Causal Reasoning in the History of Science

From Newton to Climate Change

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Intro to Logic

Causal Reasoning in Science: From Newton to Climate Change

- Scientists face unique challenges when establishing **causal relationships** in natural phenomena that span vast scales of time and space.
- Unlike laboratory experiments, many scientific questions involve causes we cannot directly manipulate or control.
- Throughout history, major scientific breakthroughs required innovative methods to demonstrate causation without traditional experiments.
- Today we'll examine how scientists established causal claims that transformed our understanding of the universe.

Our Journey Through Time

1687: Newton's Gravity $\rightarrow$ 1859: Darwin's Evolution $\rightarrow$ 1876: Germ Theory $\rightarrow$ 1950s: Smoking-Cancer Link $\rightarrow$ Today: Climate Change

How Scientists Establish Causation: Beyond the Laboratory

- Scientists use **converging evidence** from multiple sources when controlled experiments are impossible or impractical.
- Natural experiments, mathematical models, and careful observations can substitute for direct manipulation.
- **Predictive power** becomes crucial: if a causal theory correctly predicts new phenomena, it gains credibility.
- The scientific community requires extraordinary evidence for extraordinary causal claims that challenge existing beliefs.

Example (Types of Scientific Evidence)

- Observational data across time and space
- Natural experiments and comparative studies
- Mathematical models and simulations
- Mechanistic understanding of processes

The Challenge: Proving Causes in Complex Natural Systems

- Natural systems involve **multiple interacting causes** that operate over different timescales and cannot be isolated.
- We cannot rerun Earth's history with different conditions or create control planets for comparison.
- **Temporal gaps** between causes and effects (like smoking and cancer) make causal inference difficult.
- Political, economic, and religious interests often resist scientific causal claims that threaten established systems.

The Fundamental Problem

How do we prove that invisible forces cause planetary motion, that random mutations cause new species, or that greenhouse gases cause global warming when we cannot perform controlled experiments?

Newton's Revolutionary Claim: Invisible Forces Cause Motion

- Newton proposed that an **invisible force** called gravity causes all objects with mass to attract each other.
- This claim was revolutionary because it suggested action without contact - objects affecting each other across empty space.
- Previous theories required physical contact or "vortices" of matter to explain motion and planetary orbits.
- Newton's mathematical approach allowed precise predictions without explaining *how* gravity worked mechanistically.

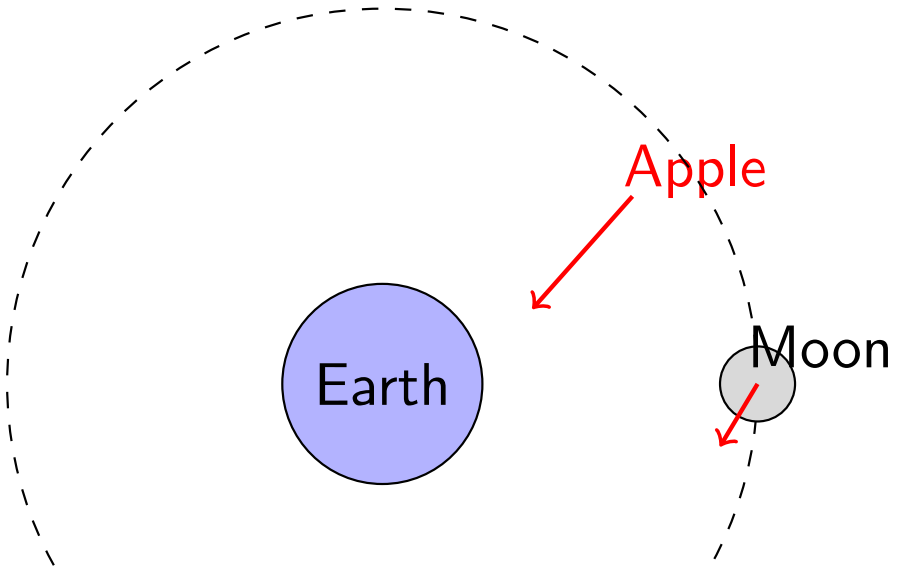
The Radical Idea

"Every particle in the universe attracts every other particle with a force proportional to the product of their masses and inversely proportional to the square of the distance between them."

$$F = G\frac{m_1 m_2}{r^2}$$

The Apple and the Moon: Unifying Terrestrial and Celestial Causation

- Newton's insight was that the **same cause** explains both falling apples and orbiting moons.
- Before Newton, earthly and heavenly motion were thought to have completely different causes and follow different laws.
- By showing that moon's orbit and projectile motion follow the same mathematical principles, Newton unified physics.
- This **causal unification** was proven through calculation: the moon "falls" toward Earth at exactly the predicted rate.



Mathematical Laws as Causal Explanations

- Newton introduced the idea that **mathematical relationships** can serve as causal explanations in science.
- Rather than describing mechanisms, Newton's law precisely predicted how gravity's causal effects vary with mass and distance.
- Critics complained "hypotheses non fingo" (I frame no hypotheses) wasn't enough - they wanted to know *why* gravity worked.
- Newton's success showed that mathematical descriptions of causal relationships could be scientifically valid without mechanical models.

Example (Causal Predictions from Math)

- Double the mass $\rightarrow$ Double the gravitational force
- Double the distance $\rightarrow$ Quarter the gravitational force
- These precise relationships allowed testing causation through measurement

Prediction as Evidence: Halley's Comet Returns

- Edmund Halley used Newton's gravitational theory to predict a comet would return in 1758 - decades after his own death.
- When the comet appeared exactly as predicted, it provided powerful evidence that gravity causes celestial motion.
- This **novel prediction** was more convincing than explaining already-known phenomena retroactively.
- The successful prediction demonstrated that Newton's causal theory could extend beyond observed data to future events.

The Power of Prediction

Successful predictions, especially of previously unknown phenomena, provide the strongest evidence for causal theories when experiments are impossible.

Action at a Distance: The Causal Controversy

- Newton's gravity implied **action at a distance** - objects causing effects without touching, which many found absurd.
- Descartes and others insisted real causes required physical contact through "vortices" of swirling matter.
- Newton himself was uncomfortable with instantaneous action across empty space but couldn't explain the mechanism.
- The debate shows how causal claims that violate intuitions about "how causes work" face extra skepticism.

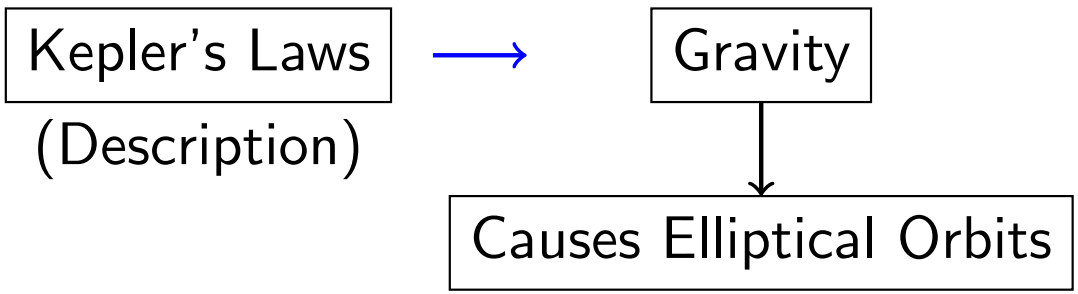
Newton's Response

"I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses... It is enough that gravity does really exist, and acts according to the laws which we have explained."

From Correlation to Causation: Planetary Orbits Explained

- Before Newton, astronomers had **correlations** - Kepler's laws described planetary motion patterns mathematically.
- Newton showed these patterns were **caused by** gravitational force, transforming description into explanation.
- Small deviations in orbits, previously dismissed as errors, were explained by gravitational pulls from other planets.
- This demonstrated how a true causal theory should explain both the regularities and the apparent exceptions.

Before Newton: **After Newton:**



Darwin's Causal Claim: Natural Selection Drives Species Change

- Darwin proposed that **natural selection** - differential survival and reproduction - causes species to evolve over time.
- This mechanism operates through variation, inheritance, and competition for limited resources in nature.
- Unlike Newton's instant forces, Darwin's cause operated over vast timescales invisible to human observation.
- The theory explained both the adaptation of organisms to their environments and the branching pattern of species relationships.

Example (The Causal Mechanism)

1. Individuals vary in traits
2. Some traits aid survival/reproduction
3. Beneficial traits are inherited
4. Over generations, populations change

Result: Natural selection causes evolution

The Galápagos Finches: Natural Experiments in Evolution

- The Galápagos Islands provided a **natural experiment** where similar finches evolved differently on different islands.
- Each island's unique environment (seeds, climate, competition) created different selection pressures.
- Darwin observed that beak shapes matched food sources - thick beaks where hard seeds dominated, thin where insects prevailed.
- This geographic variation suggested environmental conditions cause evolutionary changes through natural selection.

Natural Experiment Logic

If natural selection causes evolution, then:

- Similar species in different environments $\rightarrow$ Different adaptations
- Different species in similar environments $\rightarrow$ Convergent adaptations

Both patterns were observed!

Fossil Evidence: Causation Across Deep Time

- The **fossil record** provided historical evidence of evolution, showing species changing through geological time.
- Deeper (older) rock layers contained simpler organisms, while recent layers showed more complex forms.
- Transitional fossils like Archaeopteryx (reptile-bird) demonstrated intermediate forms predicted by evolutionary theory.
- This temporal sequence supported Darwin's claim that natural selection causes gradual transformation over millions of years.

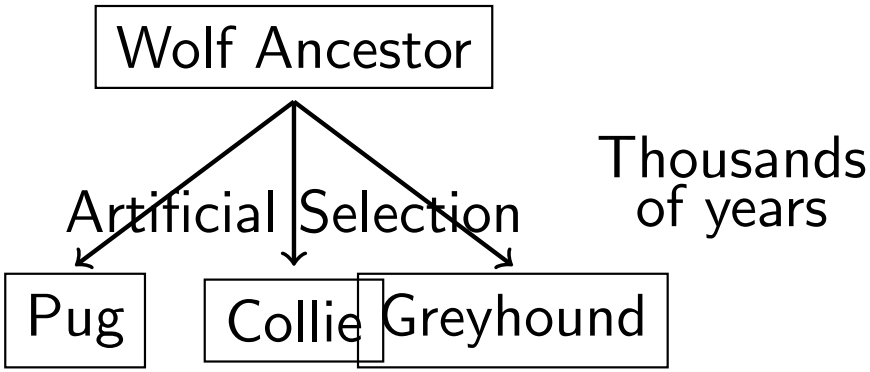
The Time Problem

Human lifetime: 80 years
Recorded history: 5,000 years
Species change: 1,000,000+ years

How do we prove causation across unobservable timescales?

Artificial Selection: Controlled Experiments with Breeding

- Darwin used **artificial selection** in domesticated species as an experimental analog for natural selection.
- Pigeon breeders created dramatically different varieties by selecting which birds reproduced - proving selection causes change.
- In just dozens of generations, humans produced varieties as different as pugs and greyhounds from wolf ancestors.
- If human selection could cause such dramatic changes quickly, natural selection over millions of years could transform species.



Biogeography: Why Isolation Causes Divergence

- **Biogeography** - the distribution of species across Earth - provided powerful evidence for evolution by natural selection.
- Islands contained unique species similar to, but distinct from, nearest mainland relatives, suggesting common ancestry.
- Geographic barriers (oceans, mountains) correlated with species boundaries, indicating isolation causes evolutionary divergence.
- The pattern made sense only if separation prevented interbreeding, allowing different selection pressures to cause different evolutionary paths.

Example (Biogeographic Evidence)

Observation	**Causal Inference**
Island species resemble mainland	Common ancestor
But show unique adaptations	Local selection pressures
More isolation = more difference	Time + selection = change

Modern DNA Evidence: Confirming Historical Causation

- **DNA evidence**, unavailable to Darwin, now provides molecular proof that natural selection causes evolutionary change.
- We can trace specific mutations and observe selection acting on them in real time in bacteria and viruses.
- Genetic similarities match the family tree predicted by fossils and biogeography, confirming common descent.
- DNA "molecular clocks" allow us to estimate when species diverged, validating the timescales Darwin proposed.

Converging Evidence

When multiple independent lines of evidence (fossils, biogeography, artificial selection, DNA) all support the same causal theory, scientists consider it confirmed beyond reasonable doubt.

Before Germs: Miasma Theory and Bad Air

- Before germ theory, the dominant **miasma theory** claimed diseases were caused by "bad air" from rotting matter.
- This theory seemed logical: diseases often occurred near swamps, sewage, and decay that produced foul odors.
- Correlation with smell led to causal inference - if places that smelled bad had more disease, smell must cause disease.
- The miasma theory led to some helpful practices (cleaning cities) but for the wrong causal reasons.

The Miasma Mistake

Observed: Bad smells correlate with disease

Inference: Bad air causes disease

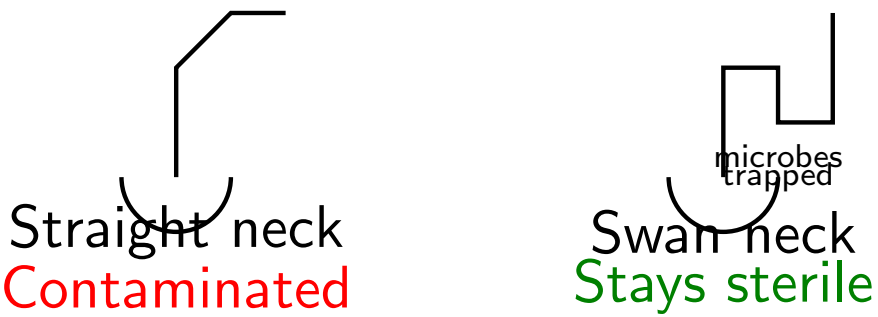
Reality: Microbes cause both bad smells AND disease

Classic case of confusing correlation with causation!

Pasteur's Experiments: Microbes Cause Fermentation and Disease

- Louis Pasteur demonstrated that **microorganisms** - not spontaneous generation or bad air - cause fermentation and decay.
- His swan-neck flask experiment proved that boiled broth stayed sterile unless exposed to airborne microbes.
- Pasteur then linked specific microbes to specific diseases, showing each disease had its own microbial cause.
- These controlled experiments revolutionized medicine by identifying the true **causal agents** of disease.

Pasteur's Swan-Neck Flask



Koch's Postulates: Criteria for Microbial Causation

- Robert Koch developed four **postulates** - criteria to prove a specific microbe causes a specific disease.
- These postulates formalized how to establish causation when dealing with invisible agents and living hosts.
- Koch's systematic approach moved beyond correlation (microbe present in sick patients) to demonstration of causation.
- This framework became the gold standard for establishing microbial causation in infectious disease.

Example (Koch's Four Postulates)

1. Microbe must be found in all cases of the disease
2. Microbe must be isolated and grown in pure culture
3. Cultured microbe must cause disease when introduced to healthy host
4. Microbe must be re-isolated from the new host

Semmelweis and Handwashing: A Natural Experiment in Hospitals

- Ignaz Semmelweis noticed that wards staffed by doctors had higher maternal mortality than those staffed by midwives.
- He hypothesized that doctors performing autopsies carried **"cadaverous particles"** (germs) to patients.
- When handwashing with chlorine was implemented, mortality dropped from 18% to 1% - a natural experiment.
- Despite clear causal evidence, the medical establishment rejected his findings for decades, showing how paradigms resist change.

Resistance to Evidence

Semmelweis had data showing handwashing prevented deaths, but doctors rejected it because:

- It implied doctors were causing deaths
- Invisible germs seemed implausible
- It contradicted established miasma theory

The Anthrax Breakthrough: Isolating a Specific Cause

- Koch's work on **anthrax** in 1876 provided the first complete proof that a specific bacterium causes a specific disease.
- He isolated Bacillus anthracis from diseased animals, grew it in pure culture, and reproduced the disease in healthy animals.
- The anthrax lifecycle discovery explained puzzling observations like why certain fields remained "cursed" for decades.
- This success established the template for proving causation in infectious disease that we still use today.

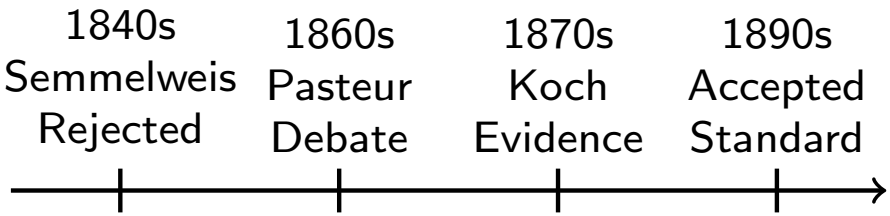
From Mystery to Mechanism

Before: "Cursed fields" where animals mysteriously died
Koch's discovery: Anthrax spores survive in soil for years
Result: Environmental persistence explained by bacterial biology

Understanding the causal agent explained the pattern!

Resistance and Acceptance: Why Causal Claims Face Skepticism

- Germ theory faced fierce **resistance** from the medical establishment for decades despite mounting evidence.
- Accepting germs meant admitting that doctors had unknowingly caused deaths and that established treatments were useless.
- The theory required believing in invisible entities that seemed almost supernatural to many physicians.
- Acceptance came only after overwhelming evidence from multiple researchers and dramatic practical successes like antiseptic surgery.



50 years from evidence to acceptance!

The Epidemiological Challenge: When Experiments Are Unethical

- Proving that smoking causes cancer faced a unique challenge: we cannot ethically randomize people to smoke.
- Unlike infectious diseases, cancer develops over decades, making the causal link harder to establish.
- **Epidemiology** - studying disease patterns in populations - became the primary tool for establishing causation.
- Scientists had to develop new methods to prove causation without controlled experiments on humans.

Example (The Ethical Constraint)

Ideal experiment: Randomly assign 10,000 people to smoke or not smoke for 30 years, measure cancer rates
Reality: Completely unethical!
Solution: Study people who choose to smoke vs. those who don't, controlling for confounders statistically

Correlation Emerges: Early Statistical Links

- In the 1950s, researchers noticed strong **statistical correlations** between smoking rates and lung cancer deaths.
- Case-control studies found lung cancer patients were far more likely to be smokers than healthy controls.
- Cohort studies following thousands of people showed smokers developed lung cancer at 10-30 times the rate of non-smokers.
- The correlation was "dose-dependent" - heavy smokers had higher cancer rates than light smokers.

The Correlation Data (1950s)

Non-smokers: 10 lung cancer deaths per 100,000
Light smokers: 50 lung cancer deaths per 100,000
Heavy smokers: 300 lung cancer deaths per 100,000

But correlation isn't causation - what if smokers differ in other ways?

The Tobacco Industry's Counter-Arguments: Confounders and Doubt

- The tobacco industry exploited the correlation-causation distinction to manufacture **doubt** about the smoking-cancer link.
- They proposed alternative explanations: genetic predisposition, personality types, air pollution, or other lifestyle factors.
- Industry-funded scientists emphasized that without randomized experiments, causation couldn't be "proven" definitively.
- This strategy of "doubt is our product" delayed public health action for decades despite mounting evidence.

Manufacturing Doubt

Tobacco Industry Playbook:

- "Correlation doesn't prove causation"
- Fund studies looking for other explanations
- Demand impossible standard of proof
- Emphasize any uncertainty in the science

Result: Public confusion despite scientific consensus

Hill's Criteria: Nine Tests for Causation Without Experiments

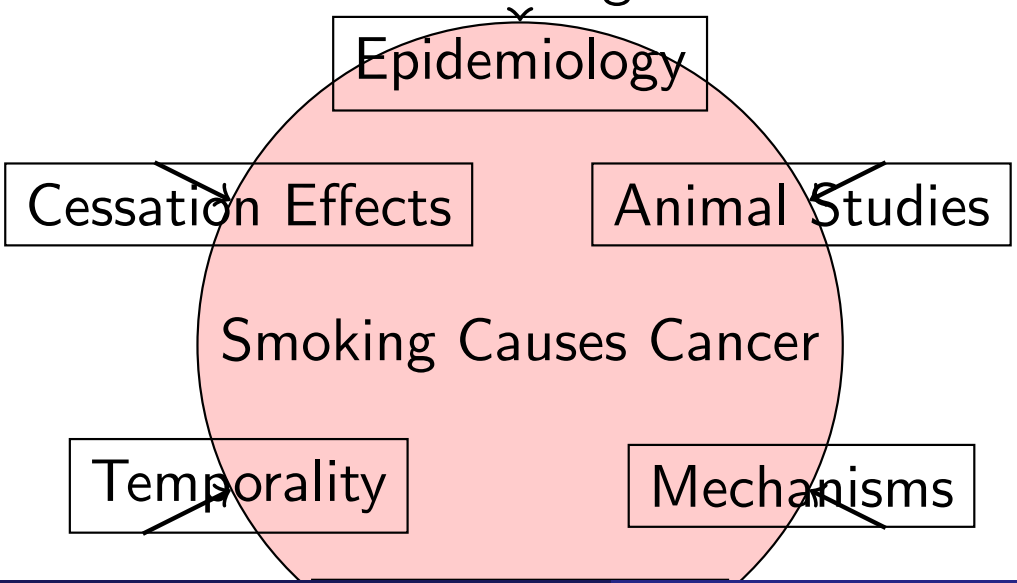
- In 1965, Austin Bradford Hill proposed nine **criteria** for establishing causation from observational data (when no experiment is possible).
- Hill emphasized that no single criterion was necessary or sufficient - rather, the totality of evidence mattered.

Example (Hill's Nine Criteria)

1. **Strength**: How strong is the association?
2. **Consistency**: Observed by different researchers?
3. **Specificity**: Specific exposure, specific disease?
4. **Temporality**: Exposure precedes disease?
5. **Biological gradient**: Dose-response curve?
6. **Plausibility**: Biologically plausible?
7. **Coherence**: Fits with other knowledge?
8. **Experiment**: Natural experiments exist?
9. **Analogy**: Similar causes known?

Converging Evidence: Animal Studies, Mechanisms, and Dose-Response

- **Animal experiments** showed that tobacco tar painted on mice skin caused tumors, providing experimental evidence.
- Scientists identified carcinogens in tobacco smoke and traced the biological mechanisms of DNA damage.
- The **dose-response relationship** - more smoking meant more cancer risk - strongly suggested causation.
- Multiple independent lines of evidence all pointed to the same conclusion: smoking causes cancer.



Policy Implications: From Causal Knowledge to Public Health

- The U.S. Surgeon General's 1964 report officially declared smoking a **cause** of lung cancer, not just a correlation.
- This causal determination justified public health interventions: warning labels, advertising bans, and smoke-free spaces.
- Smoking rates dropped from 42% (1965) to 14% (2019) in the U.S., preventing millions of deaths.
- The smoking case established precedents for how epidemiological evidence can support causal claims and policy action.

The Power of Causal Knowledge

1950s: "Smoking is correlated with cancer" $\rightarrow$ Limited action
1964: "Smoking CAUSES cancer" $\rightarrow$ Public health revolution

Establishing causation, not just correlation, enables effective intervention

The Greenhouse Effect: From 19th Century Theory to Modern Crisis

- In 1859, John Tyndall discovered that **CO_2 and water vapor** trap heat, proposing the greenhouse effect mechanism.
- Svante Arrhenius (1896) calculated that doubling atmospheric CO_2 would cause 5-6°C warming - remarkably close to modern estimates.
- These early scientists identified the causal mechanism decades before any warming was observable.
- The theoretical foundation preceded the evidence, showing how understanding mechanisms can predict future causation.

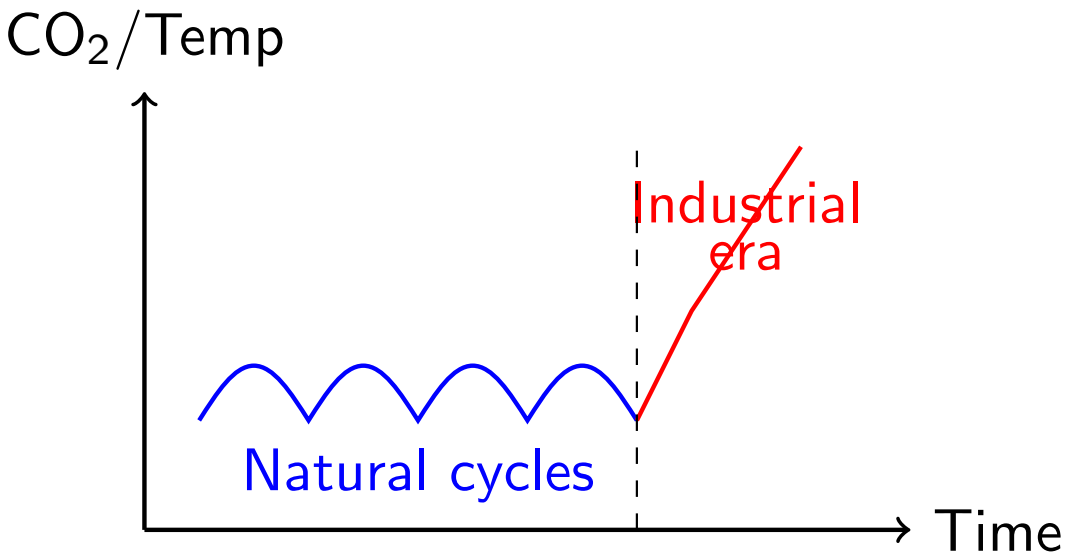
The Causal Chain

Burning fossil fuels $\rightarrow$ Increases atmospheric CO_2 $\rightarrow$
CO_2 traps infrared radiation $\rightarrow$ Earth's temperature rises $\rightarrow$
Climate patterns change globally

Mechanism understood 160+ years ago!

Multiple Lines of Evidence: Temperature Records and Ice Cores

- Global temperature records show approximately 1.1°C warming since pre-industrial times, matching theoretical predictions.
- **Ice cores** provide 800,000 years of climate history, showing CO_2 and temperature move together throughout Earth's history.
- Current CO_2 levels (420+ ppm) are the highest in over 3 million years, far exceeding natural variations.
- Multiple independent datasets (land, ocean, satellite, balloon) all show consistent warming patterns.



Natural Experiments: Volcanic Eruptions as Climate Tests

- Major **volcanic eruptions** provide natural experiments by injecting aerosols that temporarily cool the planet.
- The 1991 Mount Pinatubo eruption caused 0.5°C global cooling for 2-3 years, exactly as climate models predicted.
- These events test our understanding of climate causation - if models correctly predict volcanic cooling, they likely capture warming mechanisms too.
- The temporary cooling followed by resumed warming strengthens evidence that CO_2, not natural factors, drives long-term trends.

Example (Pinatubo as Natural Experiment)

- Prediction (1991): Models forecast 0.5°C cooling
- Observation (1992-93): 0.5°C cooling occurred
- Result: Successful prediction validates climate models
- Implication: Same models show CO_2 causes warming

Computer Models: Simulating Causal Mechanisms

- **Climate models** integrate known physical laws to simulate Earth's climate system and test causal hypotheses.
- Models can run "experiments" impossible in reality: Earth with/without human emissions, doubled CO_2, removed ice caps.
- Only models including human CO_2 emissions reproduce observed 20th-century warming - natural factors alone cannot.
- Multiple independent modeling groups worldwide reach the same conclusions, providing consistency across approaches.

The Fingerprint Test

Models run with only natural causes (solar, volcanic) = No warming trend
Models run with only human causes (CO_2, aerosols) = Matches observations
Models with both natural + human causes = Best match to reality

This "fingerprinting" identifies human causation

The Attribution Problem: Separating Human from Natural Causes

- **Attribution science** works to separate human-caused climate change from natural variability like El Niño and solar cycles.
- Scientists use "detection and attribution" studies comparing observed patterns to those expected from different causes.
- Human causation creates distinct "fingerprints": warming troposphere but cooling stratosphere, Arctic amplification, changing seasons.
- Natural causes alone cannot explain observed changes - only human factors produce the right pattern and magnitude.

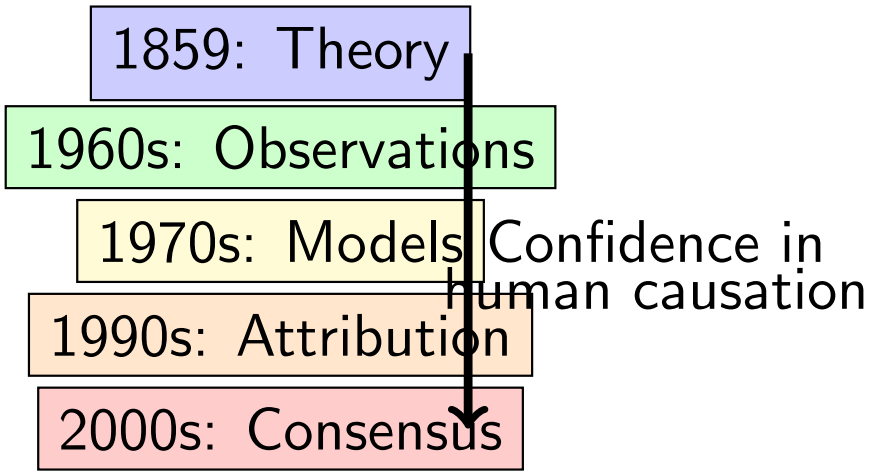
Causal Fingerprints

Observation	**Indicates**
Stratosphere cooling	Greenhouse gases (not solar)
Arctic warms fastest	Ice-albedo feedback
Nights warm more than days	Heat trapping
Ocean warming at depth	Long-term forcing

Scientific Consensus: When Multiple Methods Confirm Causation

- Over 99% of climate scientists agree that humans are causing current global warming - extraordinary consensus.
- This agreement arose from **convergent evidence**: physics, observations, experiments, and models all point to human causation.
- Like evolution and germ theory before it, climate science faced initial skepticism but evidence accumulated overwhelmingly.
- Scientific consensus doesn't determine truth, but when multiple independent methods agree, confidence in causation increases.

Evidence Accumulation



Common Patterns: How Science Establishes Causation

- Across all our cases, scientists used **multiple independent lines of evidence** to establish causation without perfect experiments.
- **Predictive success** proved crucial: Halley's comet, vaccine effectiveness, cancer rates, volcanic cooling all validated theories.
- Understanding **mechanisms** strengthened causal claims: gravity equations, natural selection, germs, carcinogens, greenhouse physics.
- Natural experiments and comparative studies substituted for controlled experiments when manipulation was impossible or unethical.

Example (Universal Strategies)

- Theory predicts $\rightarrow$ Observation confirms
- Multiple methods $\rightarrow$ Same conclusion
- Dose-response $\rightarrow$ Strengthens causation
- Mechanisms explain $\rightarrow$ Patterns observed
- Natural variation $\rightarrow$ Tests hypotheses

The Role of Time: Why Accepting Causal Claims Takes Decades

- Major causal claims in science typically take **30-50 years** from initial proposal to general acceptance.
- This delay reflects both healthy skepticism and resistance from those whose interests are threatened by new knowledge.
- Time allows evidence to accumulate, predictions to be tested, and alternative explanations to be ruled out.
- Each case study shows a similar pattern: early pioneers face rejection, evidence accumulates, and eventually paradigms shift.

The Pattern of Acceptance

Initial claim $\rightarrow$ Fierce resistance $\rightarrow$ Evidence accumulates $\rightarrow$
Predictions confirmed $\rightarrow$ Alternative explanations fail $\rightarrow$
New generation of scientists $\rightarrow$ Paradigm shift $\rightarrow$
"How could anyone have doubted this?"

Lessons for Today: Evaluating Scientific Causal Claims

- When evaluating scientific causal claims, look for **convergent evidence** from multiple independent sources and methods.
- Be suspicious of demands for impossible proof or those who emphasize uncertainty without acknowledging the weight of evidence.
- Recognize that those with financial or ideological stakes often manufacture doubt about inconvenient causal relationships.
- Remember that science's strength lies not in any single study but in the accumulation and integration of evidence over time.

Your Scientific Reasoning Toolkit

✓ Does the proposed mechanism make sense?
✓ Do multiple lines of evidence converge?
✓ Are predictions being confirmed?
✓ Who benefits from denial?
✓ What do experts in the field conclude?
✓ How long has evidence been accumulating?