactions are not well understood, and there are ample grounds for continued research to provide a better basis for understanding climate dynamics. The question of what to do about climate change is also still open. But there is a scientific consensus on the reality of human-induced climate change. Climate scientists have repeatedly tried to make this clear. Doing nothing is simply not an option!

14.3Convincing the Scientific Community (I)

We have established that there is a scientific consensus that human-induced climate change is happening, but we need to address the question of how this was established. In this, I mean what was it that convinced the

[35] Oreskes, N. (2004). The scientific consensus on climate change, *Science*. **306(5702):** 1686–1686.
[36] Cook, J., Nuccitelli, D., Green, S. A., Richardson, M., Winkler, B., Painting, B., Way, R., Jacobs, P., and Skuce, A. (2013). Quantifying the consensus on anthropogenic global warming in the scientific literature, *Environmental Research Letters*. **8(2):** 024024.

scientific community to take such a consensus position? What are the observational data and computer modelling that is so persuasive?

There are a number of questions that need to be answered. First, does the observational record show that average global temperatures are rising? Second, is the temperature rise unusual? Third, are atmospheric greenhouse gas concentrations also increasing? Fourth, is the rise in carbon dioxide due to the burning of fossil fuels? And finally, do we understand human-induced climate change? In this part of my lecture, I will address the first three questions, and address the final two in the next, and last part, of my lecture.

14.3.1 Instrumental Temperature Record

Figure 167: Logos of the National Aeronautics and Space Administration (public domain), the National Oceanic and Atmospheric Administration (public domain), UK Meteorological Office (fair use), and the Japan Meteorological Agency—the four keepers of records on global temperatures.

Let's consider the instrumental average global surface temperature record. The first issue that we are faced with when looking at the instrumental record is which instrumental record. There are four major keepers of records on global temperature. From the United States, there are the NASA and NOAA datasets, but there are also datasets from the United Kingdom and Japan.

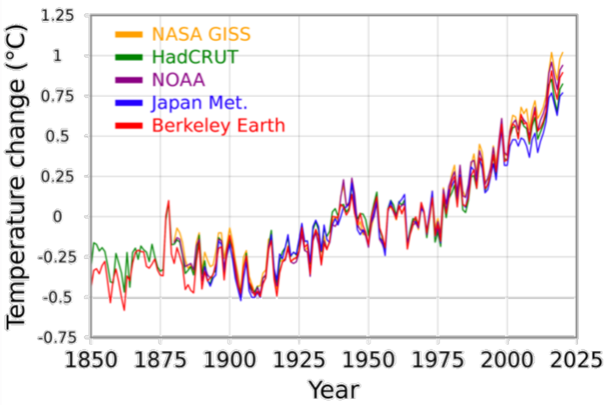


Figure 168: Average global temperatures from NASA, UK Met Office, NOAA, Japan Meteorological Agency, and Berkeley Earth (CC by 4.0).

In general, the datasets agree, but there are small differences as illustrated in Figure 10. Note that a fifth dataset from Berkeley Earth is also included. These datasets use the 1951–1980 period as the baseline for temperature change.

The average pairwise correlation between the five datasets illustrated here is 99.04%, but why don't the five datasets agree perfectly?

The answer to this question lies in the nature of the sources of the data used in these constructions. The data used in these constructions are collected at thousands of meteorological stations, buoys, and ships around the globe. The longest-running temperature record is the Central England temperature data series, which started in 1659. However, the longest-running quasi-global record starts in 1850.

Although all four major datasets have strong similarities in how they track and analyse temperatures, there are subtle differences. The NASA record tends to run slightly higher than the Japanese record, while the United Kingdom and NOAA records are usually in the middle.

There are good reasons for these differences, small as they are. Getting an accurate measurement of air temperature across the entire planet is not simple. Ideally, scientists would like to have thousands of standardised weather stations spaced evenly all around the Earth's surface. The trouble is that while there are plenty of weather stations on land, there are some pretty big gaps over the oceans, the polar regions, and even parts of Africa and South America. Figure 11 shows the global climate network of temperature stations coloured by the length of station record.

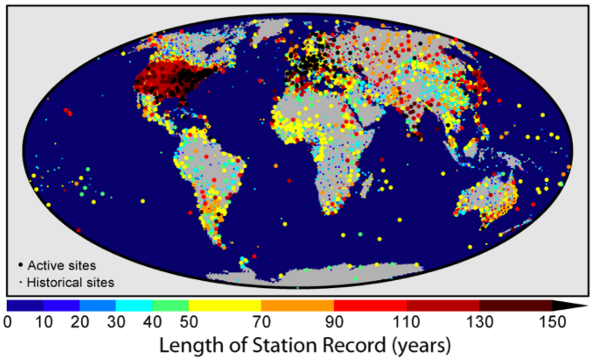


Figure 169: Map of temperature station locations with record lengths indicated by colouring (CC by 3.0).

The four research groups deal with those gaps in slightly different ways. The Japanese group leaves areas without plenty of temperature stations out of their analysis, so its analysis covers about 85% of the globe. The United Kingdom Met Office makes similar choices, meaning its record covers about 86% of the Earth's surface. NOAA takes a different approach to the gaps, using nearby stations to interpolate temperatures in some areas that lack stations, giving the NOAA analysis 93% coverage of the globe. The group at NASA interpolates even more aggressively—areas with gaps are interpolated from the nearest station up to 1,200 kilometres away—and offers 99% coverage.

Beyond these issues of coverage, the surface temperature record also goes through a series of adjustments to correct for issues, such as missing data, changes in instrumentation, movement of stations, and human or technical error. This process is known as homogenisation and, despite being a well-understood scientific practice, has been used by some climate change-sceptic commentators as evidence that scientists are 'fiddling' the data to overstate the amount of warming we've seen.

Figure 170: Artist impression of satellite in space over the Earth's surface (fair use).

You might argue that we have satellite data, so why don't we use that? Surely it would avoid these issues? The first issue is that satellite data only goes back to 1979. The second issue is that raw satellite data has to go through a far more extensive 'adjustment' process. Satellites do not directly measure temperatures, and are subject to large systemic biases due to orbital decay, diurnal sampling drifts, and changes in the satellite used (there have been 13 or so different satellites since 1979). Correcting for these biases is not straightforward, and different choices in correction parameters can lead to different trends during the period from 1979 to the present day.

So those are some of the technical issues in constructing the instrumental average global surface temperatures and why we rely on a surface network of measurements.

But has there been a temperature rise since pre-industrial times? Well, Figure 10 we showed previously had as a baseline the 1951–1980 average and showed a temperature anomaly of 0.75–1 °C depending on the dataset. Arguably the effect of industrialisation is already present in the baseline average. If instead we use the 1850–1900 period as a proxy for pre-industrial temperatures, then the temperature rise is even greater.

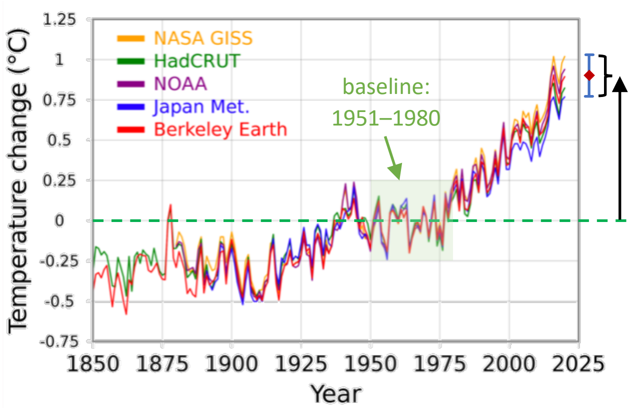


Figure 171: Correlation of instrumental temperature datasets from various sources, some dating to 1850 (CC by 4.0).

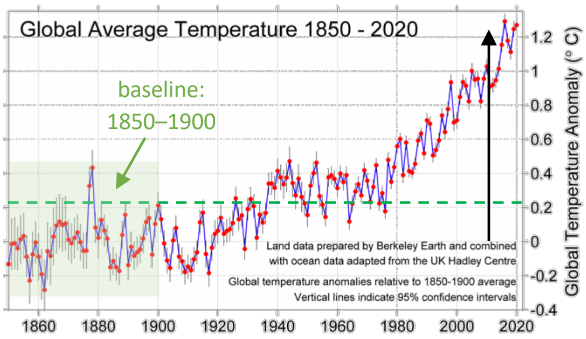


Figure 172: Berkeley Earth global temperature record (fair use).

The Berkeley Earth dataset in Figure 14 uses the 1850–1900 period as a baseline gives a temperature rise a little in excess of 1.2 °C. The IPCC in the Sixth Assessment Report reports this temperature rise as 1.1 °C.

As a bit of an aside, are we right to use the period from 1850 to 1900 as a proxy for the average global temperature for the pre-industrial period? Professor Bettens noted that the Industrial Revolution, marking the onset of humanity's dependence on fossil fuels, took place between the mid-to-late 1700s to mid-1800s. So why have I chosen a time period for my proxy after the end of the Industrial Revolution? The reason why we use the average temperature between 1850 and 1900 as a proxy for pre-industrial temperatures is for two reasons: First, we don't have reliable instrumental records to construct a global average prior to this; and second, we don't believe that carbon dioxide emissions from the coal burnt between the advent of the industrial revolution and this period would have significantly influenced global temperatures.

At the very least, we have an answer to our first question: The observational temperature record does confirm that global average temperatures are increasing.

We also highlighted an important element of how science works and how it is congruent with the Baloney Detection Toolkit. In particular, the fifth element of the BDTK is operative here: Have the claims been verified by someone else?

BDTK5: Have the claims been verified by someone else?

I have shown the instrumental temperature records from four agencies: NASA, NOAA, the UK Met Office and the Japan Meteorological Agency. These organisations all treated the data slightly differently and thus produced slightly different temperature records. However, they all agreed extremely well and certainly showed that global average temperatures are increasing. But, it could be argued that these data sets are produced by climate scientists, and if we are to believe the climate change sceptics, they have a vested interest in maintaining the climate change narrative.

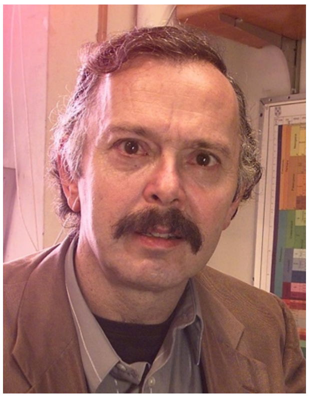


Figure 173: Photograph of Richard Muller (fair use).

However, I also showed the Berkeley Earth temperature analysis. Why this is important is due to the history behind why this analysis happened. Berkeley Earth was a project set up in 2010 with the goal of addressing concerns from outside the climate science community regarding global warming and the instrumental temperature record. Its founder, Richard Muller, *is* a highly respected physicist, but *was* a climate change sceptic.

At the outset of the project, Muller stated,

> *"...we are bringing the spirit of science back to a subject that has become too argumentative and too contentious, ...we are an independent, non-political, non-partisan group. We will gather the data, do the analysis, present the results and make all of it available. There will be no spin, whatever we find. We are doing this because it is the most important project in the world today. Nothing else comes close."*

In 2013, Muller published the findings of their analysis and declared,

> *"Call me a converted skeptic. Three years ago I identified problems in previous climate studies that, in my mind, threw doubt on the very existence of global warming. Last year, following an intensive research effort involving a dozen scientists, I concluded that global warming was real and that the prior estimates of the rate of warming were correct. I'm now going a step further: Humans are almost entirely the cause."*

Science is open and welcomes verification. Reproducibility is the cornerstone of reliable evidence. This is frequently not the case when it comes to pseudoscience.

14.3.2 Before Records Began

Now for the second question: Is this temperature rise unusual? We have seen that global average temperatures have been rising since the instrumental record began. However, perhaps the temperature rise is simply an anomaly—part of some long-term natural variability. A hundred and seventy odd years is a relatively short period, all things considered.

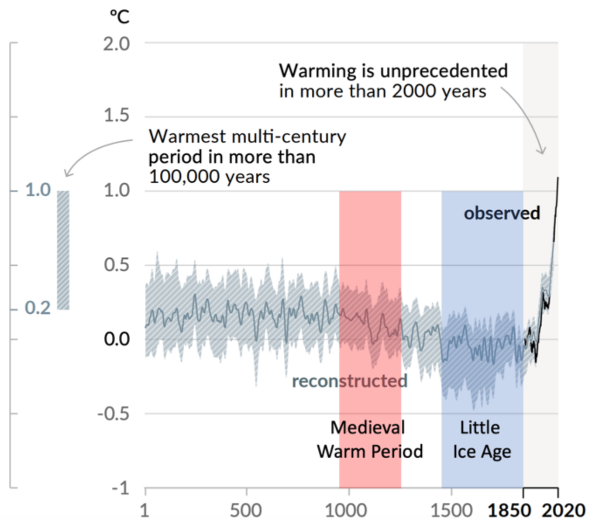


Figure 174: changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, 1–2000) and from direct observations (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged (fair use).

Well, we can address this issue. We can extend the temperature record. Figure 16 shows the temperature record of the last 2,000 years. We can see, and indeed the IPCC Sixth Assessment Report states, that the observed warming since 1850 is *"unprecedented in more than 2000 years"*.

You might have heard of the Medieval Warm Period that lasted between *c*. 950 to 1250 CE. Evidence for this comes from historical documents, botany, and extant temperature measurements. However, as you can see from this figure there is little to no evidence that it can be seen in the global temperature record. We now know that the warm period was isolated to the North Atlantic region and was not global. While the North Atlantic was unusually warm, other regions, such as the tropical Pacific, were colder than normal. The average global temperatures show no signal of this localised warming. This shows the danger of relying on data from a limited region and extrapolating that data to infer a global phenomenon.

You might be wondering how these temperature records are constructed? After all, there were no temperature records using direct measurements of temperature with thermometers earlier than the Central England temperature record that began in 1659, and which itself was certainly not global.

In science, it is sometimes necessary to study a variable which cannot be measured directly. This can be done by 'proxy methods', in which a variable which correlates with the variable of interest is measured, and then used to infer the value of the variable of interest. Proxy methods are of particular use in the study of the past climate, beyond times when direct measurements of temperatures are available.

Most proxy records have to be calibrated against independent temperature measurements, or against a more directly calibrated proxy, during their period of overlap to estimate the relationship between temperature and the proxy. The longer history of the proxy is then used to reconstruct temperature from earlier periods.

Figure 17: Photograph of tree rings seen in a cross section of a trunk of a tree (fair use).

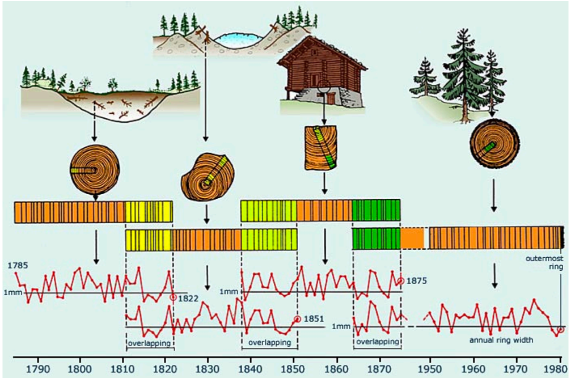


Figure 18: Principle of cross dating—first establish a chronology from a living tree, then extend back in time by matching the inner rings with the outer rings of dead wood samples (fair use).

Perhaps the most well-known proxy method in temperature reconstructions is dendroclimatology in which the width of tree rings is used to determine past climate. Tree rings are wider when conditions favour growth, and narrower when times are difficult. Using tree rings, scientists have estimated many local climates for hundreds to thousands of years previous. By combining multiple tree-ring studies, scientists have estimated past regional and global climates. One of the particular advantages of tree-ring studies is the ease with which tree rings can be dated.

Another proxy comes from studying coral reefs. Coral grows in warm, shallow waters and like their land-based counterparts, corals add seasonal layers, which appear as bands in their hard calcium-carbonate shells. These coral bands can be used to date coral samples to an exact year and season in the same manner with which tree rings are dated. Temperature is determined by measuring the composition of oxygen isotopes present in the coral's carbonate chemistry. This composition, in particular the ratio of different isotopes, is correlated with temperature, if somewhat imperfectly.

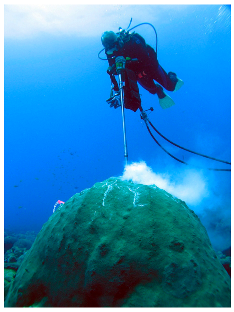


Figure 175: Photograph of a diver drilling a coral core in 2005 (fair use).

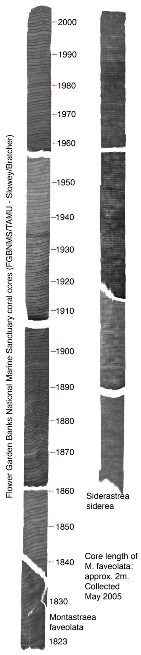


Figure 176: X-ray photographs of coral cores showing the annual growth bands (fair use).

The last proxy method I want to discuss is the study of ice cores. Ice cores are one of the best available climate proxies, providing a fairly high-resolution estimate of climate changes into the deep past. An ice core is a core sample that is typically removed from an ice sheet or a high mountain glacier. Since the ice forms from the incremental build-up of annual layers of snow, lower layers are older than upper, and an ice core contains ice formed over a range of years. Such ice cores can reach depths of over 3 km, and contain ice up to 800,000 years old. Temperature is determined in a manner similar to that used in coral samples, but this time it is the composition of oxygen found in the water itself.

Figure 177: Scientists drilling ice cores from the Greenland ice sheet in 2005 (fair use).

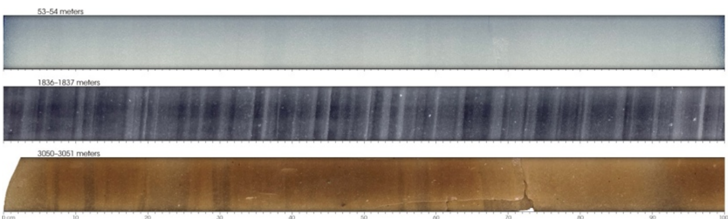


Figure 178: A 3 km ice core from the Greenland ice sheet providing a record of at least the past 100,000 years (fair use).

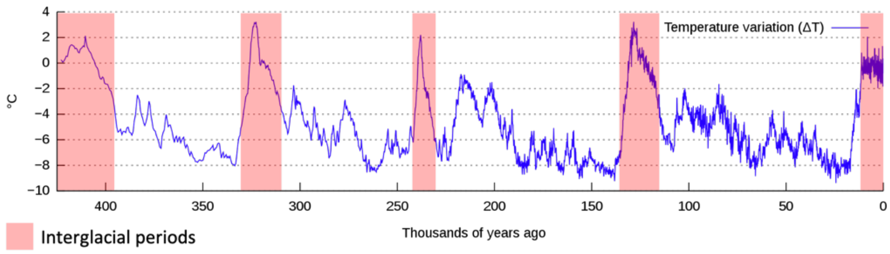


Figure 179: Figure showing the reconstructed temperature from the Vostok ice core for the past 420,000 years (CC by 3.0).

Figure 23 shows the ice-core temperature record from cores drilled at Vostok Station, a Soviet research station in Antarctica founded during the International Geophysical Year. This core enables the temperature to be reconstructed for the past 420,000 years. This record reveals past glacial and interglacial periods. The last interglacial period ended about 120,000 years ago. Thereafter, we had a glacial period that itself ended about 11,500 years ago. Since then, Earth has been in an interglacial period called the Holocene.

The glacial–interglacial cycles revealed in the ice-core temperature record are caused by Milankovitch cycles, that is the variations in eccentricity, axial tilt and precession that result in cyclical variations in the solar radiation reaching the Earth system (these variations are depicted in Figure 24). Figure 23 shows that current temperatures have certainly not been witnessed in the last 100,000 years. However, what is stark about the long-term temperature record is how unusual the recent rise in temperature is. Although temperature rises of 10 °C characterise the transition from glacial to interglacial periods, this rise takes place over several 1000 years. And with that, we have our answer to our second question: The rate of the temperature increase seen recently is very unusual—it is far more rapid than has been seen in the last 800,000 years.

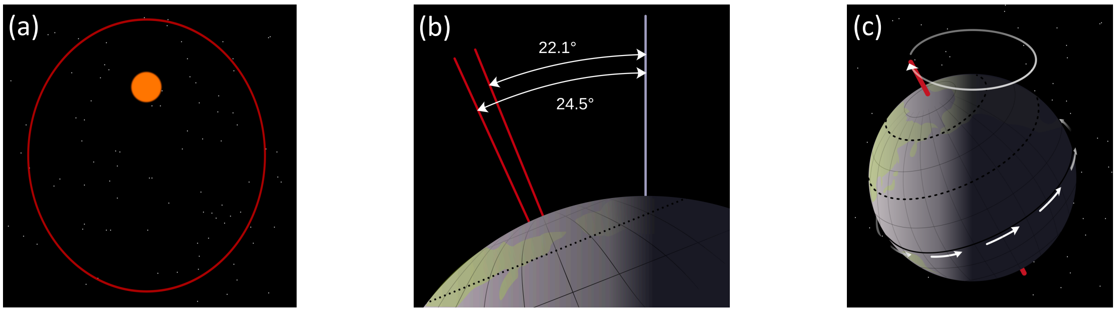


Figure 180: Variations in (a) eccentricity, (b) axial tilt, and (c) precession that results in the cyclical variations in solar radiation reaching the Earth system (public domain). The orbital eccentricity shown in (a) has been greatly exaggerated.

Data taken from trees, coral reefs, and ice cores all confirm that the recent temperature increase is unprecedented in the last 800,000 years. The multiple data sets are also concordant with the fourth element of the BDTK: Where does the majority of evidence point? This claim would also stand against the third element of the BDTK—Is the claimant providing positive evidence?

BDTK4: Where does the majority of evidence point?

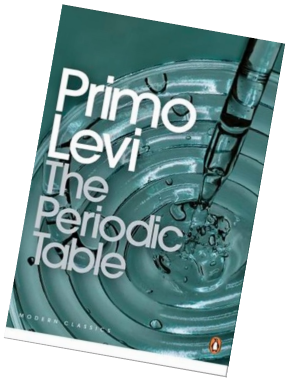
BDTK3: Is the claimant providing positive evidence?

All this evidence that temperatures have risen is positive, reliable and relevant. When we talk about positive evidence, we are talking about evidence in support of a claim. As opposed to negative evidence that seeks to discredit a rival claim. Climate change sceptics like to introduce negative evidence to discredit a scientific report without providing evidence in support of their own claim. These data showing an unprecedented temperature rise in the last 800,000 years are in support of a claim of a warming globe.

14.3.3 Concomitant Rise in Greenhouse Gases

The third question we need to answer is whether there has been concomitant increase in greenhouse gas concentrations since the Industrial Revolution.

On the face of it, this is a simple question to answer. We can view the observational records of greenhouse gases.



We can start with carbon dioxide. Carbon dioxide is an important trace gas in Earth's atmosphere. It is an integral part of the carbon cycle, that is the biogeochemical cycle in which carbon is exchanged between the Earth's atmosphere, oceans, soil, rocks, and biosphere. The carbon cycle is the subject of Primo Levi's final chapter in his wonderful book *The Periodic Table*.[37] Levi describes the importance of atmospheric carbon dioxide thus,

> *"But there is more and worse, to our shame and that of our art. Carbon dioxide, that is, the aerial form of the carbon of which we have up till now spoken: this gas which constitutes the raw material of life, the permanent store upon which all that grows draws, and the ultimate destiny of all flesh, is not one of the principal components of air but rather a ridiculous remnant, an 'impurity,' thirty times less abundant than argon, which nobody even notices."*[38]

I strongly encourage you all to avail yourselves of the opportunity to read this chapter, if not the entire book.

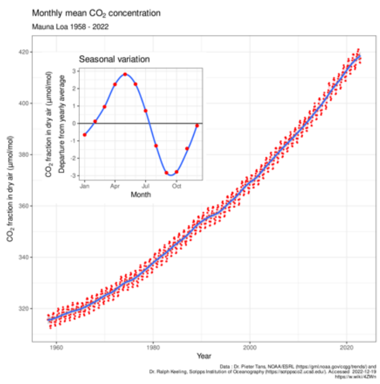


Figure 181: Atmospheric carbon dioxide (CO_2) concentrations from 1958 to 2022 (CC by 4.0).

One dataset we introduced in the last lecture was that from the Mauna Loa observatory in Hawaii. A dataset started by Charles Keeling, and which now bears his name. The Keeling curve shows atmospheric CO_2 concentrations rising from 315 ppm in 1958 to in excess of the 415 ppm levels seen today. Impressed upon this steady increase in carbon dioxide concentrations is a seasonal variation. But why do we see this seasonal variation?

The animation found at this link produced by NASA shows the global biosphere in the background and the corresponding carbon dioxide graph in the foreground. The biosphere is represented as phytoplankton concentrations over the ocean and the vegetation index over land. The carbon dioxide concentrations are from Mauna Loa in Hawaii. As each year progresses notice how the greening of the land moves south to north, then north to south. Also notice how this corresponds to the carbon dioxide graph. The carbon dioxide content falls during the Northern Hemisphere summer when photosynthesis surpasses respiration and decomposition. It then rises during the late autumn to early spring when respiration and decomposition of the previous season's crop of leaves exceeds photosynthesis. These are the seasonal oscillations in the carbon dioxide graph. This animation reveals the intimate connection between the biosphere and atmosphere that is the short-term terrestrial carbon cycle. Perhaps more poetically, this shows the Earth breathing, in and out, once per year.

[37] Levi, P. (2000) *The Periodic Table* (R. Rosenthal, Trans.). London: Penguin Books Ltd.
[38] *Op. cit.*, p. 191.

Did this upward trend though begin with the ? We can go further back in time by using the ice-core record. Carbon dioxide concentrations, and indeed the concentrations of other gases, can be determined from the composition of air in bubbles trapped in the ice. Figure 26 shows carbon dioxide concentrations during the last 800,000 years. We can clearly see variations in carbon dioxide throughout the Pleistocene from lows of about 180 ppm, during deep glaciations, to 280 ppm during interglacial periods. Pre-industrial concentrations are confirmed to be 280 ppm. The current concentrations of carbon dioxide have not been seen in at least the last 2 million years. The rate of increase of carbon dioxide since the Industrial Revolution is also profoundly unprecedented.

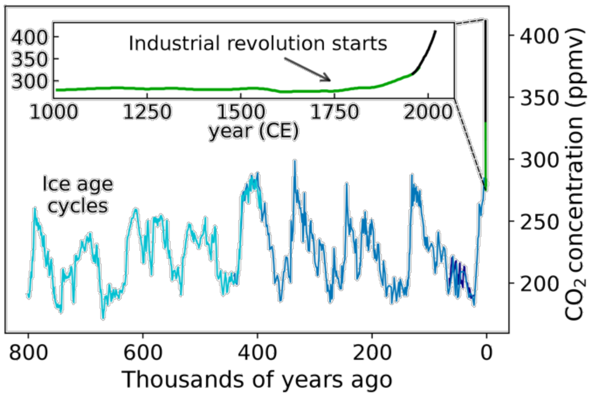


Figure 182: CO_2 concentrations over the last 800,000 years (CC by 3.0).

Similar records of other greenhouse gases tell the same story. Methane concentrations have increased from pre-industrial values of about 600 ppb to levels over 1800 ppb—a three-fold increase. Nitrous oxide concentrations have increased from some 270 ppb to 338 ppb today.

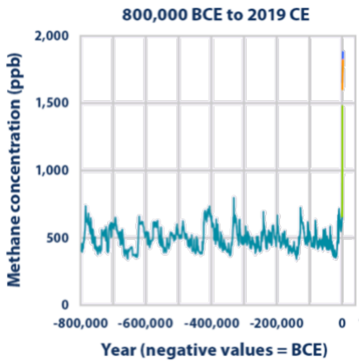


Figure 183: Methane concentrations over the last 800,000 years (public domain).

It is clear that the increase in temperatures since the beginning of the Industrial Revolution has been accompanied by increases in the concentrations of greenhouse gases. The current concentrations of greenhouse gases have not been witnessed in at least the last several hundred thousand years. The rapidity of these increases has also never been seen in our record of greenhouse gas concentrations.

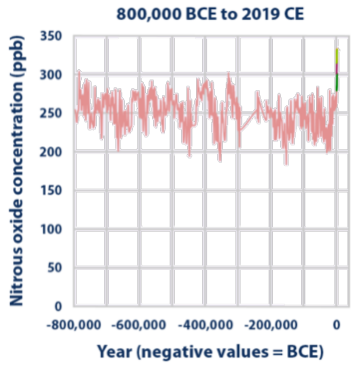
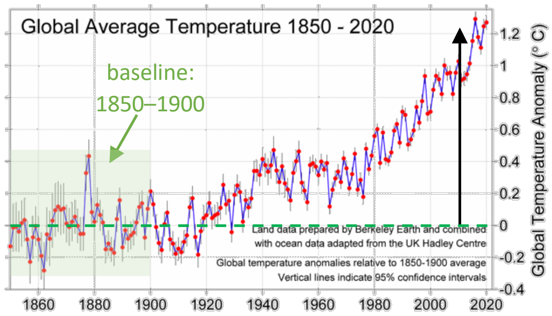


Figure 184: Nitrous oxide concentrations over the last 800,000 years (public domain).

14.3.4 Finding Correlations

In his first lecture, Professor Bettens spoke about the need when making proper scientific observations to consider any necessary comparative information. Professor Bettens noted that this was critical to Dr Semmelweis' work in identifying the cause of a heightened incidence of puerperal fever in one maternity clinic over the other. After discounting all possible differences between the clinics, Semmelweis was left with the conclusion that the only significant difference was between the individuals who worked at the two clinics. Ultimately, Semmelweis concluded that the handling of cadaverous material and a lack of cleanliness of the medical students was the cause of increased mortality.

This method of difference, that dates back to William of Ockham, is very common in science. Earlier, we saw this in perhaps a less obvious way. We subtracted baseline temperatures, such as the 1850–1900 average, from global temperature measurements to reveal changes in temperature. And we have just compared carbon dioxide, methane and nitrous oxide measurements to past levels to reveal differences. These are being used to argue that global warming is happening and that the suspected cause, that is greenhouse gases, were also increasing.



Correlations, like this one, between temperature and greenhouse gas concentrations, are important in science. They provide *prima facie* evidence for possible causal relationships. Similar positive correlations were also noted between temperature and tree ring widths. These relationships are critical to the proxy methods that enable temperatures to be estimated in the past.

Perhaps the most stunning correlation is that of the breathing Earth. We saw the seasonal variation in atmospheric carbon dioxide negatively correlating with the rates of photosynthesis in the biosphere, particularly the northern hemisphere forests.

14.4Convincing the Scientific Community (II)

We have seen that the observational record shows rising global average temperatures. We have also seen that this rise is unusual. We have evidence that the rise in temperature since the Industrial Revolution has been accompanied by rising greenhouse gas concentrations, in particular carbon dioxide. The next question that we need to answer is how can we be sure that the rise in carbon dioxide is due to the burning of fossil fuels?

14.4.1 Global Carbon Cycle

This is a challenging question. It requires us to think deeply about the carbon cycle. Carbon is a constituent of all organic compounds, many of which are essential to life. The greatest physical reservoir of carbon is not atmospheric carbon dioxide, but is instead located in the Earth's crust and is not easily accessible to biological organisms. The source of virtually all carbon found in living organisms is CO_2 either in the atmosphere or dissolved in water. The global carbon cycle can be viewed as a series of reservoirs of carbon in the Earth System, which are connected by exchange fluxes of carbon. An exchange flux is the amount of carbon which moves between reservoirs each year. Before human activities, such as land use changes and industrial processes, had a significant impact, the global carbon cycle was roughly balanced. However, CO_2 has increased by almost 50% from around 280 ppm in 1750 to the current levels of over 415 ppm.

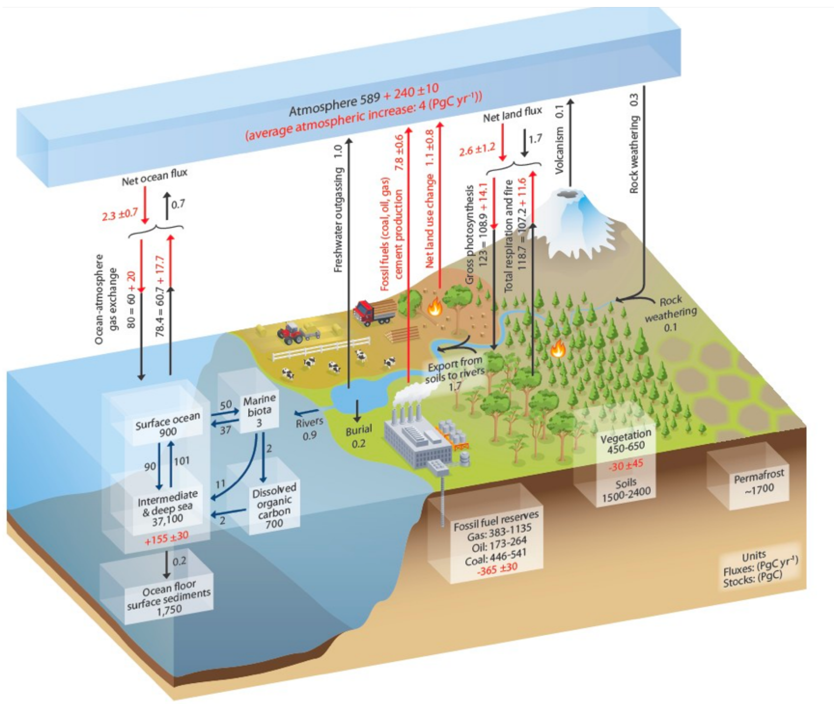


Figure 185: The changing global carbon cycle (fair use). The black numbers and arrows show the pre-industrial values. The red numbers and values show the changes to the pre-industrial values caused by humans.

Figure 29 shows the reservoirs and exchange fluxes of carbon in the global carbon cycle. The numbers represent carbon reservoirs in Petagrams of Carbon and the annual exchanges in PgC/year. A petagram is equivalent to a billion metric tonnes. The black numbers and arrows show the pre-industrial reservoirs and fluxes. The red numbers and arrows show the additional fluxes caused by human activities averaged over 2000–2009, which include emissions due to the burning of fossil fuels, cement production and land use change (in total about 9 PgC/year). Some of this additional anthropogenic carbon is taken up by the land and the ocean (about 5 PgC/year) while the remainder is left in the atmosphere (4 PgC/year), explaining the rising atmospheric concentrations of CO_2. The red numbers in the reservoirs show the cumulative changes in anthropogenic carbon from 1750–2011; a positive change indicates that the reservoir has gained carbon.

This accountancy of the carbon budget is difficult and fraught with uncertainty. The studies to estimate the exchange fluxes are some of the most challenging in Earth science. Not surprisingly many climate change deniers have argued that these studies are flawed and do not show that burning fossil fuels has increased the atmospheric carbon reservoir.

14.4.2 The Suess Effect

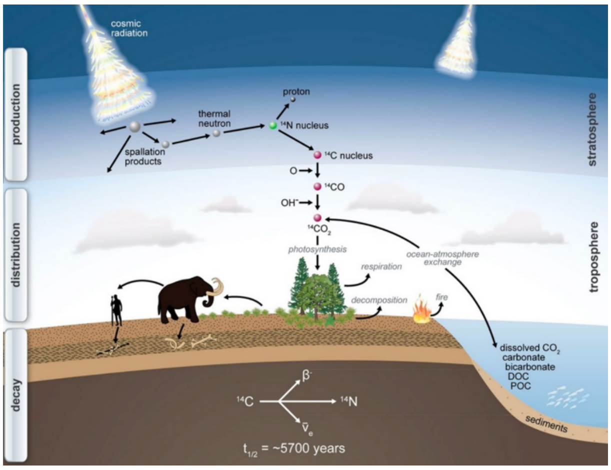


Figure 186: Production of carbon-14 and how it enters the carbon cycle (fair use).

However, scientists have been able to conclusively show that the increase in carbon dioxide in the atmosphere is due to burning fossil fuels, and they did this indirectly by measuring the atmospheric concentrations of carbon-14. Carbon-14 is formed in the upper atmosphere through the impact of cosmic radiation. The carbon-14 is eventually oxidised to carbon dioxide and through photosynthesis it is incorporated into the biosphere. Anything made of organic material will have carbon-14 present in its structure. This carbon-14 is radioactive and decays with a half-life of some 5,730 years. If we know the amount of carbon-14 as a function of time in the past, then we can use measurements of carbon-14 to date materials. This is the basis of radiocarbon dating.

Hans Suess, who we discussed earlier, realised that burning fossil fuels would dilute the amount of carbon-14 present in the atmosphere. This is because fossil fuels are devoid of carbon-14 as they are formed from the fossilised remains of animal and plant life that died hundreds of millions of years ago primarily in the Carboniferous period. Any carbon-14 originally present in the organic material of these dead animals and plants will have long ago decayed. Burning fossil fuels increases the amount of carbon-12 in the atmosphere, but leaves the amount of carbon-14 unchanged. The result is a decrease in the ratio of carbon-14 to carbon-12. Suess recognised that the influence of this dilution would affect the accuracy of radiocarbon dating. More recently, the Suess effect has been used in a wonderfully elegant argument to show that the rise in carbon dioxide in the atmosphere is due to the burning of fossil fuels.

Figure 31 shows the per mille change in the ratio of carbon-14 to carbon-12 in atmospheric carbon dioxide since the end of the Second World War. The small dilution of carbon-14 to carbon-12 in the shaded green area is the effect postulated by Suess. As you can see, there was a dramatic rise in the ratio of carbon-14 to carbon-12 in the mid- to late 1950s that continued until the early 1960s. This rise was due to the open-air testing of atomic weapons. Following the signing of the Limited Nuclear Test Ban treaty in 1963, which prohibited nuclear weapons tests in the atmosphere or under water, we can see that the ratio of carbon-14 to carbon-

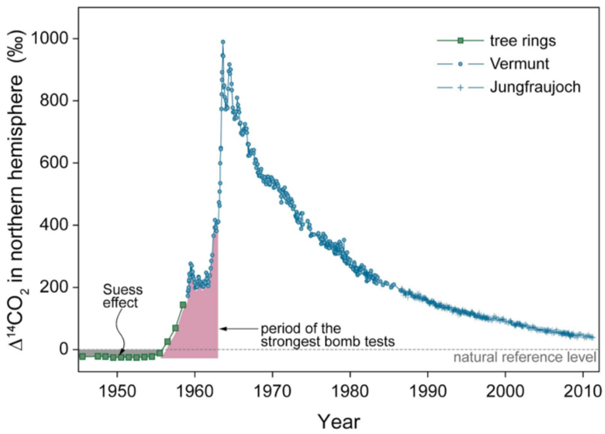


Figure 187: Graph showing the Suess effect (fair use).

12 dropped dramatically. The mechanism for this drop was not radioactive decay, after all carbon-14 has a half-life of 5,730 years and so radioactive decay would not be noticeable on the timescale in this figure, instead the mechanism was due to the dilution through the burning of fossil fuels. The rate of decay can be shown to match exactly that which would be expected given the increase in atmospheric carbon dioxide through the burning of fossil fuels. There is simply no other mechanism that can explain this decay in carbon-14. This amounts to powerful evidence that the increases in carbon dioxide in the atmosphere are due to the burning of fossil fuels.

It should be noted that this human-caused disruption to the carbon-14 amounts in the atmosphere through the testing of nuclear weapons has often been cited to mark the transition from the Holocene to the current period in which humans have become a dominant force of global environmental change. The late Paul Crutzen, the winner of the 1995 Nobel prize in chemistry, coined the term Anthropocene to denote this current period. In described his coinage in an interview:

Figure 32: Photograph of Paul Crutzen (CC by 3.0).

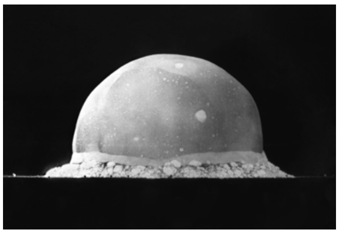


Figure 33: Photograph of the Trinity bomb test 0.016 s after the explosion on the 16 July 1945 (public domain). This date has been proposed as the start of the Anthropocene.

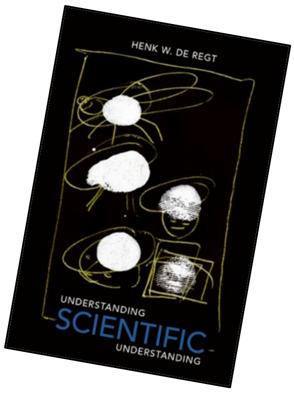
> *"I was at a conference where someone said something about the Holocene. I suddenly thought this was wrong. The world has changed too much. So, I said: 'No, we are in the Anthropocene.' I just made up the word on the spur of the moment. Everyone was shocked. But it seems to have stuck."*

The final question that needed to be answered to convince the scientific community was to show that we understand human-induced climate change. Indeed, this is one of the central aims of the IPCC.

14.4.3 Nature of Scientific Understanding

Science has not only produce d a vast amount of knowledge about a wide range of phenomena, it has also enhanced our understanding of these phenomena. Indeed, understanding can be regarded as one of the central aims of science.

But what exactly is it to understand phenomena scientifically, and how can scientific understanding be achieved? One way to argue this is that scientists achieve understanding of a phenomenon *P* if they construct an appropriate model of *P* on the basis of a theory *T*. Henk de Regt identifies the Criterion for Understanding Phenomena in the following way,



> *"A phenomenon P is understood scientifically, if and only if, there is an explanation of P that is based on an intelligible theory T and conforms to the basic epistemic values of empirical adequacy and internal consistency."*[39]

14.4.4 Testing Understanding through Models

Scientists acquire understanding of phenomena by constructing models. The climate science community has built such models. Using the relevant physical, chemical, and indeed biological theories, they have built mathematical models based on the conceptual models that describe how each part of the Earth system is inter-connected. These mathematical models are realised as computer-based climate models. The aim of

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[39] de Regt, H. W. (2017). *Understanding Scientific Understanding*. New York: Oxford University Press. p. 92.

these climate models being to attempt to quantitatively explain the rise in temperatures witnessed since the Industrial Revolution.

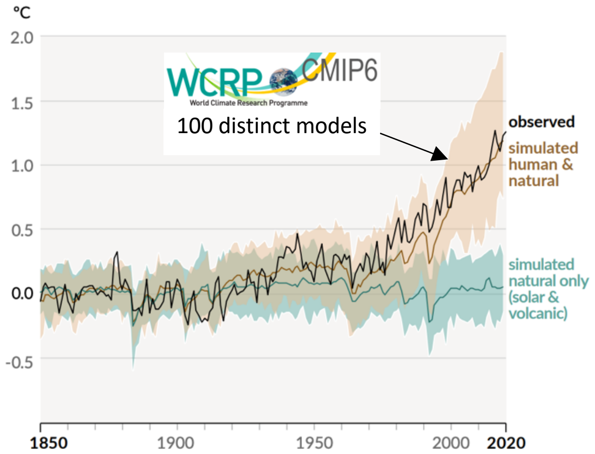


Figure 188: Change in global surface temperature as observed (black) and simulated using human and natural (brown) and only natural factors (green) from 1850–2020 (fair use).

Figure 34, from the Sixth Assessment Report of the IPCC, shows the observed changes in global surface temperature over the past 170 years, represented by the black line, relative to an 1850–1900 baseline. This is compared to the CMIP6 climate model simulations of the temperature response to both human and natural drivers, represented in brown, and to only natural drivers, that is solar and volcanic activity, represented in green. Solid coloured lines show the multi-model average, and coloured shades show the very likely range of simulations.

The CMIP6 is the sixth iteration of the Coupled Model Intercomparison Project. CMIP6 consists of simulations from around 100 distinct climate models produced across 49 different modelling groups. These models simulate the physics, chemistry and biology of the atmosphere, land, and oceans in great detail, and require some of the largest supercomputers in the world to generate their climate projections.

Note that the brown solid line, representing the average of all the model simulations that include both human and natural drivers, closely follows the observed temperature record indicated by the black line. The model simulations that exclude human influence through increasing greenhouse gases, and only include natural drivers, show no warming across the entire period from 1850 to the present day. The model simulations argue that it is impossible to reproduce the observed warming in global surface temperatures without including the increase in greenhouse gases due, in the case of carbon dioxide, to the burning of fossil fuels.

These model simulations are the result of scientists attempting to determine whether the observed increase was simply a result of natural variability, or changes in solar or volcanic activity. However, the evidence to support such ideas is simply not there. The only explanation that scientists have failed to disprove is that the increase in temperature is due to the increase in greenhouse gases, in particular, carbon dioxide. This illustrates an important premise in science that any hypothesis ought to be falsifiable. The contention of human-induced climate change is falsifiable. We have simply failed in our attempts.

These models represent our best understanding of climate science and human-induced climate change in particular. They offer convincing evidence that we do understand human-induced climate change with a great deal of fidelity.

In the last lecture, I noted the importance of Tyndall's ratio spectrophotometer in establishing the role of carbon dioxide in the greenhouse effect. As Professor Bettens had noted, new instruments can lead to new discoveries. However, perhaps the most important instrument in climate science has been the computer. The first attempt at performing a meteorological forecast through computation was conducted by Lewis Fry Richardson in 1922, well before the advent of the modern computer. Not only did his 6-hour forecast take months to calculate by hand, but it was also so grossly in error that no one repeated such calculations for 30 years. Without computers, and in particular, the supercomputers used in climate modelling, we would not be able to project the effects of climate change. It would simply not be possible to couple together all of the different

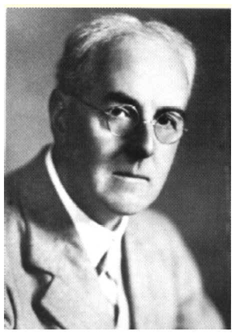


Figure 189: Photograph of Lewis Fry Richardson (public domain).

parts of the Earth system, or indeed even understand isolated elements of the Earth system.

Climate models have been critical in confirming the causal relationship between rising greenhouse gases and rising temperatures. However, in the same way that we do not rely on one organisation's instrumental temperature record, we also do not rely on one research group's climate model. The projections and analysis found in the IPCC Sixth Assessment Report come from 100 climate models themselves developed from 49 distinct research groups. The preponderance of evidence from these model simulations is that, amongst other things, global temperatures will continue to increase, that sea levels will continue to rise, that ocean pH will continue to fall, and that Arctic sea ice will continue to decline.

Figure 192: Flooding of New Orleans in 2005 exacerbated by sea level rise (public domain).

Figure 191: Coral bleaching caused by increased ocean pH (CC by 3.0).

Figure 190: Arctic sea ice loss (public domain).

In the second half of this lecture, we tasked ourselves with answering five questions. We found that global temperatures are rising, that this rise is unusual, that greenhouse gases are also rising, that this rise in greenhouse gases is due to human emissions, and that our models quantitatively reproduce the observed warming. It is for these reasons that the scientific community reached the consensus position that human-induced climate change is happening.

14.5 Optional: Milankovitch Cycles

The YouTuber, Paul Merrell, explains how variations in the eccentricity in the Earth's orbit, axial tilt, and precession over different time scales leads to ice ages in a video that can be found at this link. This goes into far more detail than is necessary for this course.

14.6 Optional: The Global Carbon Cycle

The YouTuber, Hank Green part of the Crash Course team, explains the global carbon cycle in an informative and entertaining manner in a video that can be found at this link. It discusses the connection between the carbon cycle and climate change. This goes into far more detail than is necessary for this course.

14.7What Have You Learnt?

We set ourselves five learning outcomes at the beginning of the lecture. These were that by the end of the lecture, you should be able to:

(6) *Describe* the history of the establishment of the scientific consensus on climate change including the role played by the IPCC;
(7) *Articulate* the difference between weather and climate, and between the greenhouse effect and climate change;
(8) *Outline* how proxy methods used in the reconstruction of past temperatures;
(9) *Recognise* the difference between the public perception of the scientific consensus on climate change and that of the scientific community; and,
(10)*Explain* how the scientific consensus on climate change was established.

Take out the notes you made at the beginning of the lecture.

Has your understanding changed?

What new ideas or concepts have you learnt?

How does what you have learnt connect with earlier material?

Again jot down your thoughts. Finally, do you remain unsure about your ability to meet any of the learning outcomes? Below I direct you to which section you will need to revisit to find the material you need to meet the learning outcomes.

To achieve **ILO1**, you should be able to describe what is meant by scientific consensus. You should further be able to identify the accumulation of scientific evidence of climate change following the seminal studies of Callendar. The International Geophysical Year played an important role in coordinating observational studies, whereas the formation of the IPCC helped curate the scientific evidence in support of the scientific consensus. Although scientific consensus that climate change would eventually happen was realised early, you should also be able to discuss the challenges faced by the scientific community in identifying when climate change would be observable. If you are unsure, you should review Sections 6.1.3, 6.1.4, 6.1.5, 6.2.1, and 6.2.2.

To achieve **ILO2**, you should be able to articulate what is meant by weather and climate, and how changes in the greenhouse effect leads to climate change. If you are unsure, you should review Section 6.1.1.

To achieve **ILO3**, you should be able to outline what is meant by a proxy method and be able to identify proxy methods. You should further be able to discuss how changes in the proxy relate to temperature and the time periods over which proxy methods can be used. If you are unsure, you should review Section 6.3.2.

To achieve **ILO4**, you should be able to recognise the difference between how consensus is used in the scientific community and its colloquial meaning to the public at large. You should be able to state the level of scientific consensus on climate change within the scientific community, as well as a sense of the level with which the public views this scientific consensus. If you are unsure, you should review Sections 6.1.2 and 6.2.3.

To achieve **ILO5**, you should be able to explain the questions that needed to be answered for a consensus on climate change to be established. You should be able to identify the evidence that the scientific community brought to bear that showed that temperatures were rising, that recent temperature rises were unprecedented, that greenhouse gas concentrations were also rising, that the increases in atmospheric carbon dioxide concentrations were due to the burning of fossil fuels, and that, through model simulations, we understood the human-induced climate change. If you are unsure, you should review Sections 6.3.1, 6.3.2, 6.3.3, 6.4.1, 6.4.2, and 6.4.4.

If you feel comfortable with your ability to meet the learning outcomes, then you are ready to try the quiz. Good luck!

15 Establishing the Scientific Consensus on Climate Change

Intended Learning Outcomes for Lecture 8

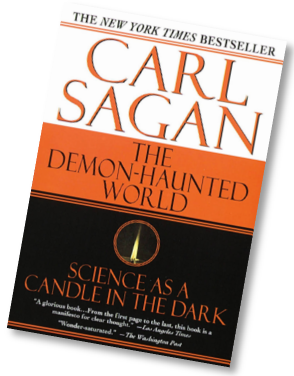
By the end of this lecture, you should be able to:

(11)*Summarise* how climate models prove their reliability through hindcasting and successful forecasting;
(12)*Predict* the effect of feedback loops and discuss the impact of feedback on model projection uncertainty;
(13)*Describe* and *contrast* the climate change projections resulting from possible future climate scenarios;
(14)*Explain* how climate change mitigation strategies relate to principles of equity; and,
(15) *Reflect* on how you incorporate new knowledge into your current understanding and on the danger of absolute certainty.

Reliability of Climate Models

In the last lecture, we discussed how the scientific consensus was undermined to delay or block climate change regulation. We looked at some of the climate change myths that have been used to promote doubt. We also identified some of the forms of denial that convince the public to delay action on climate change, and the cognitive biases that we all have that make us susceptible to these forms of denial.

15.1.1 Moving the Goalposts



We noted a transition in argument from *"There is no problem"* to *"We aren't responsible"* to *"It's too expensive to fix"*. This transition that amounts to moving the goalposts echoes the argument used to convince you that I have an invisible, floating, heatless, incorporeal dragon in my garage under questioning by Professor Bettens during his third lecture. This is of course the scenario discussed by Carl Sagan in his book *The Demon-haunted World*.[40] Whenever, Professor Bettens identified a test to detect the dragon, I gave an argument as to why it would not work; I moved the goalposts. In the same way, climate change deniers have moved the goalposts as to what is required as evidence before we enact policies to mitigate climate change.

15.1.2 Climate Modelling

In this lecture, I want to discuss the reliability of climate change predictions. How do we develop confidence in climate models? How do we estimate uncertainty in these predictions? What does the future look like, and for that matter, which future? The last question looks at the relationship between science and society, how science can inform public policy.

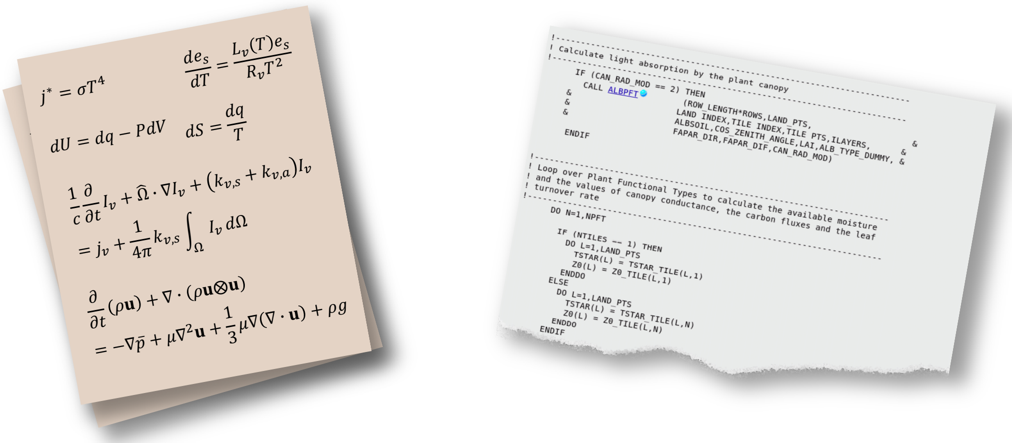


Figure 193: Some of the equations used to form a mathematical climate model together with an image of computer code written in the FORTRAN programming language from the HadGEM2-ES climate model (fair use).

Models are one of the ways in which scientists show understanding of a phenomenon. The mathematical models that incorporate our best understanding of the Earth system are expressed in the form of computer programs that are able to calculate climate and change in climate. These computer programs are known as climate models.

These climate models use some of the world's most powerful supercomputers to calculate their predictions. If you read the *Summary for Policymakers* in the Sixth Assessment Report of the IPCC, you will note that sometimes it refers to *projections* and at other times it refers to *predictions*. Projections are model-derived estimates of future climate. When a projection is branded *most likely* it becomes a prediction. The reason for this difference is that many of the climate simulations calculated are for future scenarios that are seen as possible. A scenario is a coherent, internally consistent, and plausible description of a possible future state of the world. Scenarios have a demographic, socio-political, economic, and technological storyline.

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[40] Sagan, C. (1996). *The Demon-haunted World: Science as a Candle in the Dark*. New York: Ballantine Books. pp. 171–173.

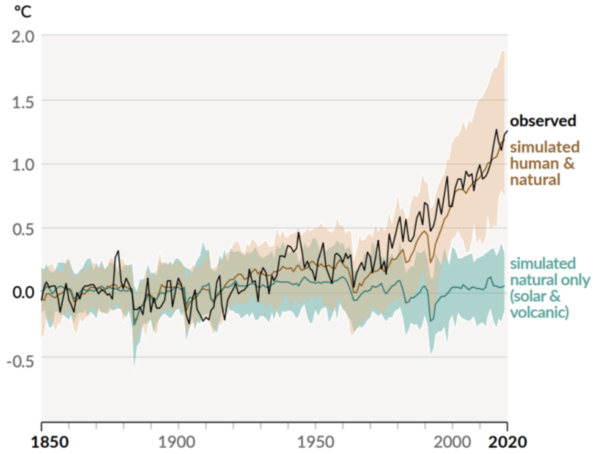


Figure 194: Change in global surface temperature as observed and simulated using human & natural and only natural forcings (fair use).

But perhaps we are getting a little ahead of ourselves. Before discussing these model projections, let's first discuss why we should have any confidence in them. This question of confidence is answered by testing models against past observations. Reproducing past observations is known as [hindcasting](). It is of course important that the model isn't tuned to reproduce past observations, because this would greatly limit the confidence we could have in any such model for forecasting the future. Models of past climate are what are known as initial-value models. They are given an initial state, say the atmosphere of 1850 or 1870, and are then allowed to freely run forward in time. Once running, these climate models do not correct themselves using observations. Such a model should be able to reproduce natural variability in the climate system. However, it will not be able to reproduce the observed changes in Earth surface temperature. Although the model is free running, it does need to be forced by natural and anthropogenic changes. Natural forcings involve incorporating solar variations and volcanic activity. Anthropogenic forcings involve the changes in greenhouse gases, sulphate aerosols, and land-use.

We have already seen the graphs of model calculations from the Sixth Assessment Report. Figure 2 shows that there is good agreement with the observed temperature record and further makes the case that the increase in temperature can only be explained by anthropogenic forcings, most importantly the increasing atmospheric burden in greenhouse gases due to the burning of fossil fuels.

Despite using some of the most powerful supercomputers on the planet,[41] these climate models need to divide the planet up into grid cells to make the calculations more manageable. This means that at every step of the model through time, it calculates the average climate of each grid cell. However, there are many processes in the climate system and on the Earth's surface that occur on scales within a single cell. For example, the topography will be averaged across a whole grid cell in the model, meaning it potentially overlooks the detail of any physical features such as mountains and valleys. Similarly, clouds can form and dissipate at scales that are very much smaller than a grid cell.

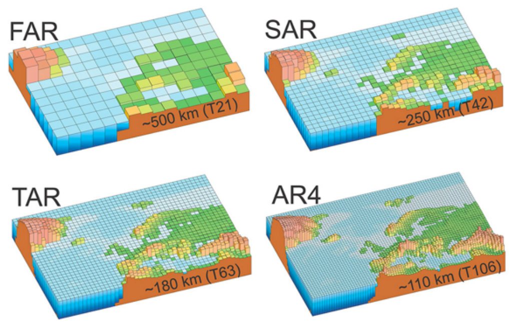


Figure 195: Increasing spatial resolution from the first IPCC assessment report to the fourth (fair use).

[41] In 2017, the U.K. Met Office installed three Cray XC40 supercomputers, each capable of 14 quadrillion calculations per second.

Figure 196: Some of the climate processes and properties that typically need to be parameterised within global climate models (fair use).

To solve this problem, these variables are *parameterised*, meaning their values are defined in the computer code rather than being calculated by the model itself. This graphic shows some of the processes that are typically parameterised in models. Parameterisations may also be used as a simplification where a climate process isn't well understood. Parameterisations are one of the main sources of uncertainty in climate models. Each research group will approach the parameterisation of a climate process in a slightly different way. Indeed, any particular research group may run their models with different parameterisation packages.

This means that the climate models in the IPCC reports give different answers even if they are initialised with the same climate state. The variance in the global average temperature from these different models gives us a sense of the uncertainty in the model calculations. This is why it is important not to rely on any one climate model, or to describe any one model as being the *best*.

These hindcast calculations give a great deal of confidence that climate models "understand" the climate processes that led to the increase in temperature since the Industrial Revolution. However, the future climate is expected to be still warmer. It could be argued that this represents an extrapolation beyond the climate states in which we know, through hindcast comparisons, that climate models perform well. To resolve this dilemma, scientists have constructed paleoclimate models that have attempted to reproduce the proxy temperature records for much earlier climates, when temperatures were vastly outside the envelope witnessed since the Industrial Revolution.

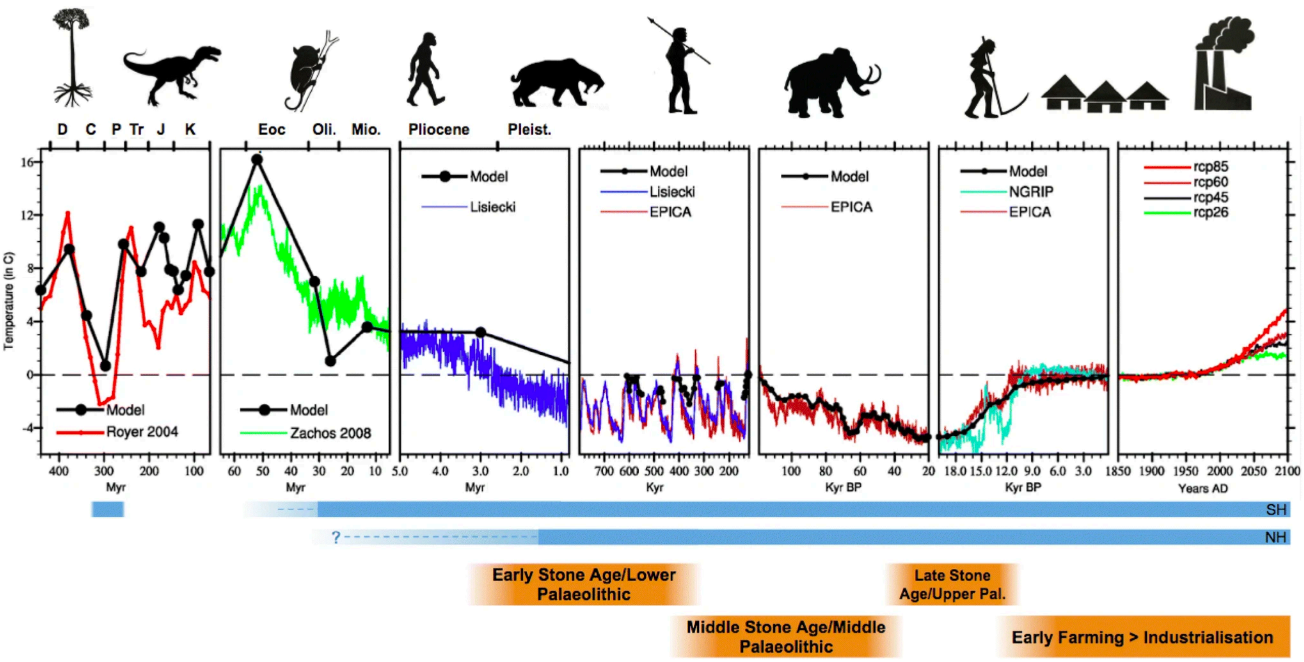


Figure 197: Average global temperature through the last 400 million years with comparisons to paleoclimate models (fair use).

Figure 5 shows global average temperature variations through the last 400 million years as predicted by the Hadley Centre Coupled Climate Model version 3, an early version of the climate model used by the U.K. Met Office. These numbers are compared with geologically derived estimates of temperature variability over the same period. Future projections of temperature change using different Representative Concentration Pathways are shown in the right-hand most panel. The fact that the same climate model is able to reproduce global average temperatures, especially during the Pleistocene period of glacial–interglacial cycles during the last 800,000 years, is stunning.

Studying paleoclimates gives us the opportunity to better understand the sensitivity of models to, among other things, changes in greenhouse gases, and glacial and sea-level histories. Many of the things that are critical to being able to predict future climate change.

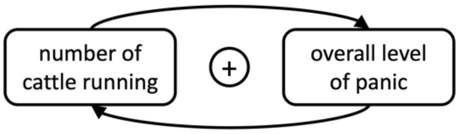
While the ability to simulate past and current climate does not guarantee the ability to simulate future climate, it is an important precursor. Today's climate models can accurately reproduce current climate, and have been able to reproduce changes to the climate that have been observed in recent years. Many of the processes that drive the climate are well understood and the ability to capture these processes in models has been tested and is constantly being improved. Climate models are not perfect, but they are the best tool we have available for explaining the current behaviour of our climate and predicting likely changes to the planet's future climate.

These models are extremely expensive to run just in terms of the energy cost. They have a distinct carbon footprint. Indeed, scientists are beginning to be concerned as to whether the carbon footprint of completing a climate model simulation is ethically sound. Unless the simulation can truly add something to our understanding of climate science or how climate change will evolve, it may be morally wrong to do the simulation.

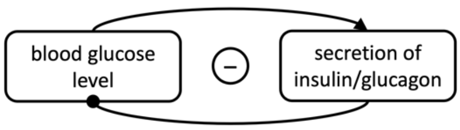
15.1.3 Feedback

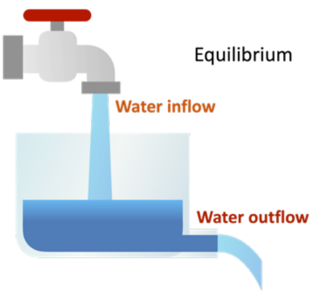
As we have just discussed, it is important that we validate models against past and current climates. This validation is important if we want to use such models to predict future climate change. We also spoke about the need to parameterise certain elements of the climate system and that these parameterisations are the sources of much of the uncertainty in climate models. I want to explain why poorly understood climate processes can lead to substantial uncertainties in climate models. The reason is *feedback*.

You are all familiar with feedback. You will all have experienced the loud squealing or howling sound on Zoom calls or at a music concert, when someone's microphone picks up sound from its loudspeakers, amplifies it, and sends it through the speakers again. This is an example of positive feedback. Another example we could imagine might be in a herd of cattle. If a small number of spooked and start running, this will lead to an increase in the overall panic in the herd, that will in turn lead to an increase in the number of cattle running. The result will be a stampede. One of the features of positive feedback is that it tends to lead to instability via exponential growth.

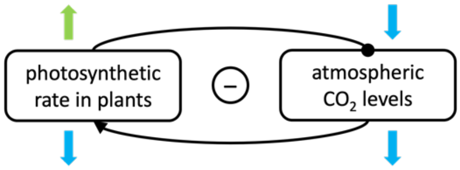


However, feedback can also be described as negative. This happens when the output of a system is fed back in a manner that reduces the fluctuation in the output. Such negative feedback loops help stabilise the system. An example of a negative feedback might be the maintenance of blood glucose levels. When the blood glucose level is too high, the pancreas secretes insulin and when the level is too low, the pancreas secretes glucagon. We saw another example earlier when I introduced the sink metaphor in my first lecture. When we turn the tap to increase the flow of water into the sink, the water height rises. This increase in water in the sink increases the pressure at the bottom that results in greater flow of water out of the sink that acts to decrease the water height. We noted that the system would find a new equilibrium with a water height that was higher than it was originally. This feature of finding a new equilibrium is at play in the Earth system. When the Earth system experiences a perturbation, such as an increase in greenhouse gases, the system responds and moves to a new equilibrium, but an equilibrium with a higher temperature.

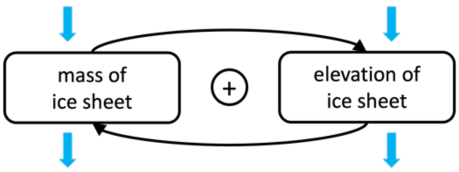




Let's look at the role feedback loops play in the Earth system.

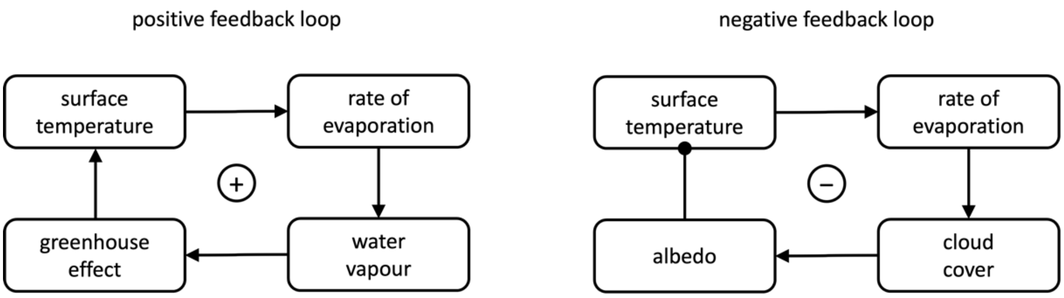


An example of a negative feedback loop might be seen in the coupling between the photosynthetic rate of plants and the concentration of atmospheric carbon dioxide. If we increase the photosynthetic rate of plants by planting more trees, then this will lead to a decrease in atmospheric CO_2. The decrease in atmospheric CO_2 will lead to a decrease in the photosynthetic rate of plants. This stabilises the system. Note that in the feedback loop between the photosynthetic rate and atmospheric CO_2 there is a negative coupling (denoted by a circle-headed arrow) and a positive coupling (denoted by a normal arrow). The negative coupling describes the effect where an increase in one element leads to a decrease in a connected element. Or vice versa, where a decrease in one element leads to an increase in the connected element. This negative response between the coupled elements will exhibit itself as a negative correlation between the elements. A positive coupling is where an increase in one element leads to an increase in the connected element. Or a decrease in an element leads to a decrease in the connected element. This time the positive response between the coupled elements will exhibit itself as a positive correlation between the elements. The changes in the elements are in the same direction for positive couplings, but are in opposite directions for negative couplings. These couplings directly describe cause-and-effect relationships, and the feedback loops describe forms of causal mechanisms.



An example of a positive feedback loop might be seen in the coupling between the mass of an ice sheet and the elevation of the ice sheet. If the ice sheet melts, then the ice sheet will move to a lower elevation where it is warmer. The ice sheet experiencing warmer temperatures will melt faster completing a positive feedback loop. This feedback loop will not stabilise. The loop will continue until the entire ice sheet has melted.

A particularly important set of feedback loops exist between surface temperature and water.



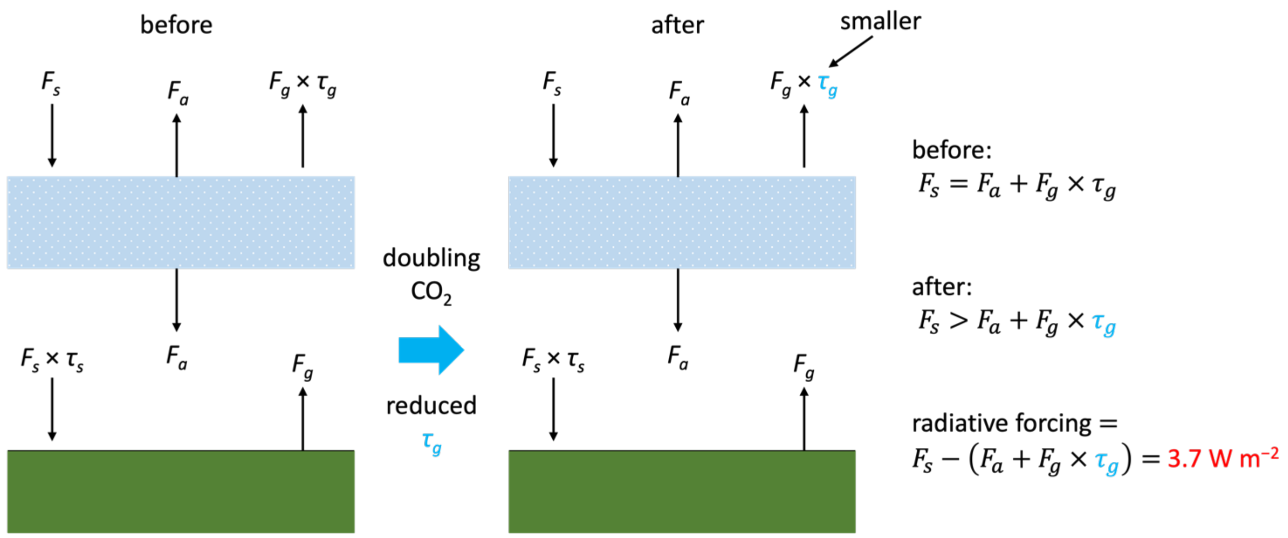
In the first feedback loop shown above, a positive feedback loop, an increase in surface temperature leads to greater evaporation. Greater evaporation leads to more water vapour in the atmosphere. Remembering that water vapour is a greenhouse gas, the increase in water vapour leads to an enhanced greenhouse effect. The enhanced greenhouse effect leads to greater surface temperature. All of the couplings are positive.

The second feedback loop is a negative feedback loop. The increase in surface temperature again leads to greater evaporation. But this time, the greater evaporation leads to increased cloud cover. Clouds are reflective. An increase in cloud cover leads to an increase in albedo. However, the increased albedo leads to a decrease in surface temperature, completing a negative feedback loop. Note that this loop includes a single negative coupling.

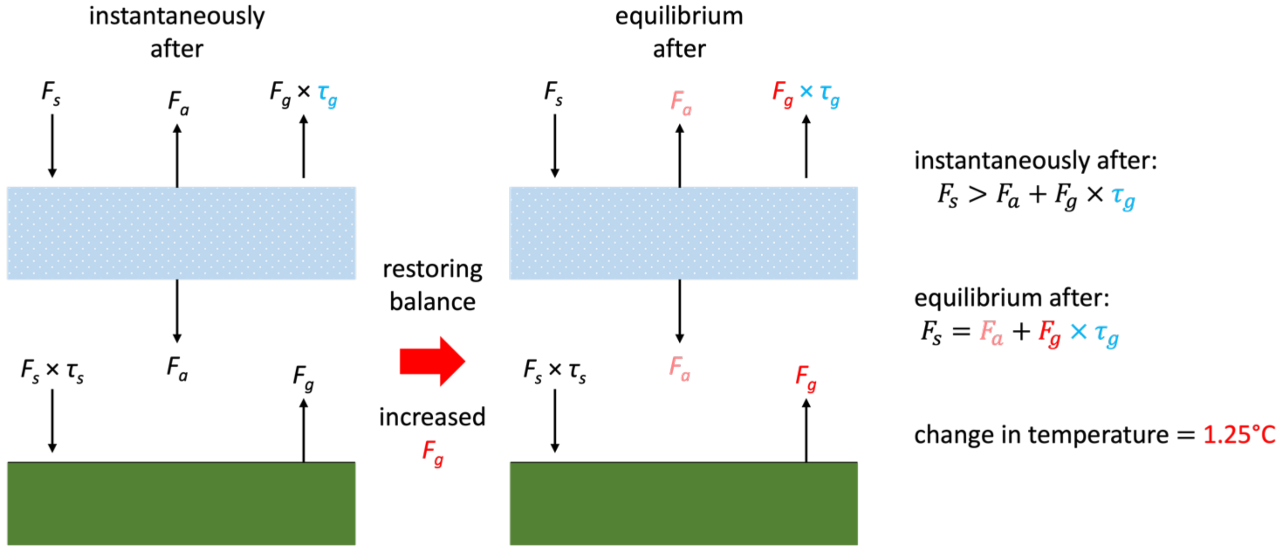
In general, any feedback loop that includes an odd number of negative couplings will be a negative feedback loop. Whereas, a feedback loop that includes zero or an even number of negative couplings will be a positive feedback loop.

Getting these feedback loops right is crucial in climate models. To understand why, let's breakdown what happens as carbon dioxide increases in the atmosphere.

A calculation that is a favourite amongst climate scientists is what would be the global average temperature in an atmosphere with double the pre-industrial CO_2 concentrations.

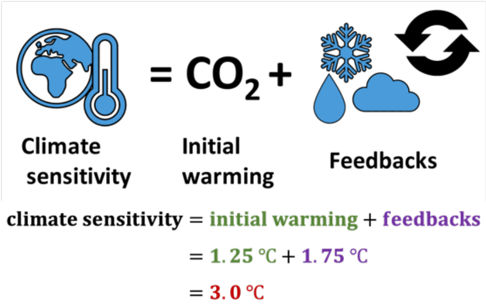


If CO_2 concentrations were doubled instantaneously, the outgoing radiation at the top of the atmosphere would be reduced by approximately 3.7 watts per square metre, because the increased CO_2 concentrations would absorb more terrestrial infra-red radiation. There would, therefore, be an imbalance between the amount of radiation entering the Earth system and the amount leaving the Earth system. This imbalance is known as the radiative forcing. With more energy entering the Earth system than leaving, the Earth system will warm up until balance is restored.



We can see how balance is restored in the effect that increased CO_2 would have on our single-layer atmosphere model. If we double CO_2, the transmittance of terrestrial infra-red radiation through the atmosphere is decreased, and less total radiation will leave the atmosphere. In order to bring the system back into balance, the temperature of the Earth surface has to increase. Assuming nothing else changes, a doubling of CO_2 will lead to an increase of surface temperature of about 1.25 °C.

However, as we noted in the feedback loops this increase in surface temperature will change other things. A major effect of increased surface temperature is greater evaporation and hence more water vapour in the atmosphere. Water vapour is a powerful greenhouse gas (the most important in fact) and so the surface temperature will increase further. The positive feedback loop will increase the initial temperature rise by a further 60%.



Other feedback loops include the melting of ice allowing the surface underneath to absorb some sunlight instead of being reflected back to space. Melting ice and exposing the underlying surface decreases the albedo. This positive feedback loop increases the initial temperature rise by a further 20%.

If the water vapour nucleates to form clouds then it is possible for there to be a negative feedback loop. However, the effect of clouds is uncertain and depends on the altitude at which the clouds form.

The net effect of the initial warming due to doubling CO_2 and the feedbacks in the Earth system is known as the climate sensitivity. The best estimate of climate sensitivity in the Sixth Assessment Report is 3 °C with a likely range of between 2.5 °C and 4 °C. Figure 6 shows how this range in climate sensitivity has changed over the years from the First Assessment Report until the current assessment report. Over these reports, the range of climate sensitivity has decreased as the models have improved.

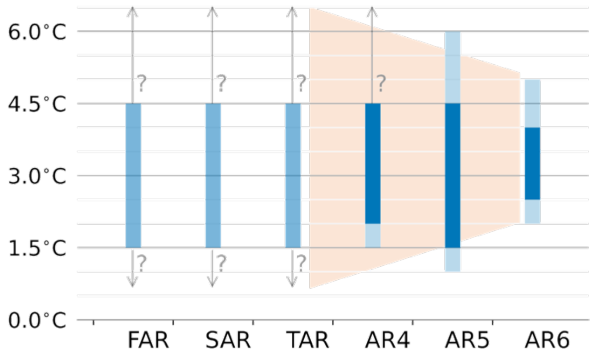
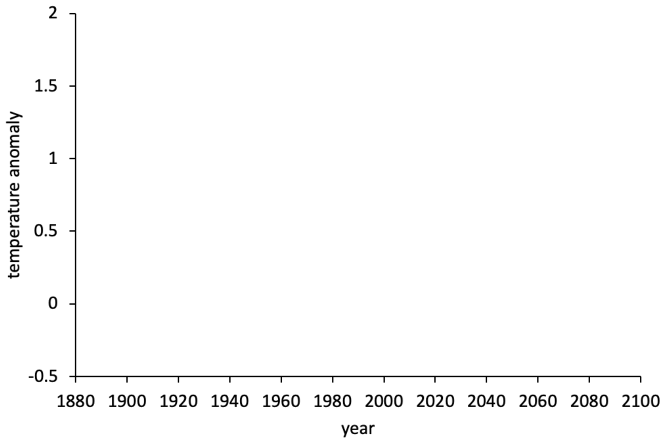
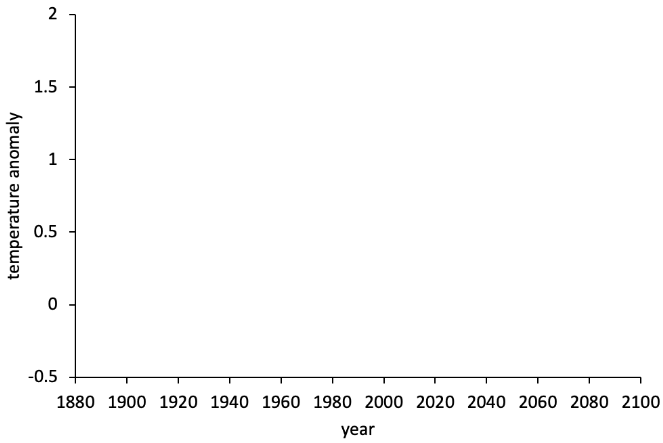


Figure 198: Improvement of climate sensitivity over the years as reported in the IPCC assessment reports (fair use).



Note that the increase in temperature due to climate sensitivity is the expected increase when the Earth system reaches equilibrium. It doesn't happen overnight. Most of the imbalance in energy entering and leaving the Earth system, as CO_2 concentrations are increased, goes into heating up the oceans. Oceans take a long time to heat up and so there is a significant lag between reaching the expected equilibrium surface temperature and the current surface temperature. For example, the current increase in Earth surface temperature since the 1850–1900 baseline is about 1.1 °C. However, the current levels of CO_2 in the atmosphere, that is about 415 ppm, imply an equilibrium Earth surface temperature of over 1.7 °C.

15.1.4 A Reason for Hope



However, there is some hope. If we reached net zero carbon emissions tomorrow, the Earth surface temperature would not continue to rise to this equilibrium amount. It would only continue to rise to 1.7 °C if human activity maintained CO_2 concentrations at 415 ppm. In a net-zero world, the oceans would continue to absorb CO_2. Detailed calculations predict that the rate with which the oceans continued to absorb CO_2 would decrease CO_2 concentrations in the atmosphere at a rate that would result in the temperature staying constant. Avoiding the equilibrium temperature associated with the current 415 ppm of CO_2 in the atmosphere requires us to not only stop adding to the atmospheric CO_2 concentration, but to reduce it to below the level at which the oceans absorb more than we are emitting.

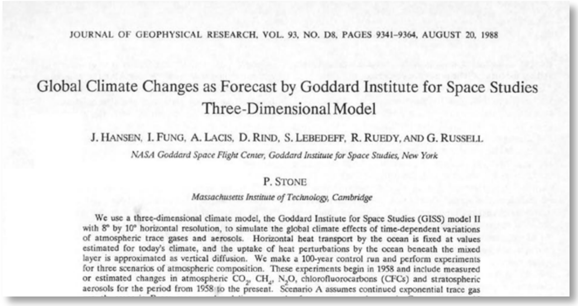
Many of the feedback loops that add to climate sensitivity involve processes that need to be parameterised. This is the reason why getting parameterisation right is so important, and why it can add significantly to the uncertainty in estimates of future climate change.

15.2 Performance of Climate Models

Climate scientists have been putting together climate models for several decades. Before looking at the projections of future climate change by current climate models, we can look at the projections by earlier climate models.

15.2.1 Models of the Past

Perhaps the most notable climate change projections of the 1980s were those of James Hansen. In 1988, Hansen and colleagues reported [climate model simulations for three different emission scenarios](). [42] *Scenario A* assumed continued exponential greenhouse gas growth. *Scenario B* assumed a reduced linear rate of growth, and *Scenario C* assumed a rapid decline in greenhouse gas emissions around the year 2000. Scenario A was essentially a worst-case scenario, whereas Scenario C was the best-case. Scenario B was the most-likely scenario. None of these future scenarios were an exact match to what happened of course, and we now understand and simulate more of the complex drivers of change which were not included in Hansen's work.


JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. D8, PAGES 9341–9364, AUGUST 20, 1988

Global Climate Changes as Forecast by Goddard Institute for Space Studies Three-Dimensional Model

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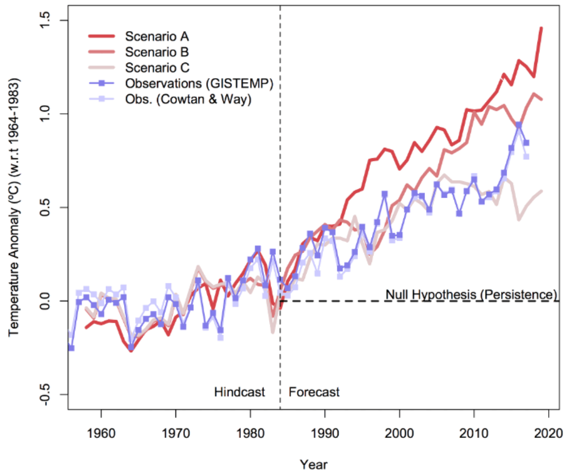
NASA Goddard Space Flight Center, Goddard Institute for Space Studies, New York

P. STONE

Massachusetts Institute of Technology, Cambridge

We use a three-dimensional climate model, the Goddard Institute for Space Studies (GISS) model II with 8° by 10° horizontal resolution, to simulate the global climate effects of time-dependent variations of atmospheric trace gases and aerosols. Horizontal heat transport by the ocean is fixed at values estimated for today's climate, and the uptake of heat perturbations by the ocean beneath the mixed layer is approximated as vertical diffusion. We make a 100-year control run and perform experiments for three scenarios of atmospheric composition. These experiments begin in 1958 and include measured or estimated changes in atmospheric CO_2, CH_4, N_2O, chlorofluorocarbons (CFCs) and stratospheric aerosols for the period from 1958 to the present. Scenario A assumes continued exponential trace gas



This animation reproduced using data from the Hansen paper shows the projections for these three scenarios, together with the observed temperature change. Essentially the data from 1958 to 1984 represent a hindcast, and that after 1984 represent a forecast. The easiest assessment of the quality of these projections is to compare the temperature trends predicted against that observed. Given that the actual greenhouse gas emissions have been closest to Scenario B, let's compare against Scenario B. Scenario B has a 0.26 °C per decade temperature trend, whereas the observed GISTEMP temperature trend has been 0.19 °C. (GISTEMP is the NASA temperature dataset from the Goddard Institute of Space Studies.) The difference between Scenario B and observations is small, but Scenario B has clearly overestimated the observed temperature trend in the forecast period. Why the discrepancy? Does this mean that Hansen's work was wrong?

Well, there are two main reasons for Hansen's overestimate. First, Scenario B, which was closest to reality, slightly overestimated how much atmospheric greenhouse gases would increase. And second, the Hansen model had a rather high climate sensitivity of about 4.2 °C for a doubling of atmospheric CO_2. To have accurately reproduced the global warming observed, the Hansen climate model would have needed a climate sensitivity of about 3.4 °C. This is within the likely range of climate sensitivity values listed as 2.5–4 °C by the IPCC for a doubling of CO_2. This would be just a little bit higher than the most likely value currently widely accepted as 3 °C. The appropriate conclusion to draw from these results is not that the projections were wrong.

[42] Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., Russell, G., and Stone, P. (1988). Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *Journal of Geophysical Research: Atmospheres*, **93(D8):** 9341–9364.

The correct conclusion is that Hansen's study is another piece of evidence that climate sensitivity is in the IPCC stated range of 2.5–4 °C for a doubling of CO_2.

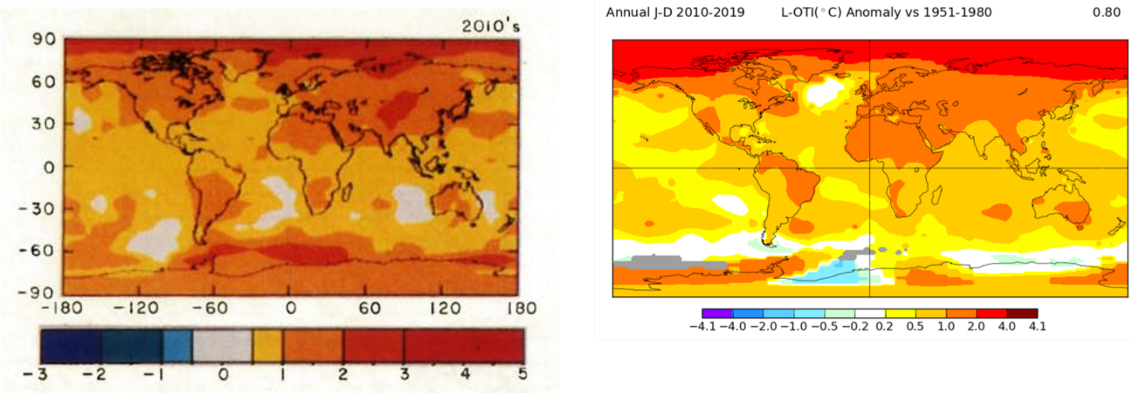


Figure 199: A map of the projected spatial distribution of global surface temperature change in Scenario B for the 2010s from the Hansen study (fair use) and the observed spatial distribution of the GISS temperature anomaly in the 2010s (public domain).

Hansen's study also produced a map of the projected spatial distribution of the global surface temperature change in Scenario B for the 2010s. We can compare this map with observed global temperature maps to evaluate the accuracy of the Hansen model's spatial distribution. This map from NASA's Goddard Institute for Space Studies shows the global surface temperature anomaly in the period 2010–2019 with respect to the 1951–1980 baseline.

Although the actual amount of warming has been less than projected in Scenario B, this is due to the fact that Hansen's climate model projected a higher rate of warming due to a high climate sensitivity. However, as you can see, the Hansen model correctly projected amplified warming in the Arctic, as well as hot spots in northern and southern Africa, west Antarctica, and more pronounced warming over the land masses of the northern hemisphere, among other things. The spatial distribution of the observed warming is very close to his projections.

Hansen's work was stunningly accurate quite frankly given the computational limitations of the mid-1980s when his projections were simulated. Modern climate models have a grid resolution of a degree or less. Hansen's model had a far coarser grid. His model grid was 8° × 10°. Given the effect that grids have on the need to parameterise climate processes, we can understand the source of the Hansen model's high climate sensitivity.

Hansen's work received a great deal of criticism from climate change deniers. A lot of the criticism of Hansen's work was made in the decade after publication. Given the horizon needed to evaluate the quality of Hansen's work this suggests that other biases were at play in the criticism. A number of commentators focussed on the worst-case scenario projections. A more appropriate approach to criticising Hansen's work would be to identify which of the three scenarios has been realised. The closest scenario to the actual evolution of the greenhouse gases in the atmosphere would have been Scenario B. However, the accuracy of Scenario B would not feed into the narrative that the climate change deniers wished to present.

Before we move on, I want to highlight the recognition given to climate science by the Nobel Committee for Physics. In 2021, the Nobel Prize for Physics was awarded to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi *"for groundbreaking contributions to our understanding of complex physical systems"*. Manabe and Hasselmann were awarded *"for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"*. Parisi was awarded for more generally helping us understand variability in complex systems.

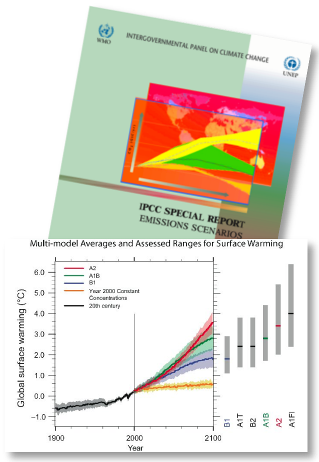
Figure 200: Photographs of Syukuro Manabe (left, CC by 2.0), Klauss Hasselmann (centre, fair use), and Giorgio Parisi (right, fair use).

I want to note in particular Manabe's contribution. Although Svante Arrhenius was the first to estimate the increase in surface temperature due to a doubling of CO_2, Manabe was the first to perform a computational experiment in which CO_2 was doubled. Further, Manabe was one of the first people to use a realistic distribution of land masses and a mixed-layer model of the very upper ocean in his modelling. He was also one of the first scientists to show that how clouds were parameterised had a large effect on a model's climate sensitivity.

I know that the atmospheric models I used during my early research career were built on Manabe's work. In part, some of the code was identical. We were standing on the shoulders of a giant.

15.2.2 Narratives of the Future

We have just seen that Hansen and colleagues developed emissions scenarios to describe possible futures. This enabled Hansen to explore future climate change and to argue why mitigation is important. Since then, this approach to exploring future climate change has become far more sophisticated.



In the 1990s, the IPCC published the Special Report on Emissions Scenarios. These scenarios were constructed to explore future developments in the global environment. They had storylines, four in total, that highlighted the main scenario characteristics and dynamics, and the relationships between key driving forces. The four storylines combine two sets of divergent tendencies: one set varying between strong economic values and strong environmental values, the other set between increasing globalisation and increasing regionalisation.

The most recent attempt to narrate future climate change is the development of a Scenario Matrix Architecture. This scenario framework was used in the recent Sixth Assessment Report of the IPCC. The construction of this framework was two pronged.

First, a set of Representative Concentration Pathways (or RCPs) were developed that described different levels of greenhouse gases and other radiative forcings that might occur in the future. These pathways were developed to span a broad range of radiative forcing in 2100. The radiative forcings range from 1.9 to 8.5 watts per square metre.

Second, a set of Shared Socioeconomic Pathways (or SSPs) were developed that described how socioeconomic factors may change over the century. These factors include population, economic growth, education, urbanisation, and the rate of technological development. In total five different pathways have been developed that describe how the world might evolve in the absence of climate policy.

The scenario matrix is formed when the different climate change mitigation targets described in the Representative Concentration Pathways are combined with the Shared Socioeconomic Pathways.

So, what are these narratives of the future captured in the SSPs?

The first narrative, SSP1, describes a world of sustainability-focused growth and equality. Titled *Sustainability—Taking the Green Road*, SSP1 narrates a future in which the world shifts gradually toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries.

The second narrative, SSP2, describes a world where trends broadly follow their historical patterns. Titled *Middle of the Road*, SSP2 narrates a future in which the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns.

The third narrative, SSP3, describes a fragmented world of resurgent nationalism. Titled *Regional Rivalry—A Rocky Road*, SSP3 narrates a future in which the world descends into resurgent nationalism, where concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic issues.

The fourth narrative, SSP4, describes a world of ever-increasing inequality. Titled *Inequality—A Road Divided*, SSP4 narrates a future in which highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries.

The fifth narrative, SSP5, describes a world of rapid and unconstrained growth in economic output and energy use. Titled *Fossil-fueled Development—Taking the Highway*, SSP5 narrates a future in which the world places increasing faith in competitive markets, innovation, and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development.

These narratives describe alternative pathways for future society. They present baselines of how things would look in the absence of climate policy, and allow researchers to examine barriers and opportunities for climate mitigation and adaptation in each possible future world when combined with mitigation targets.

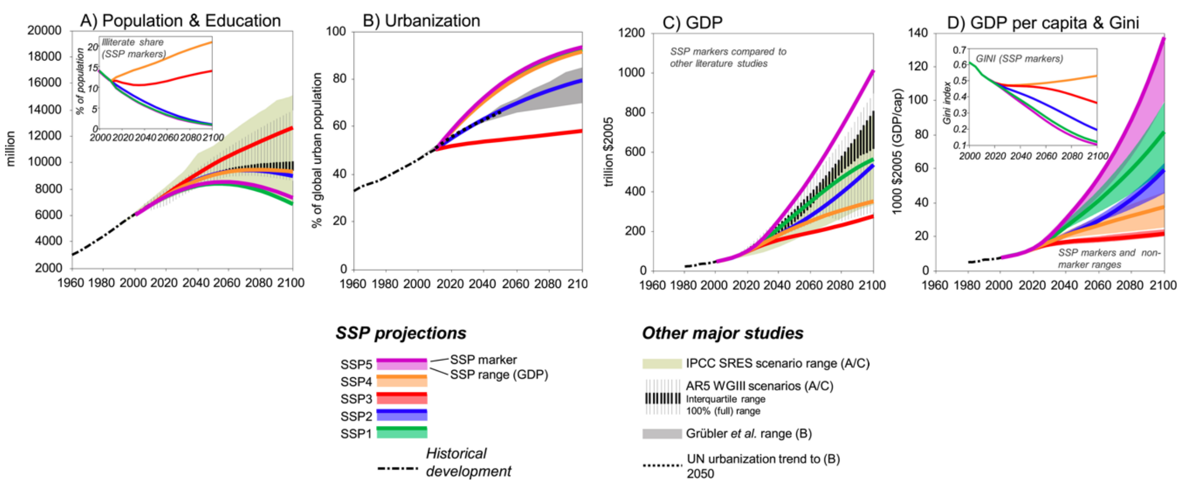


Figure 201: Demographic and socio-economic drivers in the SSPs (fair use).

In figure 9, we can see how these narratives are expressed in terms of their assumptions on global population growth, access to education, urbanisation, economic growth, and levels of inequality.

SSP1 and SSP5 envision relatively optimistic trends for human development, with substantial investments in education and health, rapid economic growth, and well-functioning institutions. They differ in that SSP5 assumes this will be driven by an energy-intensive, fossil fuel-based economy, while in SSP1 there is an increasing shift toward sustainable practices.

SSP3 and SSP4 are more pessimistic in their future economic and social development, with little investment in education or health in poorer countries, coupled with a fast-growing population and increasing inequalities.

SSP2 represents a "middle of the road" scenario in which historical patterns of development are continued throughout the 21st century.

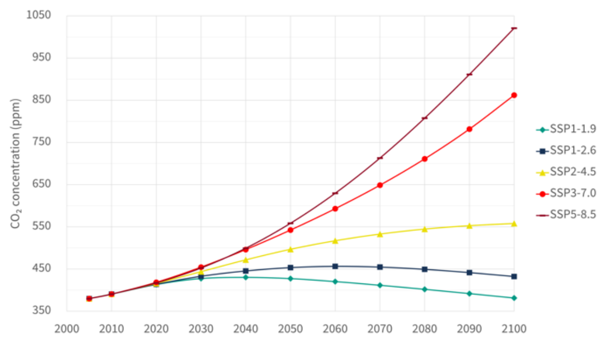


Figure 202: Graph showing future carbon dioxide concentrations according to the different SSPs (CC BY-SA 4.0).

Figure 10 shows how CO_2 concentrations will evolve under different SSPs in order to meet certain mitigation targets described by the RCPs. The RCP1.9 and RCP2.6 pathways require very stringent mitigation efforts and will require negative net carbon emissions to kick in around the middle of the century in order to reduce CO_2 concentrations. These two pathways are shown here achieved using the SSP1 narrative. (Note that the RCP1.9 pathway is the only pathway that supports a mitigation target in which warming is limited to below 1.5 °C.) The less stringent RCP4.5, RCP7.0 and RCP8.5 pathways have been achieved under the SSP2, SSP3 and SSP5 narratives respectively.

Can all Representative Concentration Pathways be achieved under all Shared Socioeconomic Pathways?

The answer is no. Figure 11 shows a combination of SSP and RCP model runs, with RCPs listed in order of increasing mitigation and SSPs in the rough order of increasing mitigation difficulty. The ratios in each cell indicate the number of models that succeeded in making the scenario "work" out of the total number of models used. Note that the models have significant difficulty in achieving RCP1.9 and RCP2.6 targets in either an SSP3 world or SSP5 world. The RCP1.9 mitigation target can only be achieved by all models used under an SSP1 narrative.

These scenarios give us the necessary information to force climate models and to help us determine what future worlds will look like, what the effect on climate will be in these possible future narratives.

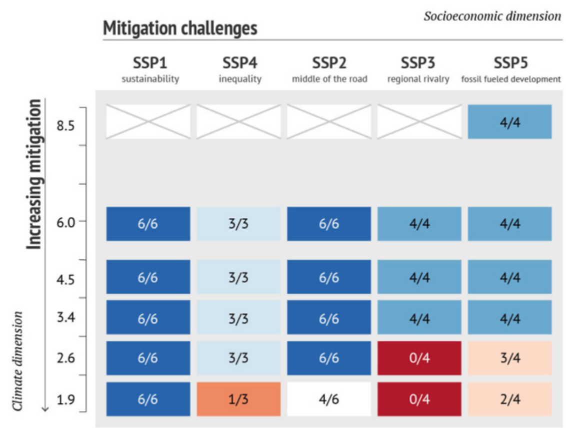


Figure 203: the combination of SSP and RCP model runs in the SSP database, with RCPs listed in order of increasing mitigation and SSPs in the (rough) order of increasing mitigation difficulty (fair use).

Inherent in our ability to project the future climate state is the need to describe the future. These narratives try to account for future geopolitical and socioeconomic factors. In developing these narratives, climate scientists want to encompass how the future will eventually unfold; that our future trajectory will find a path within these narratives. It is hoped that our future trajectory will avoid the extremities of climate mitigation and adaptability. Within these scenarios, climate scientists have attempted to determine whether we will have the faculty to limit the future climate state to certain radiative forcings; essentially limit our future to certain levels of greenhouse gas emissions. Given our current position in this timeline, models indicate that we need to limit future greenhouse gas emissions to the lowest levels considered if we want to limit temperature rises to below 2 °C. It is also clear that such a future is only possible in a subset of future narratives. This is the danger; not only do we need to restrict greenhouse gas emissions, but our ability to do so is now limited to a subset of future socioeconomic pathways.

15.2.3 Projections of Climate Change

We know that climate change has happened and is happening. And we know why it has happened and is happening. The Sixth Assessment Report of the IPCC states that global average surface temperature has increased, that September Arctic sea ice area has decreased, that global average sea level has increased, and that global ocean surface pH has decreased. These are all indicators of global climate change.

The Sixth Assessment Report further states that climate change is already affecting every inhabited region across the planet with human influence contributing to many observed changes in weather and climate extremes.

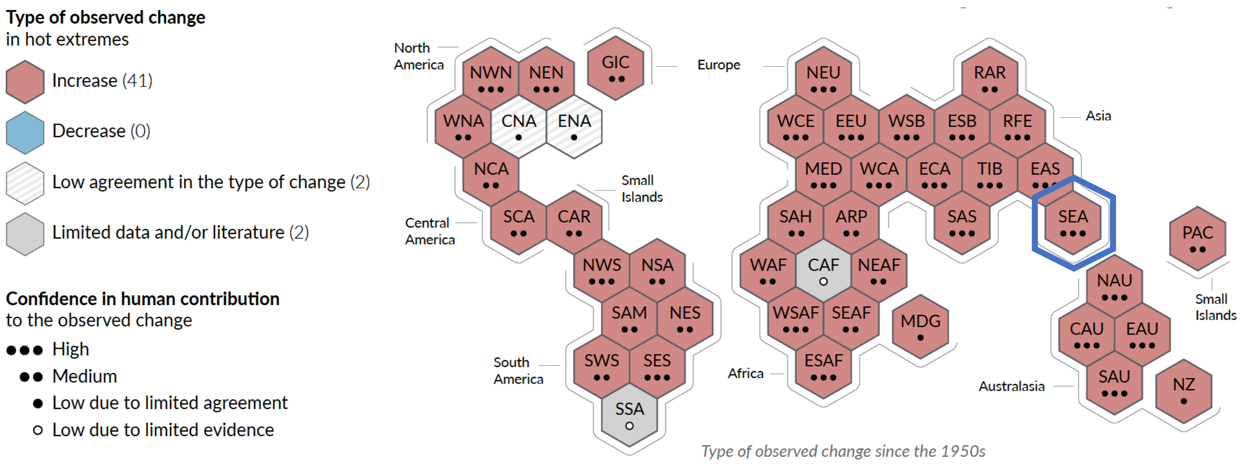


Figure 204: Assessment of observed change in hot extremes and the confidence in human contribution (fair use).

Figure 12 shows the assessment of observed change in hot extremes and the confidence in human contribution to the observed changes in the world's regions. This assessment is mainly based on changes in metrics based on daily maximum temperatures. The hexagons represent different world regions. The colours represent the outcome of the assessment. The red colour indicates that there is at least medium confidence. The confidence level for human influence on these observed changes is based on assessing trend detection and attribution, and is indicated by the number of dots: Three dots represent high confidence; two dots represent medium confidence; and, one dot represents low confidence. Note that in the SEA region for South East Asia, there has been an increase in hot extremes and there is high confidence that this increase is due to human influence.

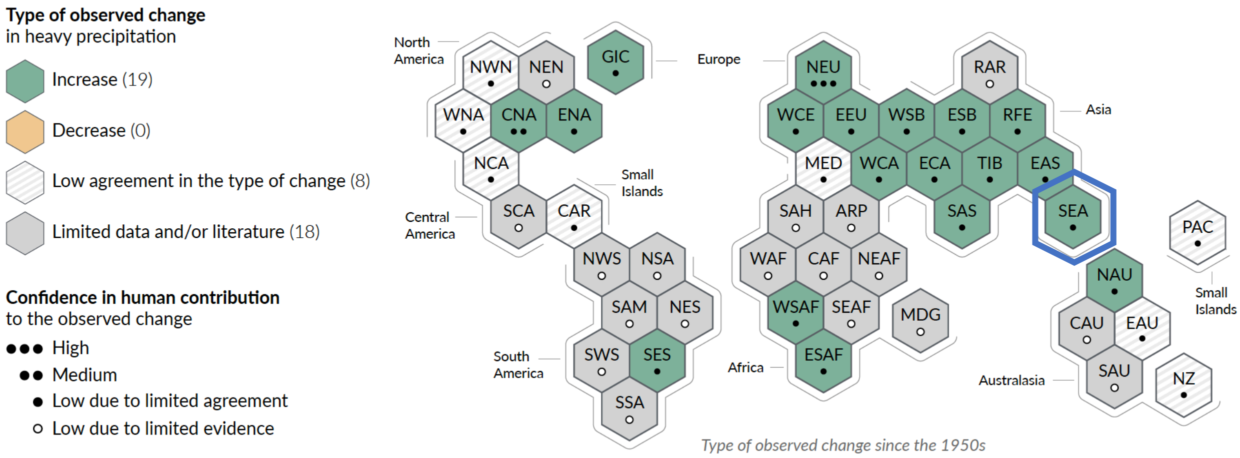


Figure 206: Assessment of observed change in heavy precipitation and confidence in human contribution (fair use).

Figure 13 shows the assessment of observed change in heavy precipitation and confidence in human contribution. This assessment is based on changes in indices of one-day or five-day precipitation amounts. Note again that in South East Asia, there has been an increase in heavy precipitation although with low confidence that it is due to human influence.

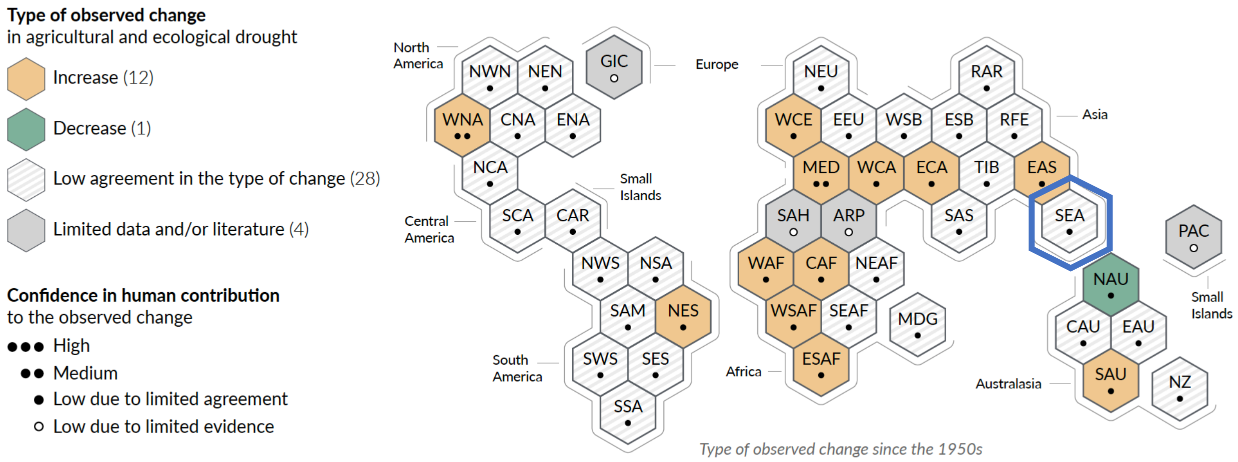
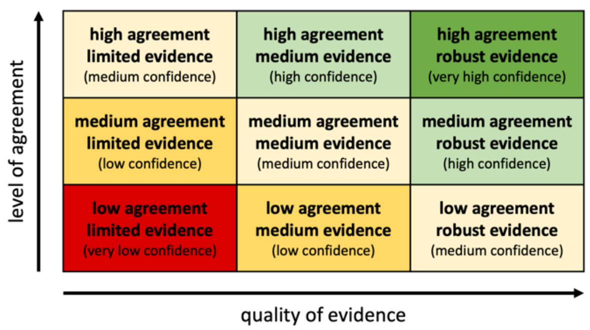


Figure 205: Assessment of observed change in agricultural and ecological drought confidence in human contribution (fair use).

Figure 14 shows the assessment of observed change in agricultural and ecological drought. This assessment is based on the observed and simulated changes in total column soil moisture. Currently there is low agreement in the type of change that is happening in South East Asia.

Okay, but what do climate models project for the future?



Likelihood Terminology	Likelihood of occurrence
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

Before looking at projections, you will have noticed that terminology has been introduced for the level of confidence in the assessment of the IPCC in their reports. This level of confidence is based on a combination of the level of agreement and the quality of evidence. A low degree of confidence translates to a 20% chance of being correct, a medium degree of confidence to a 50% chance, a high degree of confidence to an 80% chance of being correct, and a very high degree of confidence to a 90% chance of being correct.

When we look at projections, the IPCC will describe the likelihood of the results discussed using this scale. A “likely” occurrence has a 66% chance of happening, for example, a “very likely” occurrence has a 90% chance of happening, and a “virtually certain” occurrence has a 99% chance of happening.

In his fourth lecture, Professor Bettens discussed uncertainty, confidence levels and intervals. You may remember that in my first two lectures I reported on the work of James Hansen in the 1980s. He had argued on the basis of the magnitude of natural variability that it was “99% certain” that climate change had happened. As the IPCC reports evolved, it was clear that the language used needed to be simplified to effectively communicate with non-scientists. There was a conscious effort by climate scientists to convert the jargon around confidence and likelihood into language that could be readily understood by policy makers. This is the reason why terminology like “very likely” and “virtually certain” was introduced and how that was equated to the probability of occurring.

Back to the projections then, what are they?

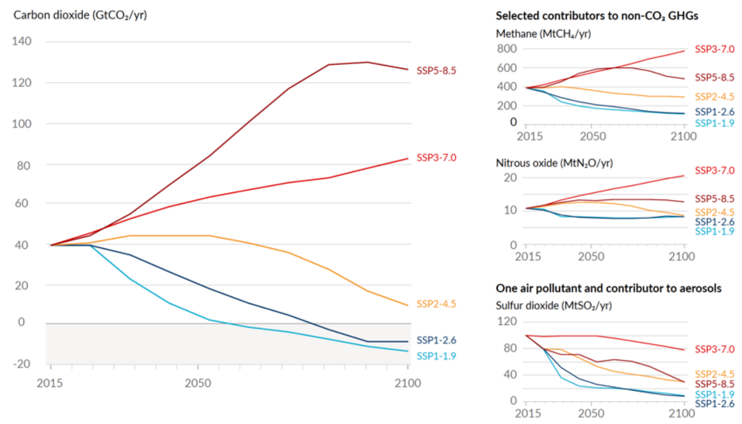


Figure 207: Projected greenhouse gas emissions in five illustrative scenarios (fair use).

The IPCC in their Sixth Assessment Report focused on five illustrative scenarios: SSP5-8.5, SSP3-7.0, SSP2-4.5, SSP1-2.6, and SSP1-1.9. The simulations begin to be forced by these scenarios in 2015. The scenarios with high and very high greenhouse gas emissions, that is SSP3-7.0 and SSP5-8.5, have CO_2 emissions that roughly double from current levels by 2100 and 2050 respectively. The scenario with intermediate greenhouse gas emissions, SSP2-4.5, has emissions that stay around current levels until the middle of the century. The scenarios with very low and low greenhouse gas emissions, SSP1-1.9 and SSP1-2.6, have emissions that decline to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions.

Okay, what did these scenarios project for temperature?

This figure shows the temperature change relative to an 1850–1900 baseline. The very likely ranges are shown for the SSP1-2.6 and SSP3-7.0 scenarios. Compared to 1850–1900, global surface temperature averaged over 2081–2100 is very likely to be higher by 1.0 °C to 1.8 °C under the very low greenhouse gas emissions scenario, that is SSP1-1.9, by 2.1 °C to 3.5 °C in the intermediate scenario, that is SSP2-4.5, and by 3.3 °C to 5.7 °C under the very high greenhouse gas emissions scenario, that is SSP5-8.5.

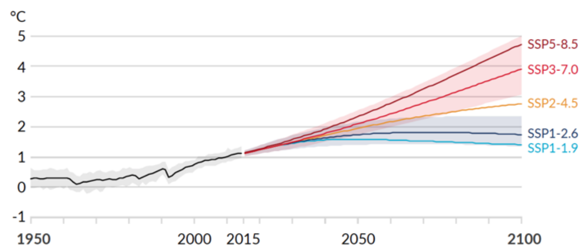


Figure 208: Projected global surface temperature change relative to 1850–1900 (fair use).

The last time global surface temperature was sustained at or above 2.5 °C higher than 1850–1900 was over 3 million years ago. The simulations indicate that global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5 °C and 2 °C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.

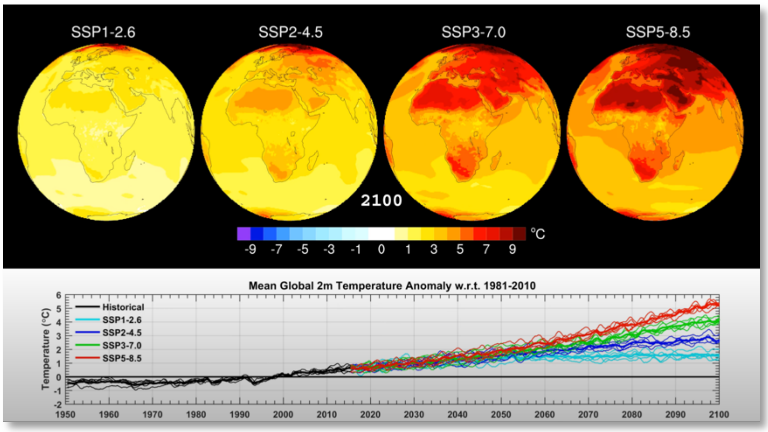


Figure 209: Irish Centre for High-End Computing global climate temperature visualisation (fair use). Click on image to open YouTube video.

While Earth's average global temperature is rising, the amount of warming is not equal in all areas of the world. Figure 17 shows the end of a series of simulations performed by the Irish Centre for High-End Computing. (Click on the image to open a YouTube video showing the full visualisation.) This visualisation shows how temperature changes will be distributed across the globe for four out of the five scenarios discussed. Note that the baseline period is different. The baseline here is 1981–2010. As the simulations progress you can see that the oceans warm more slowly than land because it takes much more heat to warm water than land. In general, the middles of continents are expected to warm more than coastal areas. Regional topography such as mountain ranges will influence this too. At high latitudes, especially in and near the Arctic, temperatures are warming faster than places closer to the equator. The Arctic is heating up about twice as quickly as the global average.

Singapore is projected to see between 1 °C to 2 °C increase in temperature for the low greenhouse gas emissions scenario, to between 4 °C to 5 °C increase in temperature for the very high greenhouse gas emissions scenario.

Next, let’s look at precipitation.

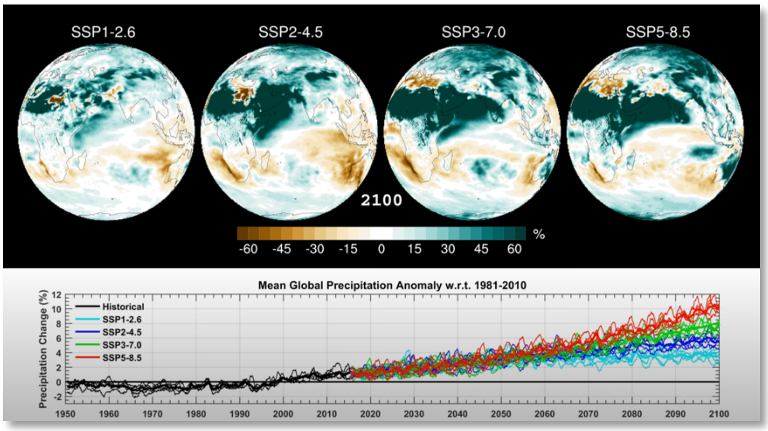


Figure 210: Irish Centre for High-End Computing global precipitation change visualisation (fair use). Click on image to open YouTube video.

Figure 18 shows the end of a series of simulations of annual precipitation change from simulations by the Irish Centre for High-End Computing. (Click on the image to open a YouTube video showing the full visualisation.) Although global average precipitation increases by between 3% to about 10%, this additional precipitation is not distributed evenly around the globe. Much of the increase in precipitation is expected to occur at high latitudes. Increased snowfall near both poles may offset some of the melting of glaciers and ice sheets in these regions by adding fresh ice to the tops of these features. Some places in Antarctica are even gaining more snow via increased precipitation than they are losing to melting caused by rising temperatures.

Some of the increased rainfall is expected to come in the form of more frequent heavy downpours. Some regions may receive a net increase in rainfall, but the increase may manifest itself as heavier rains punctuated by longer dry spells between these deluges. This change in precipitation patterns is likely to cause a greater incidence of flooding, especially in combination with land use changes such as deforestation.

However, many regions near the equator and at mid-latitudes are expected to see decreases in precipitation. Many areas, especially in low- and mid-latitude regions, are expected to suffer from more frequent and more severe droughts. Dry conditions, warmer temperatures that produce longer *fire seasons*, and changes in ecosystems are expected to generate more and larger wildfires in some areas.

Some presently dry regions may be glad to see increased rainfall, just as drier conditions may benefit some currently very wet places. However, heavy rainfall that causes flooding as well as extended or more frequent droughts are likely to be disruptive to ecosystems and agriculture in the afflicted regions.

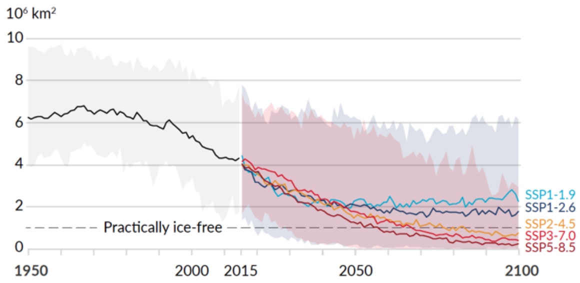


Figure 211: Projections of September Arctic sea ice area (fair use).

Figure 19 shows September Arctic sea ice area. The trends of the last few decades are expected to continue. The Arctic is projected to be practically ice-free near mid-century under intermediate and high greenhouse gas emissions scenarios.

Figure 20 shows the projected changes in global ocean surface acidity. The acidification due to the absorption of carbon dioxide from the atmosphere is expected to continue. (Note that decreasing pH indicates acidification.) Since the Industrial Revolution, the pH has dropped by 0.1 units. This might not sound like much, but the pH scale is logarithmic, so this change represents approximately a 30% increase in acidity. The low greenhouse gas emissions scenarios do project a recovery of pH before the end of the century, but the intermediate and high greenhouse gas emissions scenarios all project continued decline. This will further impact many ocean species like oysters and corals that make hard shells and skeletons by combining calcium and carbonate from seawater. If the pH gets too low, shells and skeletons can even begin to dissolve.

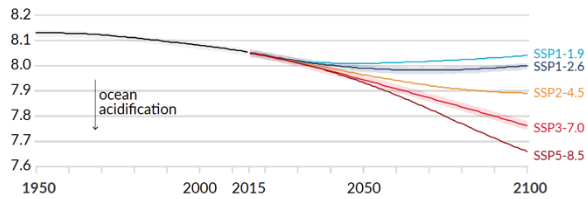


Figure 212: Projections of global ocean surface pH (fair use).

What about sea level?

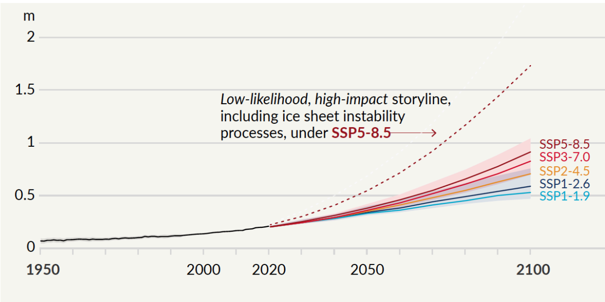


Figure 213: Projections of mean sea level change relative to 1900 (fair use).

This figure shows global average sea level change relative to 1900. It is virtually certain that sea level will continue to rise over the 21st century. By the end of the century, it is likely that sea level will rise by between 0.48–0.78 metres under the low greenhouse gas emissions scenario, and by between 0.79–1.17 metres under the very high greenhouse gas emissions scenario. Global average sea level rise above the likely range, approaching 2 metres in the very high emissions scenario, cannot be ruled out due to the deep uncertainty in ice sheet processes.

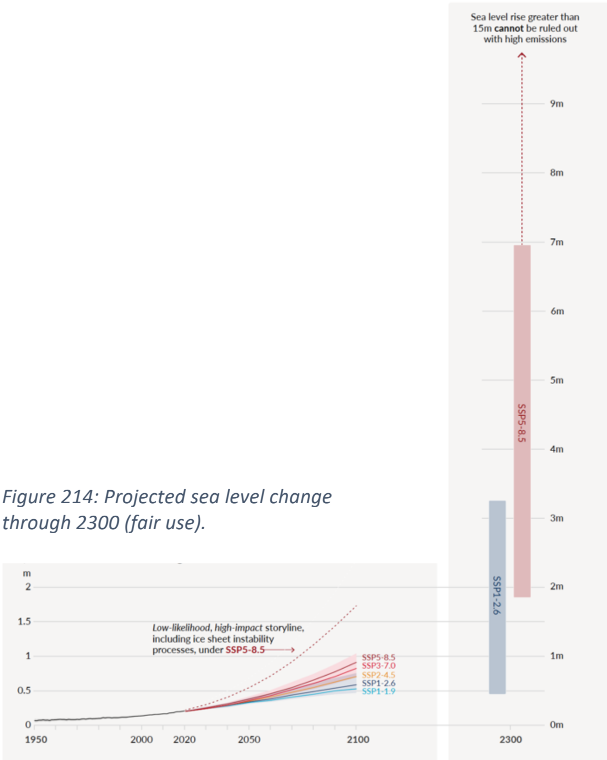


Figure 214: Projected sea level change through 2300 (fair use).

In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and will remain elevated for thousands of years. This figure shows the projected rise in sea level by 2300 in the low and very high greenhouse gas emissions scenarios. Sea level rise greater than 15 metres cannot be ruled out in the very high emissions scenario.

Qualitatively the trends seen in the climate changes to date are set to continue. There is a great deal of variability in how climate change will evolve in the next century that is highly dependent on which of the scenarios we end up following. It is painfully clear that action to mitigate climate change is urgently needed.

We know that climate change has happened and is happening, and we know why it has happened and is happening. The Sixth Assessment Report of the IPCC describes how the global community has been affected and how it will be affected in the future. This report also describes some of the expected regional changes over the course of this century. We saw the expected regional climate change in South East Asia. Before continuing, I want to emphasise that global climate change has already affected this region.

15.2.4 Climate Change in the Little Red Dot

In the Singapore's *Climate Action Plan: Take Action Today, For a Carbon-Efficient Singapore* report published by the National Climate Change Secretariat, a number of changes to Singapore's climate are noted. Annual mean temperature has risen from 26.6 °C in 1972 to 28.4 °C in 2019 (the joint warmest year on record together with 2016). However, a large fraction of this temperature rise is associated with the urban heat island effect. This effect quantifies the difference in temperature between urban and rural areas. In Singapore, incoming solar radiation heats up roads and bridges and this is compounded by heat being actively emitted by vehicles, power plants, industry, and even air conditioners. Singapore has seen bouts of very intense thunderstorms that have led to flash floods, as well as dry spells. In early 2014, Singapore experienced its longest dry spell since records began in 1869. The expectation is that we will see these records broken time and time again as we move further into the 21st century.

15.3 Safeguarding the Global Commons

The science is clear. Urgent action is needed to limit the effects of climate change. However, as was noted in the last lecture, little to nothing has happened in terms of international agreement on binding targets and timetables for emissions reductions.

Science can tell us what has happened, why it has happened, even what can fix it, but not how we should fix it. Let me explain what I mean by this. The decision of how we should fix it is a decision for society not science. How we should fix it is a question for public policy. Science can inform public policy, but it cannot define public policy.

So, what frameworks should govern the public policy towards climate change on the international arena?

15.3.1 Principles to Govern Action

Given that our main concern is the impact of global warming on human communities, perhaps a good place to start is the Universal Declaration of Human Rights. This Declaration was proclaimed by the United Nations General Assembly in Paris on 10 December 1948. In the Preamble to the Declaration, it is written that,

> *"recognition of the inherent dignity and of the equal and inalienable rights of all members of the human family is the foundation of freedom, justice and peace in the world... ."*[43]

Figure 215: Photograph of Eleanor Roosevelt holding poster of the Universal Declaration of Human Rights in the FDR Presidential Library & Museum (CC by 2.0).

The reference to *"all members of the human family"* has both spatial and temporal dimensions, which brings peoples of all countries and of all generations within its scope. The reference to *"equal and inalienable rights"* affirms the basic equality of all peoples across all generations in the human family. This argues strongly that action must be taken, but what principles should govern action?

There are three principles that are frequently put forward as those that should govern international action.

The *first principle* is the *Precautionary Principle* that states that a lack of scientific certainty should not prevent appropriate action being taken. This principle was acknowledged in Article 3.3 of the United Nations Framework Convention on Climate Change, in which it was stated,

> *"The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects."*[44]

It was included because even in 1992, the threats of climate change were seen as dangerous and potentially catastrophic. It was meant to spur international action, that a lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

The *second principle* is that *Polluters Should Pay* for the damage of their pollution. This is a well-known principle that has been written into environmental legislation for a long time. It recognises that carbon dioxide and many other greenhouse gases are global pollutants, they affect the global commons. The principle is acknowledged in Principle 16 of the Rio Declaration on Environment and Development, which states,

> *"National authorities should endeavour to promote the internalization of environmental costs and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment."*[45]

Some developing countries are asking for reparations from rich countries for the climate change impacts they are already suffering on the basis of this principle.

And the *third principle* is that of *Equity*—both intergenerational and international equity. This principle is recognised, as just discussed, in the Universal Declaration of Human Rights. Intergenerational equity argues that we hold the natural environment of our planet in common with all members of our species: past generations, the present generation, and future generations. As members of the present generation, we hold

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[43] The United Nations (1948). *Universal Declaration of Human Rights*.
[44] The United Nations (1992). *United Nations Framework Convention on Climate Change*.
[45] The United Nations (1992). *Rio Declaration on Environment and Development*.

the Earth in trust for future generations. At the same time, we are beneficiaries entitled to use and benefit from it. These ideas are further acknowledged in Article 3.1 of the United Nations Framework Convention on Climate Change, which states,

> *"The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof."*[46]

Article 3.1 also makes it clear that developed countries should take the lead in combatting climate change partly because many such countries have a legacy of historical emissions that they used to industrialise.

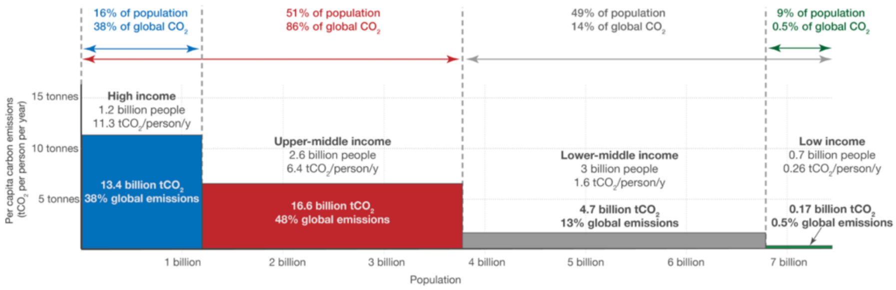


Figure 216: Graphic recognising the global inequities in CO_2 emissions (fair use).

Of the three principles, the most difficult to apply is that of equity. At the moment, in terms of income, the richest half, that is the high and upper-middle income countries, are responsible for 86% of global CO_2 emissions. The bottom half, that is the low and lower-middle income countries, are responsible for only 14%. The UNFCCC recognises this inequity by a clause that states that, because the industrialised countries have benefitted so much from fossil fuel burning, they should take the lead and the first action in combating the problem and reducing emissions.

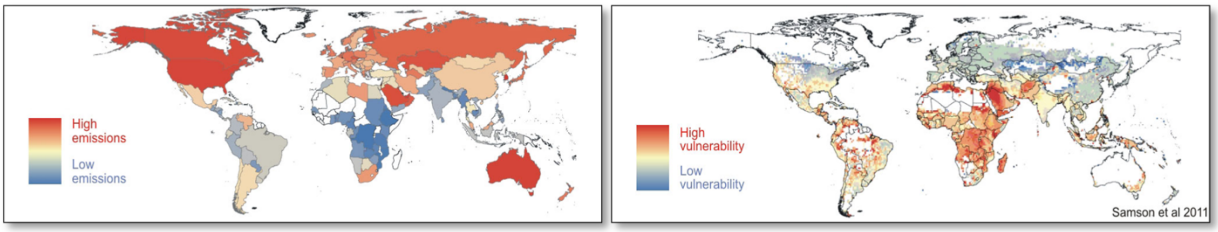


Figure 217: Graphics indicating CO_2 emissions per capita and vulnerability to climate change (fair use).

Figure 24 further recognises the inequity. It shows that the countries who contribute least to greenhouse gas emissions will be most impacted by climate change.

[46] The United Nations (1992). *United Nations Framework Convention on Climate Change*.

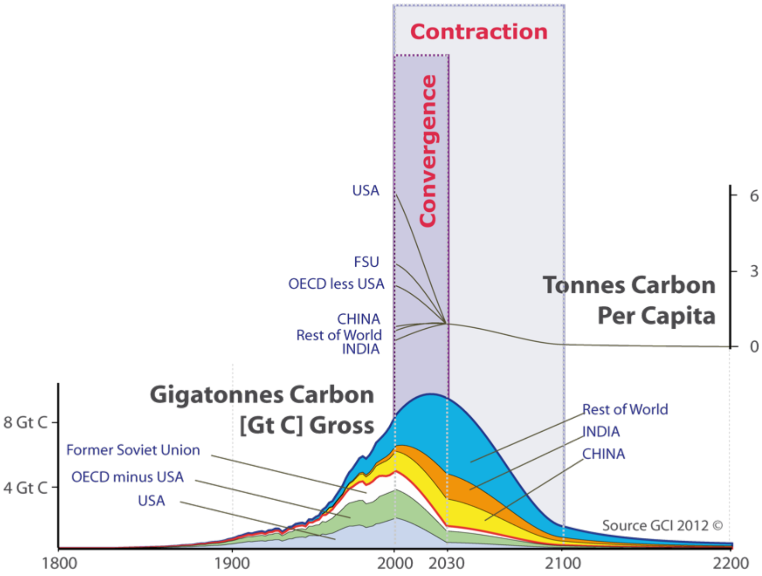


Figure 218: The rates of global Contraction and Convergence in 6 regions for a 450 ppm contraction budget with convergence by 2030 (fair use).

So, what sort of action is necessary?

One proposal that was put forward by the Global Commons Institute is called Contraction and Convergence. This figure illustrates how it works. It proposes stabilisation of atmospheric CO_2 at an agreed level. In this example, the level has been set at 450 ppm. This is approximately the level that would result in about a 2°C increase in global average temperature over pre-industrial levels. The first part of the proposal is that the world as a whole agrees to follow the envelope curve—this is the 'contraction' part of the proposal. The second part of the proposal is that eventually, from say 2030, CO_2 emissions should be allocated to countries so as to share the emissions equally between all humans. Between now and 2030, emissions need to converge to their 2030 allocations—this is the 'convergence' part of the proposal. This proposal recognises international equity as meaning that emissions should be shared on a per capita basis. This may sound completely unrealistic, but there is a third part of the proposal that allows for trading of emissions. Those that have more than they need can sell to those that want to emit more. The effect of trading would be to move money from developed nations to developing nations; that money could be used to help developing nations industrialise in sensible ways and to develop appropriate non-fossil fuel energy systems.

There are enormous problems, political, practical, and even possibly ethical, in the details of the Contraction and Convergence proposal, or indeed any other proposal that can be envisaged. But it does well to illustrate some of the essential principles that have to underlie the necessary action and the scale and the enormous challenge it presents to all countries of the world.

The issue of equity poses important questions. Which climate change risks should those living today be allowed to impose on future generations? How do we balance the rights of future generations with those alive today? How does uncertainty of the future factor into this calculus?

There is a normatively significant difference between actions which impose a major life-threatening, existential risk on others (no matter whether we are talking about present or future generations) and actions which impose limited minor risks. What are the criteria which allows one to distinguish between morally permissible and morally impermissible risk impositions on future generations?

These are some of the most pressing questions for climate ethicists. You are members of the society that will decide.

15.3.2 Mitigating Climate Change

So, how should we go about mitigating the effect of climate change? From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gases.

Let's suppose that we want to limit global warming to 2°C over pre-industrial levels. To achieve such a goal without negative CO_2 emissions we have to limit the cumulative amount of carbon emitted since the beginning of the Industrial Revolution to 1 trillion tonnes. (This amounts to around 3.7 trillion tonnes of carbon dioxide.) One trillion tonnes of carbon emitted would likely limit us to 2°C rise in temperature. Such a limit has been argued would avoid the worst impacts of climate change. However, recent projections have suggested that a 1.5°C limit may be required.

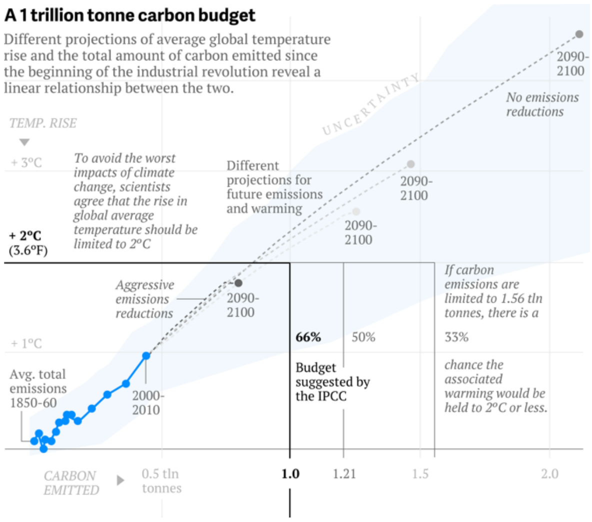


Figure 219: Graphic illustrating the relationship between temperature rise and total amount of carbon emitted (fair use).

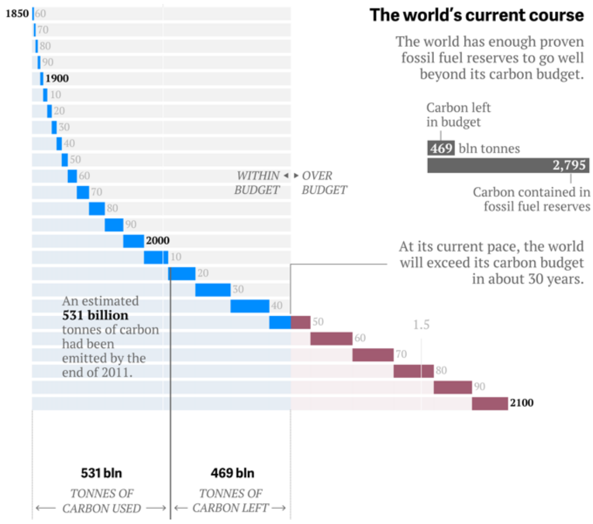


Figure 220: Graphic identifying the remaining carbon before exceeding the one trillion tonne budget (fair use).

Figure 27 shows the roughly linear relationship between temperature rise and total amount of carbon emitted. Only the very low and low greenhouse gas emissions scenarios avoid a total carbon emission of 1 trillion tonnes being exceeded by 2050.

The world has enough proven fossil fuel reserves to go well beyond this carbon budget of 1 trillion tonnes. Figure 27 shows that to keep under this budget, we need to limit our future carbon consumption to about 400 billion tonnes. At our current pace of consumption, we will exceed the 1 trillion tonne budget by around 2045.

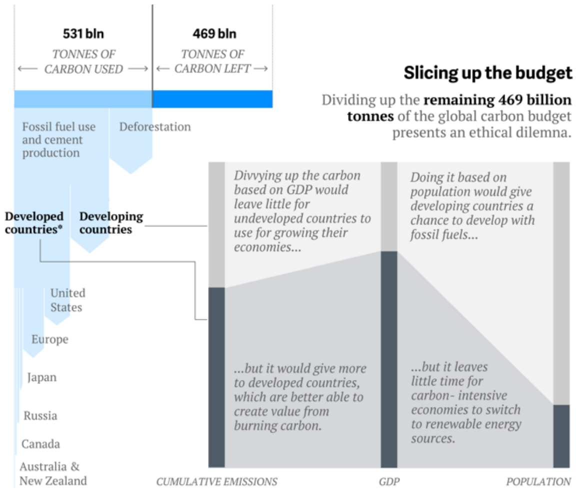


Figure 221: Graphic illustrating how the remaining carbon could be shared (fair use).

This does beg the question as to how we should slice up this budget. Divvying up the carbon on the basis of GDP would leave little for developing countries to use for their growing economies, but would give more to developed countries, which are better able to create value from burning carbon. Doing it on the basis of population would give developing countries a chance to develop with fossil fuels, but it leaves little time for carbon-intensive economies to switch to renewable energy sources.

The magnitude of the problem of mitigating climate change seems beyond our capabilities. Early debate saw the problem as needing a *silver bullet*: a single, optimum technology that could be deployed to get us from today's carbon-glutinous energy system to the carbon-free energy system of the future. Steven Pacala and Robert Socolow argued that we should be using buckshot rather than a bullet; that is, instead of finding any one single low-carbon technology to deploy, we should be taking a more diversified approach.[47] In this approach we can think of any single technology that would lower carbon emissions as an 'emissions stabilisation wedge', which, if deployed, could by itself avoid a modest one billion tonnes of carbon emissions per year. (We currently emit

[47] Pacala, S., and Socolow, R. (2004). Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, *Science*. **305(5686):** 968–972.

about ten billion tonnes of carbon per year.) While no single one-billion tonne wedge would be adequate to avoid dangerous climate change, a combination of stabilisation wedges could be. Figure 30 imagines the need for nine such wedges to stabilise emissions.

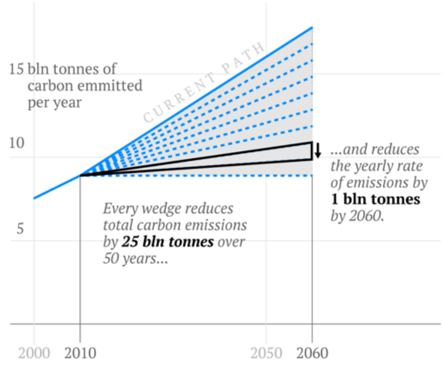
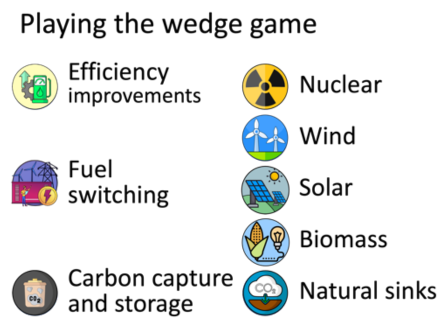


Figure 222: Graphic illustrating the stabilisation wedges strategy (fair use).



How could this be achieved? Well, Pacala and Socolow recognised that the technology already exists. Such technology wedges could be achieved through efficiency. For example, double the fuel efficiency of 2 billion cars from 30 to 60 miles per gallon, decrease the number of car miles travelled by half, use best efficiency practices in all residential and commercial buildings, or produce current coal-based electricity with twice today's efficiency. It could be done through fuel switching, for example, replace 1400 coal electric plants with natural gas-powered plants. It could be achieved through carbon capture and storage. For example, capture and store emissions from 800 coal electric plants, produce hydrogen from coal at six times today's rate and store the captured carbon, or capture carbon from 180 coal-to-synfuels plants and store the captured CO2. Through nuclear, for example, by adding double the current global nuclear capacity to replace coal-based electricity. Through wind, for example, by increasing wind electricity capacity by 10 times relative to today, for a total of 2 million large windmills. Through solar, for example, by installing 100 times the current capacity of solar electricity, or by using 40,000 square kilometres of solar panels to produce hydrogen for fuel cell cars. Through biomass fuels, for example, by increasing ethanol production 12 times by creating biomass plantations with area equal to 1/6th of world cropland. And through natural sinks, for example, by eliminating tropical deforestation, or adopting conservation tillage in all agricultural soils worldwide.

Although no single strategy will suffice, a combination of the technological strategies described here will build the stabilisation required.

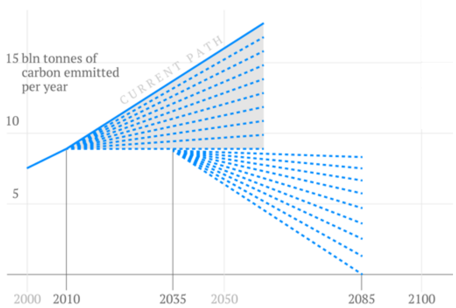


Figure 223: Graphic illustrating the additional wedges needed to reach net zero (fair use).

However, further wedges will be required to bring the world down to no carbon emissions. In addition to technology wedges, we may need behavioural wedges, such as cutting driving in half, cutting projected meat consumption by a third, or cutting projected miles flown by a third.

Breaking the problem down into manageable chunks does seems to provide a vision of the possible.

15.3.3 Tipping Points in the Climate System

The dangers of unmitigated climate change were put in stark relief in a paper published in September 2022 in the journal *Science*. David Armstrong McKay and colleagues identify a series of climate tipping elements and the threshold temperatures beyond which they become unavoidable.[48]

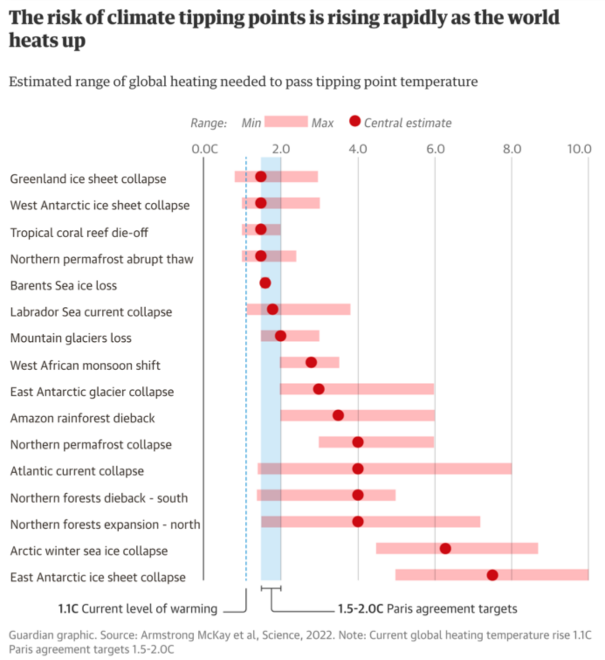


Figure 224: Graphic indicating the threshold temperatures for a variety of climate tipping points (fair use).

Figure 32, taken from the *Guardian* newspaper, illustrates the temperature thresholds beyond which these climate tipping elements will become unavoidable. The study synthesises the most current evidence on how much warming would risk passing 16 tipping points, triggering polar ice collapses, permafrost thawing, monsoon disruptions, and forest and coral reef diebacks. Many of these systems are already stressed by rising temperatures, and the study finds the world might already be within the warming range where the risk is elevated. It also concludes that even under the most ambitious scenario for limiting global warming—to 1.5°C compared with pre-industrial levels—the planet could still see dramatic changes.

At the current level of global warming—1.1°C since the pre-industrial era—Earth has already passed the low-end risk estimate for five tipping points, putting coral reefs, permafrost, and polar ice at risk. Holding global warming to 1.5°C to 2°C—the rough goal of the Paris agreement—could mean exceeding the best estimates for seven tipping points, causing the loss of mountain glaciers and the disruption of key ocean currents.

The work has synthesised a huge amount of evidence and makes it easier for policymakers and others to see how societal choices could help avoid, or hasten, tipping points. There is a danger though with such studies. The focus on specific temperature thresholds could feed arguments that nothing can be done to keep warming to safer levels.

So, will this work energise efforts to curb climate change or feed public apathy?

15.4 The Danger of Certainty

15.4.1 Tour d'Horizon

Over the last few lectures, we have looked at scientific inquiry through the lens of climate change. We have looked at how scientists discovered the mechanisms by which the Earth's surface is warmed by the presence of greenhouse gases in the atmosphere. Recognising the influence of greenhouse gases, we saw how scientists were able to predict the consequences of increasing the atmospheric concentrations of CO_2. We learnt how doubt about climate change was used to prevent regulation being enacted to mitigate climate change. We delved into why the public is susceptible to climate change denial, what types of cognitive bias make us susceptible. It is important that we arm ourselves with a critical thinking arsenal and a basic understanding of

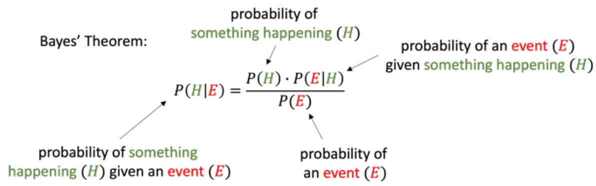
[48] Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, **377(6611):** eabn7950.

climate change if we are to be part of an informed citizenry to engage in the conversation about how humanity should confront the challenges of climate change.

15.4.2 Approaching New Knowledge

It was the space engineer and journalist, James Oberg, who said, *"Keep an open mind, but no so open that your brains fall out"*. How should we approach new knowledge that challenges our own preconceived notions?

A useful approach might be to consider Bayes' Theorem. However, let's not delve too deeply into the mathematics and apply our critical thinking skills. A classic problem you have perhaps all been asked in high school would be to consider the following scenario.



Suppose you wake up in the morning feeling a little rough and decide to visit your GP. The doctor is perplexed by your symptoms and decides to run a battery of tests. When the results come back it appears that you are positive for a rare and nasty illness that only affects 0.1% of the population. Given the nastiness of the illness, but also the discomfort of the treatment, you ask your doctor what are the chances that the test result is wrong. Your doctor tells you that the test is accurate 99% of the time. So, the question is what is the chance that you do indeed have the disease. A naïve reading might lead you to think that it is 99% certain that you have the disease, but as you probably remember this is wrong. Let's determine this critically.

Say we have 10,000 people in a population, 0.1% of that population or 10 people will have the disease. But if we were to test the entire population, then 100 people would falsely test positive (the test has a 1% false positive rate). So that means that the chances you have the disease is 10 chances out of 110 or about 9%. That is not very high and far lower than 99% accuracy of the test.

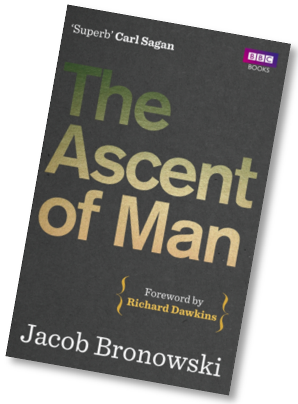
So, you decide to go to another doctor who uses a different laboratory for running tests and you ask for a second opinion. When you get the result back, it is positive again. What are the chances? Well let's suppose that the two tests are independent of one another. What would be the chances of falsely testing positive twice? That would be 1% of 1% or 0.01%. That means in a population of 10,000 people, one person would falsely test positive twice, but of that population 10 people still have the disease. So, now the chances that you have the disease are 10 chances in 11 or about 91%.

What have we learnt from this analysis? The maths is entirely unimportant. I used Bayes' Theorem as a metaphor. The take-home message is that as more evidence comes in we need to update our estimates as to whether something is true, even if our perceived chance of it being true, 0.1% chance in this example, is very small. We need to be open to new evidence as it can have a dramatic effect on how we evaluate a position. The challenge is to be receptive to evidence, and to properly evaluate its importance, especially when that evidence contradicts our preconceived notions.

15.4.3 Bias is a Human Condition

We are all susceptible to bias, to take on different forms of denial. I remember in the early 2000s, when the research about the carbon footprint of various diets was beginning to be published that showed meat having a larger footprint than vegetables. As a meat-eater, I found this research disturbing. I enjoy meat, and yet my diet was contributing to climate change. So, I denied the research, who wants to be the villain? I argued that the research hadn't taken account of changing land use, the carbon cost of deforestation to provide the additional land required to grow the necessary crops. I argued about the degradation through the use of pesticides and fertilisers. However, over time these arguments were tested and still the result that meat production has a greater carbon cost than vegetable production became steadily more robust. I had to swallow my pride and admit that I was wrong. I also had to change my behaviour. Although I still eat meat, I eat far less than I use to. These are the personal changes in behaviour that we can all make. Recognising that our opinions are fallible, being willing to acknowledge our fallibility, and to make lasting change to behaviour.

Let me echo the words of Jacob Bronowski towards the end of the chapter, *Knowledge or Certainty*, in his book *The Ascent of Man*. He said,



> *"Science is a very human form of knowledge. We are always at the brink of the known, we always feel forward for what is to be hoped. Every judgment in science stands on the brink of error, and is personal. Science is a tribute to what we can know although we are fallible. In the end the words were said by Oliver Cromwell: 'I beseech you, in the bowels of Christ, think it possible you may be mistaken'."*

There is a real danger to have absolute certainty, to dogma that closes the mind. Be open to test your reality, don't fall to the arrogance of knowing the truth. I hope that this course has provided you with some of the insight that scientific inquiry provides about how one should go about learning what is true, even if we know we cannot be certain.

Critical thinking consists of seeing both sides of an issue, being open to new evidence that disconfirms your ideas, reasoning dispassionately, demanding that claims be backed by evidence, deducing and inferring conclusions from available facts, solving problems, and so forth. There are many frameworks within which to employ our critical thinking faculties. In this course, we have argued that a valuable approach is to employ the skills of a scientist, and to exercise the elements of science inquiry.

15.4.4 Call to Arms

I want to leave you with two quotations from leaders of your generation. I hope they inspire you. Certainly such leadership inspires me.

The first is from Greta Thunberg who was speaking at the Youth4Climate summit in 2021:

> *"We can no longer let people in power decide what hope is. Hope is not passive. Hope is not 'blah blah blah'. Hope is telling the truth. Hope is taking action. And hope always comes from the people."*[49]

The second is from Amanda Gorman, the U.S. Poet Laureate, speaking at the Biden presidential inauguration again in 2021:

> *"For while we have our eyes on the future, history has its eyes on us."*[50]

Good luck!

[49] Thunberg, G. (2021, September 28). *Keynote speech at Youth4Climate Pre-COP26*.
[50] Gorman, A. (2021). *The Hill We Climb: An Inaugural Poem for the Country*, New York: Penguin Random House.

15.5 What Have You Learnt?

We set ourselves five learning outcomes at the beginning of the lecture. These were that by the end of the lecture, you should be able to:

(1) *Summarise* how climate models prove their reliability through hindcasting and successful forecasting;
(2) *Predict* the effect of feedback loops and discuss the impact of feedback on model projection uncertainty;
(3) *Describe* and *contrast* the climate change projections resulting from possible future climate scenarios;
(4) *Explain* how climate change mitigation strategies relate to principles of equity; and,
(5) *Reflect* on how you incorporate new knowledge into your current understanding and on the danger of absolute certainty.

Take out the notes you made at the beginning of the lecture.

Has your understanding changed?

What new ideas or concepts have you learnt?

How does what you have learnt connect with earlier material?

Again jot down your thoughts. Finally, do you remain unsure about your ability to meet any of the learning outcomes? Below I direct you to which section you will need to revisit to find the material you need to meet the learning outcomes.

To achieve **ILO1**, you should be able to summarise why we have confidence in climate model simulations. You should be able to describe how climate models are tested against past observations. You should further be able to explain why it is necessary to force such models with natural and anthropogenic changes in order to reproduce past observations. You should be able to report on the success on past climate model projections in forecasting future climate. If you are unsure, you should review Sections 8.1.2 and 8.2.1.

To achieve **ILO2**, you should be able to predict how changes in one element of a feedback loop will lead to either a stable result or instability depending on whether the feedback loop is negative or positive. You should be able to identify missing elements from feedback loops based on whether the feedback loop is positive or negative. You should be able to describe why net positive feedback amplifies initial warming, and why parameterisations of feedback mechanisms lead to model projection uncertainty. If you are unsure, you should review Sections 8.1.2 and 8.1.3.

To achieve **ILO3**, you should be able to identify the difference between projection, prediction and scenario. You should be able to describe the shared socioeconomic pathways and representative concentration pathways in terms of challenges to mitigation and increasing mitigation response. For future climate change in terms of global average surface temperature, precipitation, September Arctic sea ice area, surface ocean pH and sea level were presented, you should be able to explain the differences between the results seen in different future climate scenarios. If you are unsure, you should review Sections 8.1.2, 8.2.2, 8.2.3 and 8.2.4.

To achieve **ILO4**, you should be able to identify the different principles used to govern international action on climate change. You should be able to describe how principles of both international and intergenerational equity feature in proposed mitigation strategies. With reference to the contraction and convergence strategy, you should be able to explain how it will stabilise atmospheric carbon dioxide concentrations at levels that will limit global warming to below 2°C over pre-industrial levels. With reference to the emissions stabilisation wedges proposal, you should be able to identify the types of technological and behavioural changes that will be required in order to realise net zero emissions. If you are unsure, you should review Sections 8.3.1 and 8.3.2.

To achieve **ILO5**, you should be able to reflect on how you incorporate new knowledge into the knowledge schemes you already possess, and why it is important that you remain open to new knowledge that may not agree with your current understanding. If you are unsure, you should review Sections 8.4.2 and 8.4.3.

If you feel comfortable with your ability to meet the learning outcomes, then you are ready to try the quiz. Good luck!

12 Fallacies in the Name of Science & Course Wrap Up

Intended Learning Outcomes for the Final Lecture
You should be able to do the following after this lecture.

(1) Provide examples of scientific inquiry within the areas of climate change and ecology in Singapore by *relating* concepts and/or content from blocks 2 and 3 of this course to block 1.
(2) Provide examples illustrating how concepts and content taught in the HSI1000 course can be directly applied in everyday life and outside of the University community.
(3) *Describe* each of the eight fallacies put forth in the name of science, providing examples to illustrate their meaning.
(4) *Explain* the three ways that we cannot use to distinguish science from pseudoscience, and the four features that do distinguish science from pseudoscience.

In this lecture we'll firstly be making it clearer to you the relationship between the general elements of scientific inquiry we learnt about in the first block and the applications of it in the latter two blocks. Next, we'll move onto the final chapter in our textbook, "Fallacies in the Name of Science". We break the chapter into two sections, the first being on the fallacies, and the second discussing pseudoscience.

16 12.1 One more thing…

Below is an illustrated and heavily edited transcript of 12.1. The speakers can be identified using the following legend. Some of the speaker's text has been rewritten for clarity. It is a recommended read along with the video.

- Prof Ryan Bettens: RB
- Prof Adrian Lee: AL
- Prof Siva: SN
- Prof Seow Tek Keong: TK

RB: Okay, so welcome everyone to this last lecture of this course, which is a fairly short lecture. We've only got three videos of which this is going to be one. The other two videos are going to be covering the last chapter of our textbook. In this particular video, I'd like to sort of get an overall view of how the three blocks all work together to produce a holistic, entire course, which leads me to the first question I'm going to ask to Prof Lee.

16.112.1.1 Block 2 Key takeaways and connections to Block 1

RB: The students have all finished Block 2 as well as Siva's and Teck Keong's block (Block 3). So, thinking about that and the workshops that they've gone through, what do you feel is the most important message you'd like the students to have taken home or received?

AL: Well, I think that it's important that they recognize that this is an integrated course. So that the things you, for instance, were talking about in the first part, especially the baloney detection toolkit, in my block, I was using that, in order to, to be able to sort of critique some of the information and misinformation that is spoken about in terms of climate change. I feel as if that element of it was by far the most important thing that students can take away with them because it is vital skills really to be able to use in their own lives to critique what you know. That is, what is quality information and what is poor information. I think that's going to be a really powerful thing that they'll be able to take away from this course, apply it [the BDTK] throughout their career as a student, but also, outside of university life as well.

16.212.1.2 Block 3 Key takeaways and connections to Block 1

RB: And the same question goes to you two [TK and SN] as well. So, they've just, well, hopefully they've all should pretty much have finished the workshop for block 3 by now. So, having done block 3 and the workshops, what do you also think is the most important message that you'd like the students to have taken home with them?

SN: Well, in the first webinar we talked about how excited we were that they were going to be applying the scientific method. They were seeing that there's a definite philosophy behind how we approach problem solving. And, by block 3, having experienced the earlier two blocks, they now practiced it, and they get to apply it in the labs. In block 3 they get to apply it in a situation in Singapore. They are asking questions of statements that are made quite regularly in the media and in our lectures. They go and demonstrate that, okay, there's actually a basis behind it. You can accumulate data to provide evidence that you test against an idea. So that's a critical skill, as part of their problem-solving tool kit. So, whether they are from the humanities or the sciences, this will be a fundamental tool that they take with them, like Adrian (AL) says, throughout their undergraduate career and beyond.

TK: And taking on from that, yes, just not our block, but also Adrian's (AL) block. There were many concepts that were introduced, and it is our hope that you do not focus on the concepts alone, but to see that the concepts were derived using the scientific method – that they were not plucked out of thin air. It's not someone's imagination. A lot of work has been done to be able to establish the concepts. We've tried to give you some form of evidence to show that the concepts are real, the concepts are tested, the concepts can be relied upon. I think that is very important, as you go on to take other courses, whether it be science based, social sciences, or even the humanities, there will be concepts that you will be learning. The question is, were these concepts people's imagination, or were these concepts derived after looking at all the available evidence? Later on in life too, in fact, in every day life, we are bombarded by various claims. Are they reliable, or are they not?

AL: I think one of the things that students should take away is quite frankly that there is value in thinking like a scientist. Whether you're a scientist or not, that the kind of skills that you witness during this course have value to you and will put you in good stead for how you approach things in life in general.

RB: Yeah, that's right. This is the point of this particular course. It's meant to have students appreciate and understand just where the knowledge comes from in the textbooks. Which brings me to the second question…

16.312.1.3 HSI1000 **IS** a *Science* Course

RB: Some students tend to think that this is not a science course. Their idea of science, in my opinion is erroneous. Many seem to think that science is subjects like physics, chemistry, biology – that sort of thing. That's science to them. In fact, that's not science. That's just simply an output that science has produced. It's a product of actually taking and doing science. Science is an activity, as we've already learned from the definition. Recall that it's that activity that aims to further our understanding of the natural world and it does that using the scientific method. This was a big chunk of this course, and, in essence, it exemplifies what science is. I was hoping that you guys would not disagree with this statement.

AL: I think it is difficult to disagree with that. In fact, I think we could think about expanding on it. What I mean is that one would hope also that what the students take away from this is recognizing: Yes, this is a science course, but the examples that we have chosen to illustrate the scientific method; the way that they have heard about how scientists have interrogated nature, has perhaps raised the inquisitiveness of students in the cohort so that when they look at things in nature, they wonder why is that so? And it's derived from the title of this course, "Why does science work? How does science work?" Hopefully we've pushed our students to start thinking about the natural world in ways that they weren't thinking about it before. Again, it doesn't matter whether you're a science student or not a science student, but that you've grown to love a little bit more the world around us.


Figure 225 Tree planting with students

SN: Central to all of this is asking questions, and I'm glad to see this more in our students now because of what I observe when I invite students to come for tree planting (Figure 225). You surely know that there's a general acceptance that tree planting is a wonderful thing, right? But the question is why are you doing tree planting? There are several reasons why you do it. They sometimes think it's to immediately mitigate climate change, but there's a whole host of other questions. So I notice now when they come, they start asking the questions. They do it very nicely because they seem to feel that asking questions is terrorizing you. But they don't realize we're really excited to receive the questions because it tells us that the students are trying to understand the basis behind activity – that they're not just blindly doing it.

To the point where you indicated that some students expect to see an unloading of large amounts of content onto them [i.e., be given lots of chem, physics and bio, etc. to study], then it's not science. But we've tried to reduce that component so that they have the space to ask questions, and then realize **how these questions are answered**. So, I really enjoy questions, and I know all of you Prof's would enjoy that as well because it gets us to rethink. In fact, interacting with students forces us to have a firm grasp on what's going on. There may be areas that are a bit shaky, but when you have the question, and you need to explain yourself, it's wonderful how that firms things up.

TK: Yes, and that whole culture, or the whole habit of asking questions should persist, right? There are so many things that are happening around us, you know, that sometimes we take for granted or sometimes we just accept it. For example, recently the Wall Street Journal had to make some correction about something they said about Singapore (Figure 226). They said that Singapore had banned the food from Japan because of the Fukushima water release. However, they did not ask whether the article that they were referring to was current [very sloppy journalism]. The article they cited was a very old article published years ago when the Fukushima earthquake occurred.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WORLD

Corrections & Amplifications

Sept. 4, 2023 12:32 pm ET

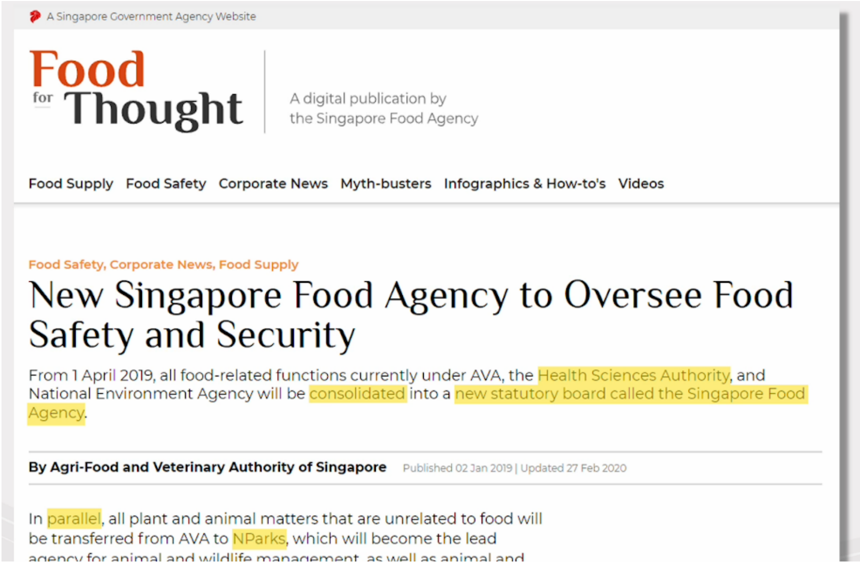
Share Resize Listen (40 sec)

The Wall Street Journal on Sept. 4, 2023, removed from its website an article incorrectly dated Aug. 24, 2023, which reported that several countries had detected radioactive contamination in Japanese food exports. The article was an erroneous republication of a Dow Jones Newswires article from 12 years ago that was accurate at the time but is now outdated. A version of the original article remains on WSJ.com with its March 25, 2011, time stamp.

Source: https://www.wsj.com/world/corrections-amplifications-ee28de47

Figure 226 Wall Street Journal retracts a news article containing false statements.

A big clue when you read the article is the fact that they referred to AVA, which no longer exists (Figure 227). It has been split into SFA – the Singapore Food Agency – with the rest of it absorbed into NParks. They had to literally retract it. At the moment I can't remember which ministry actually pointed out the error. Anyway, do keep asking the questions when you read articles. Asking questions is at the heart of science.


A Singapore Government Agency Website

Food for Thought

A digital publication by the Singapore Food Agency

Food Supply Food Safety Corporate News Myth-busters Infographics & How-to's Videos

Food Safety, Corporate News, Food Supply

New Singapore Food Agency to Oversee Food Safety and Security

From 1 April 2019, all food-related functions currently under AVA, the Health Sciences Authority, and National Environment Agency will be consolidated into a new statutory board called the Singapore Food Agency.

By Agri-Food and Veterinary Authority of Singapore Published 02 Jan 2019 | Updated 27 Feb 2020

In parallel, all plant and animal matters that are unrelated to food will be transferred from AVA to NParks, which will become the lead

Figure 227 AVA no longer exists.

Source: https://www.sfa.gov.sg/food-for-thought/article/detail/new-singapore-food-agency-to-oversee-food-safety-and-security

16.412.1.4 Explanations Play a Pivotal Role in Science

16.4.1 12.1.4.1 Explanations guide you on where to look, or what to do next.

RB: This again brings me to my next point, which I think is particularly important especially since I don't think that students may not have realised just how important scientific explanations are for some phenomenon. Scientific explanation plays a very crucial role in moving science forward – moving our understanding of the natural world forwards.

Say you observe something very mysterious. You can't get very far by just performing observations only. You need some kind of explanation for what is going on. Okay, let's say you do have an explanation. This explanation then points to what experiments that you can do, or what tests that you can do to prove, or show, or support whether this explanation is true. The tests of the explanation tells you whether or not that is what's going on. However, if it's particularly mystifying phenomenon and you can't actually think of an explanation, then you're really stuck. So you should see just how critical the explanation is – it plays a pivotal role in science because they tell you where to start looking to figure out what's going on. Now, the thing is, what's interesting about this is that the initial explanation is just pure speculation, even if it's plausible, right? It may or may not be true. We don't know. But at least you've got something to work with now – something which you can use to test.

16.4.2 12.1.4.2 Creativity and Imagination are a Prerequisite for Scientific Explanations

RB: You see, this part of science requires an awful lot of imagination and creativity. And I've heard a lot of people criticize scientists by saying that they've got no imagination or creativity, they're just boring people. In fact, I would argue that we're exactly the opposite. You cannot possibly come up with an explanation for particularly mystifying phenomena without this imagination and creativity skill set. So, I wanted to throw that out there to see if you guys wanted to add anything to that.

AL: Well, I know that I'm going to get in trouble for this: Yes, scientists are incredibly creative people. They must have an awesome imagination to create the kind of explanations that could possibly explain what is being observed.

RB: It must be a *plausible* explanation.

AL: Of course, it has to be, but that's the point! The explanation that you come up with, the curiosity, the creativity that you have to employ, in order to explain what's being observed is constrained by nature. This makes it a more difficult form of creativity because of that constraint. One could argue that anybody can be creative if it doesn't have any constraint. And one might argue that might be the difference between a scientist and a non-scientist. Which is the reason why I might get myself in trouble.

16.4.3 12.1.4.3 Creative scientific explanations can emerge though understanding and appreciation of previously developed scientific knowledge and through engagement with the scientific community.

SN: This creativity depends on the body of information that has affected the individual. Therefore, reading and interacting and learning from diverse disciplines helps you formulate ideas. The other thing is that we are resting on the body of work. Let me give a simple example. Why are otters behaving like they are in Singapore? And what they do, their behaviour, keeps changing. So, we are desperately trying to keep up because there are different explanations for their behaviour for the public, and for national governmental managing agencies because the otters do different things.

To figure this out, the first thing I borrow on is from ideas that came from other carnivorans from around the world. All scientists need to be quite well read otherwise one cannot do this. Then the second thing is in conversations with other scientists. It’s here you see this creativity at work. Sometimes a published paper will provide an answer to what the authors think is going on, and they give this and that as evidence and conclude that this is how it works out. However, what the paper doesn’t tell you about are the ten other ideas that were thrown away that sound ridiculous now because they were so speculative and ultimately wrong. You can see that there is a creative effort to produce those ideas then throw out those that fail the tests before a plausible explanation that fits all the evidence emerges.

And then the other thing is meeting people and talking. When you meet scientists at a symposia, or in the corridor, and you have these conversations there's actually a back and forth. Us sitting here, we all look quite civilized today, but in most of our [the Prof’s present] other conversations, they're quite wild because there's a thrust and parry of ideas, which is a very robust experience. I wish we were able to squeeze the students in on it if not for the fact there are 1,200 of them. It would have been fun to see because we get quite wild knowing that there's a constraint of nature that will have to shake out reasonable ideas which aren’t supported by evidence.

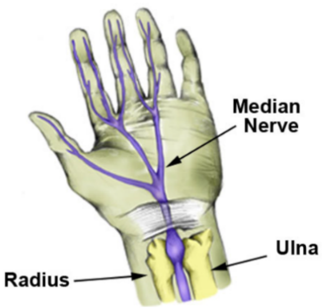


Figure 228 Illustration of the median nerve. (From: https://www.sportsinjuryclinic.net/sport-injuries/elbow-pain/forearm-pain/median-nerve-injury)

TK: Not just to shake out, but sometimes to shake up ideas, or get rid of previously accepted ideas that are now no longer supported by new evidence because they are found to be no longer true anymore. As an example, I was just reading why our fingers tend to wrinkle after being in water for a while (*Figure 229*). The accepted idea, or explanation, was that it's due to osmosis. However, in the 1930s it was shown that it's not necessarily true. It was found that people whose median nerve, the nerve that connects to the fingers (Figure 228), was damaged doesn't exhibit that kind of wrinkling. Plus, the entire body doesn't wrinkle when immersed in water.

Clearly it has nothing to do with the with osmosis. Nevertheless, it took many, many more creative experiments, creative testing, to find out what is now the most widely accepted explanation (check this write up all about it found in BBC Future). The currently accepted explanation is that it has to do with the fact that the water goes into our sweat glands and then it produces some kind of nervous reaction. It was also discovered that it helps someone whose hands are wrinkled to be able to grasp something better in the water. However, there are still many things that are not known yet. Why is it that this happens faster in men compared to women?

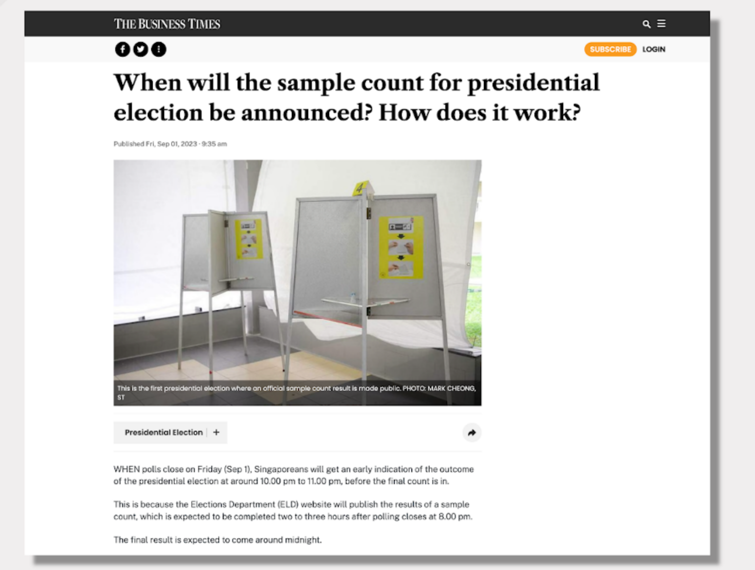
Figure 229 Prof Bettens demonstrates the wrinkled finger effect after soaking hands in fresh water (lower panel is before and after soaking).

AL: This also illustrates one of the other things that we've been speaking about in the course which is the fact that science needs an open scientific community. We're always building on the work of previous scientists – we're all standing on the shoulders of giants. By the way, I know that Newton wasn't the first person to say that. I recently heard the reason why he said that was because he was in an argument with Robert Hooke at the time and the two of them couldn't get along. But Hooke was famously short, so when Newton was saying, "standing on the shoulders of giants", he was making a pointed statement about the Hooke's lack of height.

16.512.1.5 Course content is directly applicable to the real world.

Following on from the earlier discussion (in 12.1.1) of the value of the BDTK and its application in everyday life…

16.5.1 12.1.5.1 E.g., confidence intervals and margins of error


THE BUSINESS TIMES

When will the sample count for presidential election be announced? How does it work?

Published Fri, Sep 01, 2023 · 9:35 am

This is the first presidential election where an official sample count result is made public. PHOTO: MARK CHEONG, ST

Presidential Election +

WHEN polls close on Friday (Sep 1), Singaporeans will get an early indication of the outcome of the presidential election at around 10.00 pm to 11.00 pm, before the final count is in.

This is because the Elections Department (ELD) website will publish the results of a sample count, which is expected to be completed two to three hours after polling closes at 8.00 pm.

The final result is expected to come around midnight.

Source: https://www.businesstimes.com.sg/singapore/when-will-sample-count-presidential-election-be-announced-how-does-it-work

Figure 230 Sample count article on the presidential election can be found [here](https://www.businesstimes.com.sg/singapore/when-will-sample-count-presidential-election-be-announced-how-does-it-work).

RB: Occasionally, I've heard some students say that margins of error and confidence intervals, introduced in the last lecture of block 1 and discussed in the other blocks too, were concepts that were only useful in this course. In fact, that's absolutely not true. I was reading a little while ago in the Business Times an article talking about something called a "sample count" for the presidential election. In the article, it specifically discusses margins of error and confidence level when you take a sample of how people voted before you've done the full count of all votes and try to figure out who's going to win. Now because you've done this course you have a much better appreciation of exactly what these things mean. You see, so there's quite a number of things that you can definitely use, just in your daily lives, that you can take out of this course, and this is directly one of those.

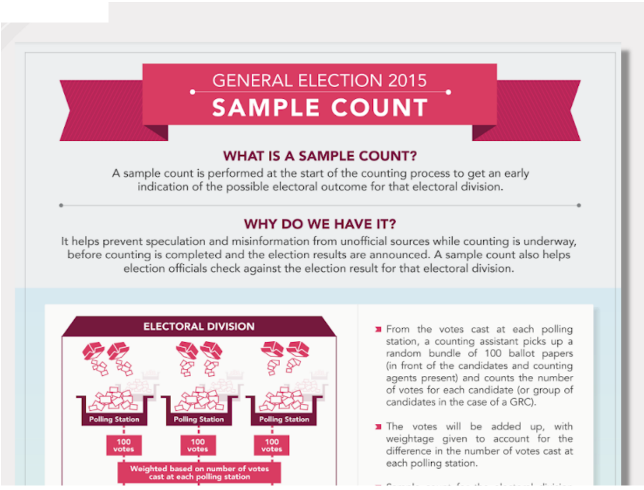


Figure 231 Sample count explainer by the government can be found here: https://www.eld.gov.sg/mediarelease/SampleCount_Generic.pdf

Source: https://www.eld.gov.sg/mediarelease/SampleCount_Generic.pdf

SN: That sort of is the role of quantification in society. People use it in a variety of walks of life. It's not as uncommon as it used to be. Everyone's comfortable with numbers now. Almost anything that you encounter that provides, or increases your literacy with, your numeracy is this regard definitely has a value subsequently in life. This is because if your margins of errors are overlapping each other, then we know that you've actually not found anything [i.e., the difference isn't statistically significant].

This is an interesting thing because we all have a predilection toward certain ideas. Remember when we were talking about throwing out creative ideas? Sometimes you like the idea so much you just want to go with it. What helps us not get blinded by our biases and our prejudices is that this sort of quantification really helps. If it's showing you there's no difference then you learn to let go, and this is because it's a very good guide as to the underlying value of such ideas. And I think being open minded means hearing other alternative plausible ideas.

It can sometimes be hard, but you've got to not be so egoistic, or fall in love too much in an idea. You have to learn to let go when the evidence is clear. Sometimes this can be quite painful. I remember one time when I was an undergrad and I really thought trees were floating because they got elevated by the tide. To test this idea we did a whole series of measurements, and no, trees weren't elevated – it was absolute nonsense. It was just a trick of the senses (e.g. *The Dress*) and I just had to let go of that idea. Now, if you want to, if you still believe your original idea and think there's more to it, then you have to come up with another test, but when the numbers have told you something different, it's time to let go[51]. This is quite relevant to when people come to you with different ideas that you don't like, then it's the evidence that persuades you in the end. Notice I used the terms "like" and "dislike". That's the reason why people might think scientists are so boring because there's this objective element which overlays your decision making – "like" and "dislike" don't really come into it – you can't be so passionate about an idea because if it's disproven then we're going to set it aside.

16.5.2 12.1.5.2 There's more than just the CIs and MoEs to "take away" from this course...

TK: Margins of error is just one of the things that you might not have liked when you were taking this course, and there may be a whole lot of other things too that you might think are not relevant. You might be thinking, "What has this got to do with me?", but we hope that you will find that at the end of the day there are very important things that you have learned, and they are very relevant. Maybe those things are not in the subsequent courses that you're going to take, but you will actually see some of these come back again later on, when you look at everyday occurrences in your life.

AL: I think what Siva (SN) was just saying in terms of biases we all have is relevant because scientists are human too. You can't separate our humanity from our science. However, we both spoke about in our blocks the importance of how you need to be open to new ideas which could potentially challenge your preferred (predilection) way of looking at the world. It's difficult because we don't want to feel as if we're mistaken. It's natural for us to have confidence in our views, but sometimes those views are going to be challenged and being open to the evidence that challenges those views is difficult for everybody. However, if you possess the humility to acknowledge this, you will find yourself in a much better position when it comes to navigating your life. This is yet another one of the important things that students can take away from this course.

Figure 232 Selley's advertisement at bus stop.

TK: I wonder whether you remember there was this advertisement at the bus stops mentioning that Selly's was trusted by most Australians (Figure 232). I pointed that out to Ryan (RB) and he said, "Yes, that's true. It is trusted by most Australians." Then I said, "Really? Were's the evidence? Did they do any poll or something similar?"

RB: LOL, I don't know, it's just a household name.

TK: Yeah, right. So, again, that shows you we are biased, actually, inherently biased. In this case a national bias.

SN: I don't think we cling onto our ideas so much so that we don't want to hear others. We welcome challenges to our ideas because if yours is solid, it will survive the test. However, if it's not that solid, and it turns out that there are better ideas, then we want to see those fall. This brings us back to the point where we welcome questions. E.g., if a student challenges an activity by asking, "Why do we want to do this, etc.?" We are embracing the questioning because the challenge is making sure that whatever it is that we are doing has been well thought through with evidence for it. It makes sure we're not just spouting an idea that we enjoy. E.g., maybe I just like planting trees, so I'm imposing these kinds of ideas on others. Well, when people challenge

[51] Not "letting go" and doing more and more tests to show that your idea is right, yet each time the evidence suggests you are wrong again and again is a common "fallacy in the name of science" called an "ad hoc rescue", which we discuss in 12.2.7.

that, do I have a ready response? In fact, I’m wanting to hear these challenges. It’s what allows you to be fair when you're mediating, or you're engaged in conflict resolution, this allows you to be a fair individual in society. And I think that's very helpful.

16.612.1.6 Conclusion

RB: Okay. Well, that's all we have. Of course, we could continue here for a long time because there's a lot more topics that could be discussed, but we can't really go on for too long in this particular video, so we need to leave it there with just this sample of topics. After this video, there'll be two more videos that will finish off this entire course as we cover Chapter 6 of the textbook, so I’ll see you in the next video.

17 12.2 Fallacies in the Name of Science

In this and the next section we'll be going through the last chapter of our textbook which is on fallacies in the name of science and pseudoscience – no introductory course on scientific inquiry would be complete without it. These topics complement and enhance what we've learnt from the Baloney Detection Toolkit and helps you become more aware of the sort of "tricks" people can try to pull when attempting to convince you of something that just isn't so.

Now what we mean my "fallacy" here *isn't* a genuine scientific mistake made based the evidence available at the time of the error. What we mean by fallacy here is either flawed reasoning or logic, incorrect or improper use of the scientific method, or a deliberate act to misrepresent something.

17.112.2.1 False Anomalies

Following our textbook, we note that the first type of fallacy is called "False Anomalies". If you recall, we've discussed anomalies a number of times in this course, and that genuine anomalies are important for science as they can lead to either more evidence to support a currently established theory, or may require revision of a theory, or even create an entirely new scientific field.

However, with false anomalies the claimant will typically fraudulently present some phenomenon as being mysterious, not explicable by science, then provide their own explanation for the phenomenon, which is very often an extraordinary claim. However, the slight-of-hand occurs when they purposefully leave out evidence in support of a regular scientific explanation, or worse, misrepresent or falsify evidence in support of their own extraordinary claim.

Figure 233 Example of Crop Circles. Jabberocky, Public domain, via Wikimedia Commons.

Our textbook gives us numerous examples of this, so we only mention one in a bit of detail here. Crop circles (Figure 233) are large, symmetrical geometric figures, circular and otherwise as shown here. They have "mysteriously" appeared in wheat and corn fields in Southern England and have since been observed in many other countries. These mysterious strange shapes are made out to be anomalies with advocates suggesting there is no explanation for how they could be generated. The patterns are typically found in the middle of crop fields where there were no obvious signs of human intrusion. Then the extraordinary claim is made that the patters were made by aliens (Figure 234) or their spaceships (Figure 235).

However, what is purposefully disregarded are "tramlines", seen in Figure 236, which are either near or even run through these patterns. These tramlines are indentations made by tractors as they travel through the crop fields. It has been clearly demonstrated that a hoaxer can simply walk down these tramlines, and with a few simple tools, create these circles quickly and easily. Indeed, several hoaxes have come forward and admitted just this. If you'd like to read up more about this, then Wikipedia is a good place to start, and the link is provided here: https://en.wikipedia.org/wiki/Crop_circle.

Figure 234 Alleged creator of crop circles. User:Crobard~commonswiki, Public domain, via Wikimedia Commons

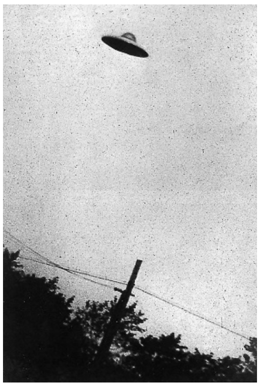


Figure 235 Another alleged creator of crop circles. George Stock [4], Public domain, via Wikimedia Commons

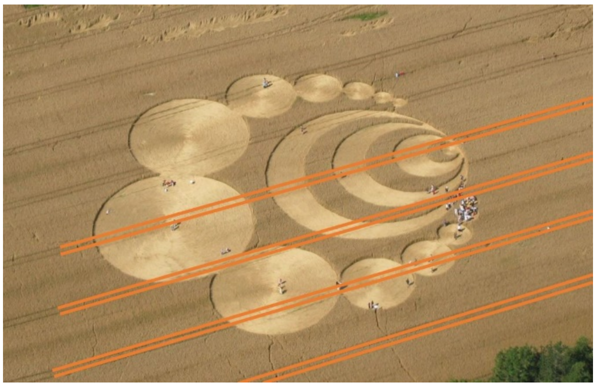


Figure 236 Tram lines (shown in orange) ignored when this false anomaly is presented. Figure modified from the source: Jabberocky, Public domain, via Wikimedia Commons.

Anyway, here we see an example of a false anomaly being proposed by neglecting to mention the "tramlines", and that it is easy for a people to construct these same patterns with a few simple tools. Neglecting to mention this additional evidence creates a "mystery" when there isn't one. And then they go on to make wild untested explanations without evidence for how these patterns might have otherwise been created.

17.212.2.2 Questionable Arguments by Elimination

The next type of fallacy mentioned in our text is "Questionable Arguments by Elimination". Actually, we've encountered this type of fallacy before in tool number three of the BDTK which is "Is the claimant providing positive evidence?". Here the claimant considers evidence that an alternative explanation is wrong to be actual evidence in support of their explanation for some phenomenon.

As an example, let's consider extrasensory perception, or ESP. Often a strategy used to "prove" that someone can read another person's mind is to simply show that their ability cannot be explained by random guessing, or luck. For example, let's say a so-called ESP sensitive can tell what playing card someone else is looking at more frequently than chance. Even under tightly controlled experimental conditions if this were so, it *does* rule out the possibility of luck at guessing the card, but it does **NOT** prove that the person has ESP.

This would only be the case if there were only two possible explanations for what is observed (1) The claimant has ESP and (2) the claimant is just lucky at guessing the cards. By eliminating the luck explanation does not provide positive evidence for ESP.

This is because anyone can come up with another explanation. As a silly example, consider that a magical invisible imp (Figure 237) is indicating to the person claiming to have ESP which card the other person is thinking about. The point here is that there is just as much evidence that the claimant has ESP as there is for the magical invisible imp. In fact, the only conclusion we can draw from this experiment is that something quite interesting is occurring that isn't fully understood.

Figure 237 Alternative explanation for claimed ESP sensitive's ability. Simon Blocquel (1780–1863, under the pseudonym Julia Orsini), Public domain, via Wikimedia Commons.

What we can NOT conclude here is that we HAVE evidence for ANY explanation for the phenomenon yet – all we have shown is that luck isn't the explanation. So just by eliminating rival explanations doesn't provide evidence for your favourite explanation. One needs to find *positive* evidence directly in support of it.

17.312.2.3 Illicit Causal Inferences

The next type of fallacy is “Illicit Causal Inferences”, and we encountered examples of this already when we learnt that correlation doesn’t imply causation, so we won’t discuss this further here. However, there’s another example of this type of fallacy, and it can simply be that some out of the ordinary occurrence precedes some other out of the ordinary occurrence, so one jumps to the conclusion that that there is some causal link between the two, but is there really?

For example, you’re thinking of a friend and then the phone rings, and it was the exact same person you were think about! Does this mean you have ESP? Well perhaps it does, but it’s far more likely that it’s just coincidence. Think of how many times you’ve thought about your friend, and they didn’t call you, or how many times they called you and you weren’t thinking of them. That the two events should occur in close proximity every so often seems not all that unusual.

As another example, just because you enter a lift as someone else exits it and then you smell something quite bad in the lift doesn’t mean that the person that just left the lift had anything to do with the stench. This is another illicit causal inference.

17.412.2.4 Unsupported Analogies and Similarities

Unsupported Analogies and Similarities is our next fallacy. Scientists sometimes use analogies to something that is well understood to help explain something puzzling. However, this type of thing can be fallaciously exploited when the fact that an explanation works in one case is given as **evidence** for the correctness of a similar explanation in another case. This is because, at the very most, a well-chosen similarity guides us to a possible explanation; it should not be thought of as providing *evidence* that the explanation is correct. Only careful testing can provide such evidence.

As an example of this we use a quote from the textbook on astrology, which is a pseudoscience. Astronomy is science normally, but astrology is not. Astrology proports that the positions of the stars and planets at the time of our birth can influence our personalities or even our choices of profession, so here’s an example of an unsupported analogy and similarity:

> *“Much as the moon influences the tides and sunspot activity can disturb radio transmissions, so do the positions of the planets have an important influence on formation of the human personality. Modern science is constantly confirming the interconnectedness of all things. Is it any surprise that distant events, like the movement of the planets and the decisions people make, should be connected?”*

So, because the moon influences the tides on Earth, which it does, and sunspot activity can disturb radio transmissions on Earth, which it does, we can conclude that the positions of the planets have an important influence on formation of the human personality? Of course not. There is zero evidence to be found in the analogy and similarity that the positions of the planets have any important influence on the formation of the human personality.

17.512.2.5 Untestable Explanations and Predictions

Our next fallacy is “untestable explanations and predictions”, and we have encountered this already in the course where we considered “fate” as being an explanation for something occurring, or the “dragon in my flat” conversation with Prof Lee.

Remember, if an explanation cannot be experimentally shown to be false, then it isn't a scientific explanation. Again, it really could be the explanation, but there's no way for us to check whether it is or not, so Science has nothing to say on the matter. We should always ask ourselves when accepting some explanation for something: "Under what conditions would we be willing to set aside the explanation on the grounds that it is false?" If you can't think of any such conditions, then the explanation you have isn't a scientific explanation.

Interestingly, many conspiracy "theories" fall under this category, and in fact, they can seem attractive and even plausible *because* they are immune to falsification. They can be circular in their "evidence" for their theory, like the typical nine-eleven conspiracy theories described in our textbook.

You see, these "theorists" believe they have uncovered various anomalies in the nine-eleven attacks, then provide an explanation involving powerful government conspirators, and when asked for evidence of this they simply rehash the anomalies they believe they uncovered in the first place (Figure 238). There is no body of independent evidence here. An anomaly isn't evidence. It's an anomaly that requires a falsifiable explanation.

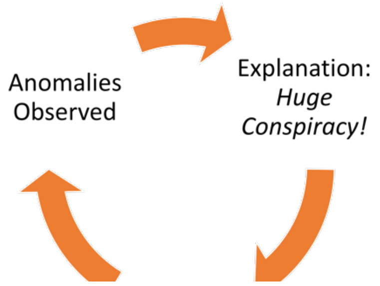


Figure 238 typical conspiracy theory circular argument.

Any real evidence that their theory is wrong is claimed to be fabricated by the conspirators, and lack of evidence they also claim IS actual evidence of their conspiracy because all the evidence has been disposed of and covered up! Such explanations are not scientific as they are not falsifiable. Period.

17.612.2.6 Empty Jargon

Use of Empty Jargon is the next fallacy that can be used to convince people that something is scientifically proven but isn't. Science itself is full of jargon, which exists so that communication between scientists can be brief without having to constantly explain concepts and objects the jargon represents.

However, conmen can highjack this language and string together a bunch of terms, which means nothing, in order to try and convince you that something is scientifically established. Perhaps I'm trying to sell you on my extraordinary powers to move objects at a distance with just the power of my mind – something known as telekinesis. Presuming this were even possible, you ask me how that works, and I reply:

"It's a bit complicated, but in simple terms it's a type of quantum entanglement which I can trigger with my mind by creating an Einstein–Schwartzchild gravity trap at the target location. This enables the destabilization of the wavefunction of the object which can then be relatively easily propagated to the trap's location by tunnelling through the various Riemann manifolds of quantum electrodynamic barriers. The object's wavefunction then promptly collapses thus allowing me to move the object."

What did I just say?

Nothing; it was totally made-up pure nonsense, but it did sound, perhaps, impressive and scientific. Believe it or not, but this kind of dirty trick, which amounts to nothing more than lying, does and is used today to help move hard earned cash out of your hands and into those of the conman.

17.712.2.7 Ad Hoc Rescues

Next up on our list of fallacies are ab hoc rescues. This particular fallacy is referring to a situation where a scientific test of an explanation or claim continues to fail those tests. Of course, it is quite normal in science for an experiment to give negative results when a different outcome was expected. Perhaps we overlooked something? Maybe we have a flawed experiment, and are about to falsely reject our explanation, or maybe we just need to make some minor adjustments and we will get the expected results. This kind of thing definitely occurs in science, but there must come a point where no matter what one tries the explanation or claim simply cannot be verified.

At this point we have to admit that the explanation or claim just isn't right. However, if one just continues over and over to refuse to admit that they're wrong, then we are engaging in an ad hoc rescue. That is, an attempt to still accept something to be true despite now quite a lot of evidence that it isn't. We now have to ask if there's any point where we will admit our explanation or claim is false? If not, then this explanation or claim is untestable and thus not scientific.

17.812.2.8 Exploiting Uncertainty

Our final fallacy discussed in our textbook is one we have meet before in this course and that is exploiting uncertainty. We heard about the doubt mongering from Prof Lee in video around well-established causal links between lung cancer and cigarette smoking, CFC emissions and the stratospheric ozone hole, even the link between UVB radiation and skin cancer and SO_2 emissions from coal burning power plants producing acid rain that in turn destroys forests (note a causal mechanism here), and finally attacking climate change.

The clearest and most upsetting example, however, is given where Prof Lee quotes a memo by Frank Luntz. There Luntz clearly states that their position against the scientific consensus on climate change is closing. Luntz directly said that "you need to continue to make the lack of scientific certainty a primary issue in the debate".

Science, as we know, is fraught with uncertainty. We've seen that even in just making a simple measurement of something there is a $\pm$ associated with the reading, we also have confidence levels in all manner of results in science. We also know that conclusions regarding explanations can be wrong because of errors due to false confirmation or rejection, and that what once was a well-established scientific theory can be overturned and become obsolete as new evidence comes to light and a new theory established.

But far from being a weakness, this uncertainty is Science's major strength. Science IS self-correcting because of this ever-present uncertainty. And because of this it ensures that we inch asymptotically towards the truth. If ever there was a point where science was able to state some scientific conclusion with absolute certainty, then we are no longer talking about science because at that point we have shifted into an authoritarian world view.

However, just because something isn't 100.000…% certain doesn't mean that it isn't certain for all practical purposes. Think of Prof Lee's example of the medical test in lecture 8. A third positive test would mean we are now 99.9% certain we have the disease instead of 91% from two positive tests. As we have learnt from the Salk vaccine field trial in lecture 4, we can be very confident that something is correct to an extremely high degree, and a great preponderance of evidence for something provides an equally great deal of confidence and credibility in conclusions drawn and explanations given.

It's the merchants of doubt that want to recast tiny levels of uncertainty into large ones – turning somethings that has 99.99% confident into a 50-50 conclusion either way. To me, such machinations are truly immoral and evil, and we hope that with this course you are now more aware of fraud of this nature when you read or hear about something that seems to be at odds with what a large number of scientists are saying.

17.912.2.9 In Conclusion

OK, that's it for our eight fallacies put forward in the name of science taken from our textbook. In the following section we'll finish off chapter 6 by taking a look at science and pseudoscience.

18 12.3 Science & Pseudoscience

We've heard about science, the scientific method and scientific inquiry in this course, but we haven't mentioned anything about pseudoscience. What is pseudoscience? The word "pseudo" means "not genuine", "spurious" or "sham", that is, fake – so pseudoscience isn't actual science, although it may appear to be, it's fake science.

Pseudoscience often uses the fallacious methods we discussed in the last section in an attempt to establish credibility when there is little to none present. Unfortunately, however, sometimes telling pseudoscience from genuine science can be quite tricky, so in this section we'll be discussing the ways we can and cannot distinguish between the two.

18.112.3.1 Ways that **can't** be used to differentiate between science and pseudoscience.

There are three ways that can't be used to tell the difference between genuine science and pseudoscience. The first should go without saying but is mentioned for completeness as it's listed in the textbook.

18.1.1 12.3.1.1 The distinction between science and pseudoscience has nothing to do with the distinction between "hard" and "soft" sciences.

Occasionally you might hear arrogant people state that pseudoscience is soft science, which is totally wrong. What is soft and hard science? They are just terms that refer to different fields of study. Hard science refers to the fields of physical, chemical and biological sciences, whereas the so-called soft sciences involve fields engaged in the study of human behaviour like sociology, anthropology, psychology, political science, just to name a few.

Both soft and hard sciences aim at explaining phenomena of the natural world whether that's the behaviour of light, space-time, matter or living organisms, including people. All fields use the rigorous methods for observing, explaining and testing we have encountered in this course, so none deserve the label of pseudoscience.

18.1.2 12.3.1.2 The distinction between science and pseudoscience cannot be drawn along lines of scientific discipline.

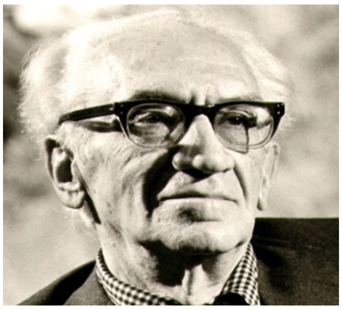


Figure 239 Immanuel Velikovsky (1895 – 1979). Photographer: Donna Foster Roizen. Copyright holder: Frederic Jueneman, CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0, via Wikimedia Commons

We also cannot distinguish between science and pseudoscience just because the hypothesis, theory or claim may exist within one of the hard or soft sciences. For example, just because something is in the field of astronomy, doesn't automatically mean that its science. This is because nonsense can be promulgated in any subject area.

Our textbook gives an example of Immanuel Velikovsky (Figure 239) who in the 1950s hypothesized that the planet Venus was created out of an enormous volcanic eruption on Jupiter. He speculated that during its voyage from Jupiter to is current orbit, as it passed by the Earth, it caused several cataclysmic events.

Of course, there is zero evidence to support such a claim, but even the hypothesis itself is in direct violation of well-established science making it literally impossible to have occurred. Nevertheless, this nonsensical hypothesis lies within the broad area of astronomy, so a claim or hypothesis being within a respected scientific discipline doesn't automatically make it science.

If you'd like to read more about various other pseudoscientific outpourings of Immanuel Velikovsky, follow the link here to Wikipedia.

18.1.3 12.3.1.3 Science cannot be distinguished from pseudoscience simply on the basis of the results each produces.

You also can't claim something is a pseudoscience based on the fact that ultimately it turned out to be wrong. We heard from Prof Lee about Phlogiston Theory, which became an obsolete theory after Lavoisier's work. Lavoisier was one of those scientists that then established a new theory in its place – Caloric theory (where the word calorie comes from), but also ended up becoming obsolete.

Both obsolete theories were considered "well-establish" theories for their time with various scientific evidence in support of them and having been subjected to the all the rigours of the scientific method. The fact that these theories ultimately ended up being wrong, doesn't make them a pseudoscience.

18.212.3.2 Ways that **can** be used to differentiate between science and pseudoscience.

Now let's talk about where science differs from pseudoscience. This has been summarized for you in the Table 1 below:

Science	Pseudoscience
Is self-correcting	Not self-correcting
As a scientific discipline develops, it will gradually produce a maturing body of explanatory or theoretical findings.	Produces very little theory.
The findings, theoretical and otherwise, are always open to revision.	Rarely do pseudoscientific claims change much over time.
Embraces skepticism.	Tends to view skepticism as a sign of narrow-mindedness.

Table 1 summary of the differences between science and pseudoscience

18.2.1 12.3.2.1 Genuine science tends to be self-correcting; pseudoscience is not

Indicated first in Table 1 we see that genuine science is self-correcting, whereas pseudoscience isn't. This means that when evidence comes to light in science indicating a current explanation requires revision, a pseudoscience simply ignores it.

18.2.2 12.3.2.2 As a scientific discipline develops, it will gradually produce a maturing body of explanatory or theoretical findings; pseudoscience produces very little theory.

Because pseudoscience in not self-correcting it rarely develops and matures producing a coherent theory. Whereas a scientific discipline continues to develop and change, due to its self-correcting nature, gradually producing a maturing body of explanatory or theoretical findings. A pseudoscience produces very little theory.

18.2.3 12.3.2.3 The findings, theoretical and otherwise, of genuine science are always open to revision; rarely do pseudoscientific claims change much over time.

As part and parcel of any scientific inquiry the findings of science, both theoretical and otherwise, are always open to revision as new evidence comes to light. This is how a scientific discipline develops. However, in pseudoscience it is quite rare for the claims, assertions, or speculations to change much as time goes by.

18.2.4 12.3.2.4 Genuine science embraces scepticism; pseudoscience tends to view scepticism as a sign of narrow-mindedness.

The reason, of course, for this continual revision taking place in science is because science embraces scepticism. Remember the motto of the Royal Society? *Nullius in verba*. Scepticism is ever present in science, which is why the *testing* part of the scientific method in a nutshell is required. However, in pseudoscience, rather than embracing scepticism of the claims, the claimants tend to view such as narrow-mindedness. Which clearly isn't a valid argument not to test an explanation, nor to provide proper scientific evidence in support of it.

As an aside here, you should be aware that anecdotal evidence, or testimonials, or eyewitness accounts, carries little to zero weight in science.

18.312.3.3 Examples of Pseudoscience Encountered in the Course

OK, now that we've covered the main ways our textbook points out where the differences lie between science and pseudoscience. I'll finish off this section by examining Table 2 which provides just a few examples of pseudoscience. These examples are ones we've mentioned here and there in this course. Table 2 also provides the Wikipedia links for you to further investigate if you're interested.

Pseudoscience	Concerns	Wikipedia Link
Astrology	Predictions of human affairs and events by studying the movements of heavenly bodies.	https://en.wikipedia.org/wiki/Astrology
Ufolofy	Aliens visit us in their spaceships.	https://en.wikipedia.org/wiki/Ufology
Parapsychology	Study of alleged psychic phenomena (ESP, telepathy, precognition, clairvoyance, telekinesis, etc.) and other paranormal claims.	https://en.wikipedia.org/wiki/Parapsychology
Immanuel Velikocsky's Work	E.g., volcano on Jupiter creates Venus and causes various cataclysmic events. Also involved in pseudohistory.	https://en.wikipedia.org/wiki/Immanuel_Velikovsky
Cryptozoology	Study of the existence of entities like Big Foot, Loch Ness Monster, Yeti, the Chupacabra, Bukit Timah Monkey Man, etc.	https://en.wikipedia.org/wiki/Cryptozoology

Table 2 examples of pseudoscience encountered in the course.

Running through Table 2 we first meet Astrology, which we mentioned last section and elsewhere. Note that this area isn't the same as Astronomy. Next, we have Ufology, which we encountered in the Baloney Detection Toolkit video. This isn't the same as the SETI program, which is solid science devoted to the search for extra-terrestrial life.

Our third example is Parapsychology. Do note that this is NOT psychology. Within parapsychology we have ESP, which we've mentioned a few times already. There's also telekinesis and clairvoyance within this domain, but there's a whole bunch of other stuff that comes under this pseudoscientific area. Check the provided Wikipedia link if you're interested.

Next, we have Immanuel Velikocsky's work discussed in section 12.3.1.2, who was also has engaged in pseudohistory, and finally I've listed cryptozoology, which involves the study of the existence of Big Foot, the Loch Ness Monster and even the Bukit Timah Monkey Man, the latter being mentioned in Workshop 1.

This list here is very far from complete. There is an awful lot more pseudoscience out there, so you should always be *en garde* to identify it with the tools we've equipped you with in this course. Of course, just because something at present is a pseudoscience, for example parapsychology, doesn't necessarily mean that at some point in the future hard evidence may come to light that indicates otherwise. If this ever happened, then it would most certainly be a very exciting time as the scientific community gears up to fully understand the newly reported results. However, at present these pseudosciences remain at the fringe and carry very little credibility with the scientific community at large.

18.412.3.4 In Conclusion

This now marks the end of this lecture which is the last lecture of this course. On behalf of the entire HSI1000 team we do hope you've come to better appreciate exactly just what is scientific inquiry. We also hope we've armed you with a set of tools, based solidly around how scientific investigations are conducted, that will enable you to differentiate between what is supported scientifically, and what is not.

This course is just the beginning of your learning journey. You will have the opportunity to become even more familiar with scientific inquiry within the SI2 courses present in the common curriculum.

And with that I bid you all fare-thee-well and good luck with all your exams and future endeavours.