# Causal Reasoning: Case Studies from the History of Science

## An Introduction to Logic and Experimental Design

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# Introduction: The Power of Causal Reasoning

- Scientific progress depends on our ability to identify cause-and-effect relationships
- Causal reasoning allows us to:
  - Explain natural phenomena
  - Make predictions about future events
  - Design interventions to solve problems
  - Develop technologies that improve human life
- Today we'll explore how scientists across different fields have used causal reasoning to make breakthrough discoveries

**Key Question**

How do scientists establish that X causes Y when direct observation is often impossible?

# Foundations of Causal Reasoning

- John Stuart Mill's Methods provide a logical framework for causal inference:
  - **Method of Agreement**: If multiple instances of a phenomenon have only one factor in common, that factor may be the cause
  - **Method of Difference**: If two similar situations differ only in one factor and the outcome, that factor may be the cause
  - **Method of Concomitant Variation**: If changes in a factor correlate with changes in the outcome, a causal relationship may exist
- These methods form the foundation for modern scientific investigation
- They help distinguish causation from mere correlation

**Example**

If we notice that plants grow better after rain but not after watering with salt water, the difference (fresh vs. salt water) suggests freshwater is a causal factor in plant growth.

# Case Study: John Snow and Cholera (Medicine)

- In 1854, London faced a deadly cholera outbreak that killed hundreds of people.
- At the time, most doctors believed that "miasma" (bad air) caused the disease.
- Dr. John Snow suspected contaminated water might be the real cause.
- He created a map showing cholera deaths clustered around the Broad Street water pump.

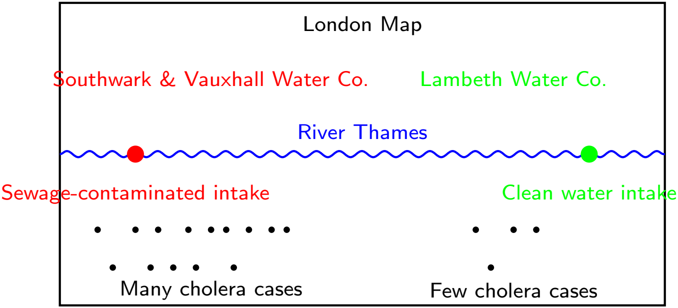
## Snow's Causal Reasoning

Snow used Mill's Method of Difference by comparing:

- People who drank from the Broad Street pump (many got sick)
- Nearby brewery workers who drank beer instead of water (stayed healthy)
- A workhouse with its own water supply (few cases despite being in the area)

# John Snow's Investigation: Causal Reasoning in Action

- Snow noticed that a water company supplying South London was taking water from a sewage-contaminated part of the Thames River.
- Another company supplied water from a cleaner source upstream.
- Snow compared cholera rates between households supplied by the different companies.
- This created a natural experiment where the only major difference was the water source.



# The Significance of Snow's Discovery

- Snow's work represents one of the first systematic applications of causal reasoning in epidemiology.
- He didn't know about bacteria (they weren't yet discovered), but correctly identified the causal pathway.
- His method combined mapping techniques, statistical analysis, and logical reasoning.
- This led to improved water systems and helped establish public health as a field.

## Causal Principles Demonstrated

Snow's work shows:

- The power of natural experiments
- How to reason about invisible causes
- The importance of ruling out alternative explanations
- How good causal reasoning can save lives even before understanding the exact mechanism

# Case Study: Newton's Theory of Gravity (Physics)

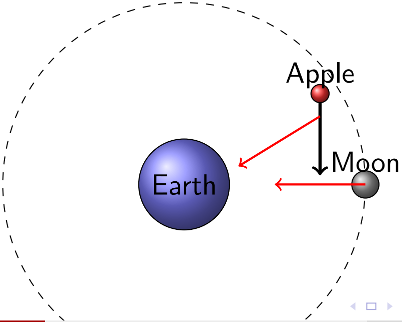
- In the 17th century, people knew objects fell to the ground but didn't understand why.
- According to legend, Newton observed an apple falling from a tree.
- He wondered if the same force that pulled the apple down also kept the moon in orbit around Earth.
- This insight led him to develop his theory of universal gravitation.

**Example**

Newton asked: "Why does the apple fall straight down rather than sideways or up?"
His revolutionary idea was that there must be a force pulling it toward the Earth's center.

# Newton's Causal Reasoning Process

- Newton used **Method of Concomitant Variation** to study how gravitational effects change with distance.
- He showed mathematically that the force of gravity weakens with the square of the distance between objects.
- This explained why the moon stays in orbit rather than falling to Earth or drifting away.
- Newton's laws provided a unified causal explanation for both earthly and celestial motion.



# Testing and Refining Newton's Theory

- Newton's theory made testable predictions about the motion of planets, moons, and comets.
- Astronomers could calculate where planets should be and then check if observations matched.
- When the planet Uranus didn't exactly follow predicted paths, scientists hypothesized another planet must be affecting it.
- This led to the discovery of Neptune in 1846, confirming the causal explanation.

| **Causal Element** | **How Newton's Work Demonstrated It** |
|---|---|
| Universality | The same force explains falling apples and planetary motion |
| Mechanism | Mathematical equations describe precisely how the force works |
| Predictive power | Theory correctly predicts astronomical observations |
| Falsifiability | Theory could be proven wrong if predictions failed |

# Case Study: Darwin and Natural Selection (Biology)

- In the 19th century, people recognized that species seemed well-adapted to their environments.
- The prevailing explanation was that a divine creator had designed each species perfectly.
- Charles Darwin sought a natural causal explanation for these adaptations.
- His voyage on the HMS Beagle provided crucial observations that shaped his thinking.

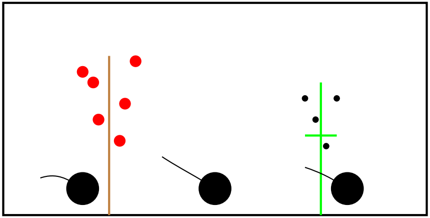
**Key Observations**

Darwin was particularly struck by:

- The variety of finch species on the Galápagos Islands, each with different beaks suited to different foods
- Similarities between living species and fossils in the same regions
- Patterns of species distribution across continents and islands

# Darwin's Process of Causal Discovery

- Darwin couldn't conduct controlled experiments over evolutionary time scales.
- Instead, he used natural variation among species as a kind of "natural experiment."
- He combined the **Method of Agreement** across many species with the **Method of Difference** for closely related species.
- Darwin was influenced by Thomas Malthus's work on population growth, which helped him identify competition as a driving force.



# Natural Selection: A Causal Mechanism

- Darwin identified a clear causal chain to explain adaptations in species:
- 1) Organisms vary in their traits (some finches have larger beaks than others).
- 2) These variations can be inherited by offspring.
- 3) More individuals are born than can survive with limited resources.
- 4) Individuals with advantageous traits survive and reproduce more successfully.

**The Revolutionary Insight**

Darwin recognized that no intelligent designer was needed to create complex adaptations. Given enough time, the simple causal process of natural selection could transform species and create new ones.

# Darwin's Legacy in Causal Thinking

- Darwin showed how a simple causal mechanism could explain complex patterns observed in nature.
- His work demonstrated how to infer causal processes that operate over time scales too long to observe directly.
- He used multiple lines of evidence (comparative anatomy, fossils, geographic distribution) to support his causal theory.
- Evolution by natural selection united disparate biological facts under a single causal framework.

**Example**

Modern verification: We now see natural selection happening in real time with:

- Bacteria evolving antibiotic resistance
- Insects developing resistance to pesticides
- Changes in beak size in Galápagos finches during drought years when only large, tough seeds are available

# Case Study: Semmelweis and Handwashing (Medicine/Chemistry)

- In the 1840s, many women died from "childbed fever" after giving birth in hospitals.
- At Vienna General Hospital, Dr. Ignaz Semmelweis noticed a puzzling pattern.
- Women in the doctor-run maternity ward died at rates 3 times higher than in the midwife-run ward.
- Semmelweis needed to find out what caused this deadly difference.

| First Division (Doctors) | | Second Division (Midwives) |
|---|---|---|
| 10-18% Mortality Rate | ? | 2-3% Mortality Rate |

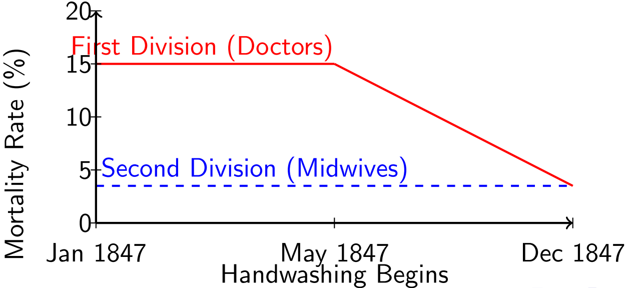
# Semmelweis's Detective Work

- Semmelweis systematically ruled out possible causes using Mill's Methods.
- He eliminated factors like overcrowding, climate, and medical care—these were similar in both wards.
- A crucial clue came when his colleague died with symptoms similar to childbed fever after cutting himself during an autopsy.
- Semmelweis realized doctors (not midwives) performed autopsies and then examined women without washing their hands.

| **Hypothesis** | **First Division** | **Second Division** | **Could Explain Difference?** |
|---|---|---|---|
| Overcrowding | Yes | Yes | No |
| Rough examinations | Maybe | Maybe | No |
| Hospital diet | Same | Same | No |
| Perform autopsies | Yes | No | Yes |

# Testing the Cadaveric Material Hypothesis

- Semmelweis hypothesized that "cadaveric material" (particles from dead bodies) was causing the infections.
- In May 1847, he instituted mandatory handwashing with chlorinated lime solution before examining patients.
- This created an experimental intervention: changing only one variable in the doctors' ward.
- The results were dramatic: mortality rates fell from 18% to below 2%, similar to the midwives' ward.



# Semmelweis's Legacy and Lessons

- Semmelweis identified a causal link between cadaveric material and childbed fever decades before germ theory was established.
- His work illustrates how causal connections can be established without understanding the exact mechanism.
- He effectively used the Joint Method of Agreement and Difference: the only relevant difference between wards was contact with cadavers.
- Despite strong evidence, many doctors rejected his findings because they seemed implausible and implied doctors were causing harm.

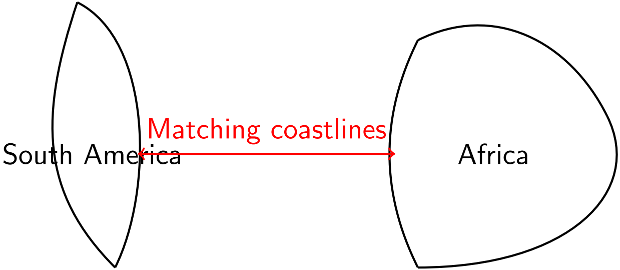
## Causal Reasoning Lessons

Semmelweis's work teaches us:

- The power of natural experiments (comparing two similar wards)
- How to isolate a single causal variable through intervention
- That dramatic results provide strong causal evidence
- That causal findings may face resistance when they challenge existing beliefs

# Case Study: Alfred Wegener and Continental Drift (Geology)

- In the early 20th century, scientists noticed that the coastlines of South America and Africa seemed to fit together like puzzle pieces.
- Most geologists considered this a coincidence, believing continents were fixed in place.
- German meteorologist Alfred Wegener proposed in 1912 that continents had once been joined and had drifted apart.
- His challenge: proving a process too slow to observe directly.



# Wegener's Evidence for Continental Drift

- Wegener used Mill's **Method of Agreement** by gathering multiple lines of evidence supporting his theory:
- **Fossil evidence**: Identical plant and animal fossils appeared on continents now separated by oceans.
- **Geological matching**: Similar rock formations and mountain ranges lined up across continents.
- **Climate evidence**: Coal deposits in Antarctica suggested it once had a tropical climate.

**Example**

The fossil Mesosaurus, a freshwater reptile, was found only in South America and Africa. Since it couldn't have swum across the Atlantic Ocean, Wegener argued these continents must once have been connected.

# Rejection and Later Vindication

- Despite his evidence, Wegener's theory was widely rejected by the scientific community.
- The main criticism was that he couldn't explain a plausible mechanism that could move entire continents.
- Geologists believed the Earth's crust was too rigid to allow for continental movement.
- It wasn't until the 1950s and 1960s that new evidence from seafloor mapping and paleomagnetism provided the missing mechanism.

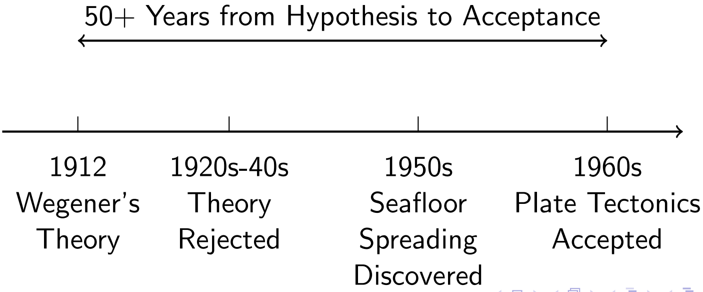
### The Missing Mechanism: Plate Tectonics

Scientists eventually discovered that:

- The Earth's crust is divided into plates that float on the semi-liquid mantle
- Convection currents in the mantle drive plate movement
- New crust forms at mid-ocean ridges and old crust sinks at subduction zones

# Causal Reasoning Lessons from Continental Drift

- Wegener's case demonstrates the importance of multiple converging lines of evidence for establishing causation.
- It shows how scientists can infer causal processes that operate too slowly to observe directly.
- The initial rejection illustrates that causal explanations are stronger when they include a plausible mechanism.
- The story reveals how science is self-correcting: new evidence eventually confirmed Wegener's core insight.



# Case Study: Natural Experiments in Minimum Wage Research (Economics)

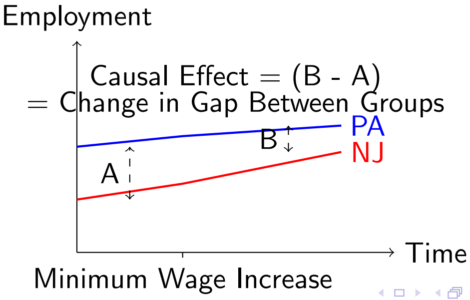
- Economic theories often predict that raising minimum wages will reduce employment.
- Testing this causal relationship is challenging because we can't randomly assign minimum wages to different areas.
- In 1994, economists Card and Krueger used a natural experiment to study this question.
- They compared employment at fast-food restaurants in New Jersey and Pennsylvania before and after a minimum wage increase.

## The Natural Experiment Setup

- New Jersey raised its minimum wage from $4.25 to $5.05 in April 1992
- Neighboring Pennsylvania kept its minimum wage at $4.25
- Restaurants just across the state border shared similar economic conditions

# Difference-in-Differences: A Modern Causal Method

- Card and Krueger used a causal inference technique called "difference-in-differences."
- This method compares the change in one group (New Jersey) to the change in another group (Pennsylvania).
- It controls for both fixed differences between states and time trends affecting both states.
- This approach helps isolate the causal effect of the minimum wage change.



# Surprising Results and Causal Implications

- Contrary to basic economic theory, Card and Krueger found no evidence that the minimum wage increase reduced employment.
- In fact, they found slight employment increases in New Jersey compared to Pennsylvania.
- This challenged conventional economic wisdom about the causal relationship between minimum wages and employment.
- Their findings sparked debate about alternative causal explanations in labor markets.

| **State** | **Before** | **After** | **Change** |
|---|---|---|---|
| New Jersey | 20.4 employees | 21.0 employees | +0.6 |
| Pennsylvania | 23.3 employees | 21.2 employees | -2.1 |
| Difference-in-differences: +2.7 employees | | | |

# Economic Causal Reasoning: Challenges and Advances

- Economics faces unique causal reasoning challenges because controlled experiments often aren't possible at scale.
- Modern economics has developed sophisticated methods to approximate experimental designs using observational data.
- Besides difference-in-differences, economists use methods like instrumental variables, regression discontinuity, and propensity score matching.
- These techniques help isolate causal effects from complex economic systems with many interconnected variables.

## Key Lesson for Causal Reasoning

The minimum wage studies demonstrate how apparent correlations may conflict with our causal theories. When this happens, we need to:

- Examine our assumptions about causal mechanisms
- Consider alternative causal explanations
- Gather more evidence from different settings
- Refine our causal models to account for new evidence

# Case Study: The Marshmallow Test (Psychology)

- In the 1960s-70s, psychologist Walter Mischel conducted the famous "marshmallow test" experiments.
- Children were offered a choice: eat one marshmallow immediately or wait 15 minutes to receive two marshmallows.
- Researchers observed how long children could delay gratification.
- Years later, they followed up with the participants to study long-term outcomes.

# The Original Causal Claim

- The original follow-up studies suggested a strong causal relationship between:
- Self-control at age 4 (measured by waiting time) $\rightarrow$ Better life outcomes in adolescence and adulthood
- Children who waited longer reportedly had higher SAT scores, better educational outcomes, lower BMI, and other positive life outcomes.
- This led to popular interpretations that early self-control abilities determine future success.

**Example**

A child who waited the full 15 minutes at age 4 was reported to score on average 210 points higher on the SAT than a child who couldn't wait at all, suggesting a powerful causal relationship between early self-control and later cognitive abilities.

# Reexamining Causality: Confounding Variables

- Later studies revealed important confounding variables that complicated the causal story.
- Family socioeconomic status strongly predicted both waiting ability and future outcomes.
- Children's trust in the researcher (based on previous experiences) influenced their waiting behavior.
- A 2018 replication study with a larger, more diverse sample found much smaller effects.

### Complex Causality

The updated causal model shows how:

- Family background influences both self-control and later outcomes
- Environmental reliability affects strategic decision-making
- What looked like a simple A $\rightarrow$ B relationship was actually much more complex

# Lessons in Psychological Causal Reasoning

- The marshmallow test case illustrates how initial causal conclusions may be oversimplified.
- Psychological phenomena often involve complex interactions between individual traits and environmental factors.
- Longitudinal studies (following subjects over time) are valuable but prone to confounding variables.
- Replication with larger, more diverse samples helps establish the reliability of causal claims.

Original model

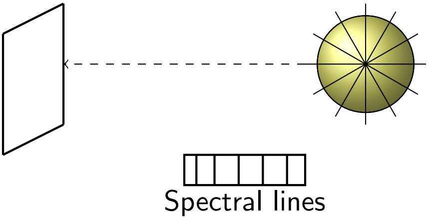
Self-control $\longrightarrow$ Life outcomes

$$
\begin{tikzcd}
 & \text{Family SES} \arrow[dl] \arrow[dr] & \\
\text{Self-control} \arrow[rr] & & \text{Life outcomes} \\
\text{Environmental trust} \arrow[u] & &
\end{tikzcd}
$$

Updated causal model

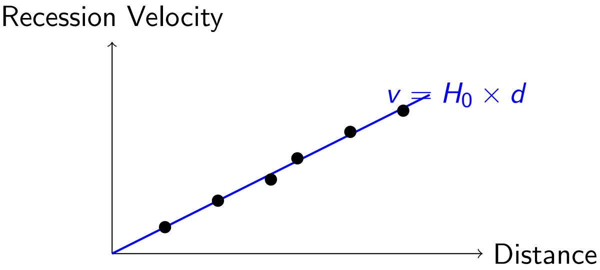
# Case Study: Hubble and the Expanding Universe (Astronomy)

- In the early 20th century, most astronomers believed the universe was static and unchanging.
- Edwin Hubble studied distant galaxies using the 100-inch telescope at Mount Wilson Observatory.
- He measured both the distances to galaxies and their spectra (the light patterns they emitted).
- His observations led to one of the most important causal discoveries in astronomy.



# The Red Shift Pattern and Hubble's Law

- Hubble observed that light from distant galaxies was shifted toward the red end of the spectrum.
- This "redshift" phenomenon was known to occur when a light source moves away from an observer (the Doppler effect).
- Hubble discovered that the farther away a galaxy was, the greater its redshift.
- This relationship, now known as Hubble's Law, revealed that galaxies are moving away from us—and from each other.



# From Observation to Causal Understanding

- Hubble's observations provided evidence that the universe is expanding in all directions.
- This led to the inference that if we "run the film backward," the universe must have had a beginning—the Big Bang.
- Hubble didn't directly observe the expansion itself but inferred it as the causal explanation for the redshift pattern.
- This demonstrates how careful pattern recognition and mathematical analysis can reveal causal mechanisms at cosmic scales.

## From Effect to Cause

Hubble's reasoning process:

1. Observe effect: Galaxies show redshifts proportional to their distance
2. Apply known principle: Redshift indicates motion away from observer (Doppler effect)
3. Infer cause: The universe must be expanding in all directions
4. Further inference: The expansion implies a beginning point in the past

# Multiple Lines of Evidence: Strengthening Causal Claims

- Hubble's expansion theory was later supported by additional evidence, strengthening the causal case.
- The cosmic microwave background radiation (discovered in 1965) provided evidence of the Big Bang.
- The abundance of light elements in the universe matched predictions from Big Bang nucleosynthesis.
- The large-scale structure of the universe aligned with models of how matter would distribute during expansion.

## Causal Reasoning Lessons

The Hubble case demonstrates:

- How mathematical relationships can reveal causal patterns
- The importance of converging evidence from multiple sources
- How causal inference can work at scales far beyond direct human experience
- That revolutionary causal insights often involve rethinking our fundamental assumptions about the world

# Common Patterns Across Scientific Disciplines

- Across our case studies, successful causal reasoning often involves:
  - Careful observation of patterns that violate expectations
  - Identifying natural experiments or creating interventions
  - Ruling out alternative explanations systematically
  - Gathering multiple lines of converging evidence
  - Proposing mechanisms that explain how causes produce effects
- Scientists may not always understand the full causal mechanism at first (Snow, Semmelweis, Wegener)
- Initial causal models are often refined or revised as new evidence emerges (Marshmallow Test)

**From Simple to Complex Causality**

Scientific progress often involves moving from simple causal models (A causes B) to more complex understandings with multiple interacting factors and feedback loops.

# Modern Approaches to Causal Inference

- Contemporary science has developed sophisticated tools for causal reasoning:
  - Randomized controlled trials – the "gold standard" in medicine
  - Natural experiments and quasi-experimental designs
  - Statistical methods like difference-in-differences, instrumental variables
  - Causal graph theory and structural equation modeling
  - Computer simulations to test causal theories
- These tools extend and formalize Mill's classic methods
- They allow us to tackle increasingly complex causal questions

$$A \longrightarrow B \longrightarrow C \qquad \begin{tikzcd} D \arrow[r] \arrow[d] \arrow[dr, bend left] & E \arrow[d] \\ F \arrow[r] & G \end{tikzcd}$$

# Why Causal Reasoning Matters

- Casual reasoning is essential for:
  - Scientific understanding - Explaining why natural phenomena occur
  - Problem-solving - Identifying effective interventions
  - Critical thinking - Evaluating claims about cause and effect
  - Personal decision-making - Understanding consequences of our actions
- Mistaking correlation for causation leads to:
  - Ineffective policies and interventions
  - Wasted resources on non-causal factors
  - Missed opportunities to address real causes
  - Potentially harmful actions based on flawed understanding

**The Legacy of Scientific Causal Reasoning**

The scientific breakthroughs we've examined didn't just solve specific problems—they transformed how we understand our world and demonstrated the power of human reason to uncover causal relationships that are not immediately obvious.

# Discussion Questions

1. How might Snow's approach to cholera investigation be applied to modern public health challenges?
2. Which do you think is more important in science: having a causal mechanism or having strong statistical evidence of a relationship?
3. Why do you think Semmelweis and Wegener faced such resistance to their causal theories, despite compelling evidence?
4. What are some everyday examples where people commonly mistake correlation for causation?
5. How might causal reasoning in science be strengthened or improved in the future?

**Final Thought**

"No amount of experimentation can ever prove me right; a single experiment can prove me wrong." - Albert Einstein
This captures an important asymmetry in causal reasoning: disproving causal claims is often easier than conclusively proving them.