Causal Reasoning: From Mill to Modern Experiments

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Introduction to Logic

What Does It Mean When We Say 'A Causes B'?

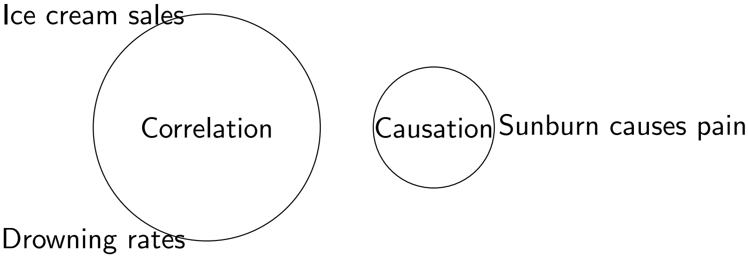
- When we say "A causes B," we mean that A makes B happen in some way.
- A causal relationship implies that if we change A, B will also change as a result.
- **Causality** refers to the relationship between events where one event (the cause) brings about another event (the effect).
- Understanding causality helps us explain why things happen and predict what might happen in the future.

Key Question

How can we be sure that A really causes B, and it's not just coincidence or something else causing both A and B?

Correlation vs. Causation: Why They're Not the Same

- **Correlation** means two things tend to happen together or change together.
- **Causation** means one thing actually makes the other thing happen.
- Just because two things happen together doesn't mean one causes the other.
- Both events might be caused by a third factor we haven't considered.



The History of Causal Reasoning: From Aristotle to Today

- Aristotle (384-322 BCE) identified four types of causes: material, formal, efficient, and final causes.
- David Hume (1711-1776) questioned whether we can truly observe causation or just regular succession of events.
- John Stuart Mill (1806-1873) developed systematic methods for establishing causal relationships.
- Modern scientists use statistical methods and controlled experiments to determine causality.

Important Development

The shift from philosophical reasoning to empirical scientific methods has been crucial for establishing reliable causal relationships.

John Stuart Mill and the Quest for Causality

- John Stuart Mill was a British philosopher who systematized approaches to find causal relationships.
- Mill's work "A System of Logic" (1843) formalized methods for scientific inquiry.
- Mill believed that careful observation and comparison could reveal causal connections.
- His methods remain influential in scientific reasoning and experimental design today.

Example

Mill was concerned with questions like: "Does this medicine cure this disease?" or "Does this educational technique improve learning?"

Introduction to Mill's Methods: Five Ways to Find Causes

- Mill developed five systematic methods to identify causal relationships through observation.
- These methods provide a framework for thinking about what causes what.
- Mill's methods help us differentiate between coincidence and true causation.
- These techniques form the foundation of modern experimental design.

Mill's Five Methods

1. Method of Agreement
2. Method of Difference
3. Joint Method of Agreement and Difference
4. Method of Residues
5. Method of Concomitant Variation

Method of Agreement: Finding What's Common When Effects Are Similar

- The **Method of Agreement** looks for the one factor that is present in all cases where the effect occurs.
- If multiple instances of a phenomenon have only one circumstance in common, that circumstance is likely the cause.
- This method works by examining different scenarios that produce the same effect.
- It helps identify necessary conditions for an effect to occur.

Case	Factor A	Factor B	Factor C	Effect X
1	Present	Present	Absent	Occurs
2	Present	Absent	Present	Occurs
3	Present	Absent	Absent	Occurs
Factor A is likely the cause of Effect X				

Method of Agreement Example: Professor Frink's Lab Explosion

Scenario: Professor Frink is investigating what causes his laboratory experiments to explode. He examines five recent explosions.

Explosion	Heat Source	Chemical X	Lightning	Glavin!	Result
1	Yes	Yes	No	Yes	Explosion
2	No	Yes	Yes	Yes	Explosion
3	Yes	Yes	Yes	No	Explosion
4	No	Yes	No	No	Explosion
5	Yes	Yes	No	Yes	Explosion

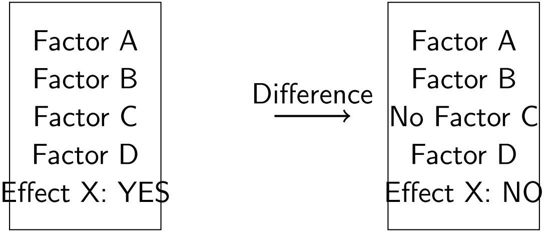
Analysis: Chemical X is the only factor present in ALL explosions.
Conclusion by Method of Agreement: Chemical X is likely the cause of the explosions.

Professor Frink says:

"Glavin! The data clearly indicates that Chemical X is the necessary ingredient for my spectacular laboratory failures!"

Method of Difference: The Power of Comparison

- The **Method of Difference** compares two scenarios: one where the effect occurs and one where it does not.
- If the scenarios differ in only one factor, that factor is likely the cause.
- This method is powerful because it isolates a single variable that makes a difference.
- It closely resembles modern controlled experiments.



Method of Difference Example: Dexter's Growth Serum

Scenario: Dexter wants to test whether his new growth serum causes plants to grow taller. He sets up two identical experiments.

Plant A	**Plant B**
Growth Serum: YES	Growth Serum: NO
Sunlight: 8 hours	Sunlight: 8 hours
Water: 100ml daily	Water: 100ml daily
Soil Type: Potting mix	Soil Type: Potting mix
Temperature: 22°C	Temperature: 22°C
Height: 15cm	**Height: 8cm**

Analysis: The only difference is the growth serum, yet Plant A grew much taller.

Conclusion by Method of Difference: The growth serum causes increased plant growth.

Dexter concludes:

"The experimental data supports my hypothesis with 93.7% confidence!"

Joint Method of Agreement and Difference: Combining Approaches

- The **Joint Method** combines the strengths of the Methods of Agreement and Difference.
- It looks for a factor that is present whenever the effect occurs and absent whenever the effect is absent.
- This method provides stronger evidence than either method alone.
- It reduces the likelihood of coincidental associations being mistaken for causes.

Case	Factor A	Factor B	Factor C	Effect X
1	Present	Present	Absent	Occurs
2	Present	Absent	Present	Occurs
3	Absent	Present	Present	Does Not Occur
4	Absent	Absent	Present	Does Not Occur
Factor A is most likely the cause of Effect X				

Joint Method Example: Rick's Portal Gun Malfunctions

Scenario: Rick is investigating when his portal gun malfunctions. He needs to find what's present when it fails AND absent when it works.

Test	Drunk	Morty Nearby	Battery Low	Burping	Malfunction?
1	Yes	Yes	No	Yes	YES
2	Yes	No	Yes	Yes	YES
3	No	Yes	Yes	No	NO
4	No	No	Yes	No	NO
5	Yes	No	No	Yes	YES
6	No	Yes	No	No	NO

Analysis: Being drunk is present in ALL malfunctions (tests 1, 2, 5) and absent in ALL successful uses (tests 3, 4, 6).
Conclusion by Joint Method: Rick's drunkenness causes portal gun malfunctions.

Rick's response:

"Listen Morty, *burp* the science clearly shows that alcohol actually IMPROVES my inventions... this data must be wrong, Morty!"

Method of Residues: What's Left When Everything Else Is Explained

- The **Method of Residues** applies when part of an effect has already been attributed to certain causes.
- If we subtract the known causes and their effects, what remains must be caused by the remaining factors.
- This method builds on existing knowledge of causal relationships.
- It helps identify complex causal relationships where multiple factors are involved.

Key Formula

If ABC causes XYZ, and we know A causes X and B causes Y, then C must cause Z.

Method of Residues Example: Jimmy Neutron's Rocket Fuel

Scenario: Jimmy's rocket achieves 1000 units of thrust, but he wants to understand what contributes to this total power.

Previous Knowledge:

- Liquid oxygen contributes 400 units of thrust
- Fuel stabilizer contributes 250 units of thrust
- Ignition system contributes 150 units of thrust

Current Rocket Components:

- Liquid oxygen (400 units)
- Fuel stabilizer (250 units)
- Ignition system (150 units)
- NEW: Neutronium catalyst (? units)

Analysis by Method of Residues:

$$\text{Total thrust} = 1000 \text{ units} \tag{1}$$

$$\text{Known components} = 400 + 250 + 150 = 800 \text{ units} \tag{2}$$

$$\text{Neutronium catalyst} = 1000 - 800 = 200 \text{ units} \tag{3}$$

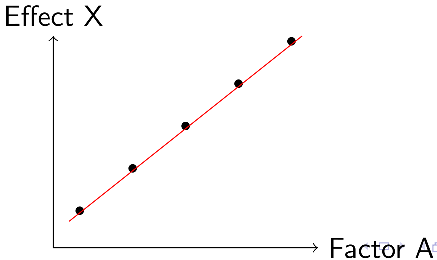
Conclusion: The neutronium catalyst contributes 200 units of thrust.

Jimmy says:

"Brain blast! The neutronium catalyst accounts for exactly 20% of our total propulsion!"

Method of Concomitant Variation: When Things Change Together

- The **Method of Concomitant Variation** examines how changes in one variable relate to changes in another.
- If a change in Factor A consistently corresponds with a change in Effect X, they are likely causally related.
- This method is especially useful for factors that cannot be completely removed.
- It helps identify causal relationships that involve quantities rather than just presence or absence.



Applying Mill's Methods: Real-World Examples

- Medical research often uses the Method of Difference to test whether a treatment causes improvement.
- Epidemiologists use the Method of Agreement to identify common factors in disease outbreaks.
- Social scientists apply the Method of Concomitant Variation to study how education affects income.
- Environmental scientists use the Joint Method to establish links between pollutants and ecosystem effects.

Example

Snow's Cholera Investigation (1854): John Snow used Mill's methods to determine that contaminated water caused cholera by mapping cases and identifying a common source (the Broad Street pump).

The Limitations of Mill's Methods

- Mill's methods assume we can identify all relevant factors, which is often impossible in complex situations.
- They don't account for probabilistic causation, where causes increase the likelihood of effects rather than guaranteeing them.
- The methods can be misled by coincidental correlations or hidden variables.
- They struggle with situations where multiple causes interact or where feedback loops exist.

Important Consideration

Mill's methods provide a useful starting point but modern science has developed more sophisticated approaches to address these limitations.

From Philosophy to Science: The Evolution of Causal Thinking

- Modern causal reasoning builds on Mill's methods but adds statistical analysis and experimental controls.
- The scientific method formalizes the process of hypothesis testing through controlled experiments.
- Randomized controlled trials emerged in the 20th century as the gold standard for establishing causation.
- Computer science and statistics have developed new mathematical tools for causal inference from data.

Mill's Methods 1843 → Statistical Inference 1900s → Randomized Controlled Trials 1950s → Causal Inference Models 2000s

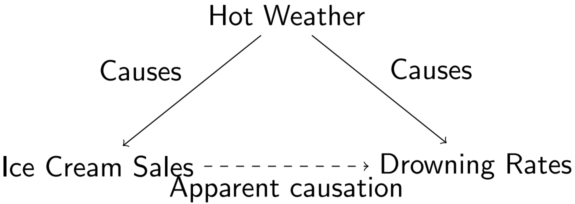
Variables 101: Dependent, Independent, and Control

- An **independent variable** is what researchers manipulate or change to see if it causes an effect.
- A **dependent variable** is what researchers measure to see if it was affected by the independent variable.
- **Control variables** are factors kept constant to ensure they don't influence the results.
- Understanding these variables is essential for designing experiments that can establish causation.

Variable Type	**Example in Plant Growth Experiment**
Independent	Amount of fertilizer applied to plants
Dependent	Height of plants after 2 weeks
Control	Type of soil, amount of water, amount of sunlight, temperature

Confounding Variables: The Hidden Troublemakers

- **Confounding variables** are factors that affect both the independent and dependent variables, creating a false impression of causation.
- They can make it appear that A causes B when in reality C causes both A and B.
- Identifying and controlling for confounding variables is one of the biggest challenges in causal research.
- Failure to account for confounders is a common source of incorrect causal conclusions.



Controlled Experiments: The Gold Standard of Causal Discovery

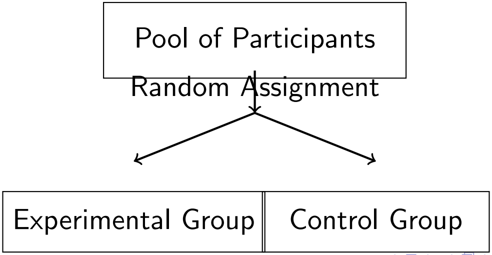
- A **controlled experiment** systematically manipulates one variable while keeping all others constant.
- The experimental group receives the treatment while the control group does not.
- This design isolates the effect of the independent variable on the dependent variable.
- Controlled experiments provide the strongest evidence for causal relationships.

Key Components of a Controlled Experiment

- Control group and experimental group(s)
- Random assignment of subjects
- Manipulation of the independent variable
- Measurement of the dependent variable

Randomization: Why Leaving Things to Chance Makes Scientific Sense

- **Randomization** means assigning subjects to groups by chance, not by choice or pattern.
- Random assignment helps distribute unknown confounding variables equally across groups.
- This ensures that differences between groups are likely due to the treatment, not pre-existing differences.
- Randomization is a crucial innovation that strengthens Mill's Method of Difference.



Sample Size and Statistical Power: Why Numbers Matter

- **Sample size** refers to the number of subjects or observations in a study.
- Larger samples make it more likely to detect true effects and less likely to be misled by random variation.
- **Statistical power** is the ability of a study to detect an effect if one actually exists.
- Small studies may miss real causal relationships due to insufficient power.

Sample Size	**Implications**
Small ($n < 30$)	High variability, low reliability, susceptible to outliers, low power
Medium ($30 < n < 100$)	Moderate reliability, may detect large effects
Large ($n > 100$)	More reliable, can detect smaller effects, more generalizable

Blind and Double-Blind Studies: Removing Bias

- In a **blind study**, participants don't know whether they're in the experimental or control group.
- In a **double-blind study**, neither participants nor researchers know who is in which group.
- Blinding prevents expectations from influencing behavior and measurements.
- This approach eliminates psychological biases that can create false impressions of causality.

Example

A medication trial where patients receive either the real drug or a placebo that looks identical. Neither patients nor doctors evaluating responses know who received which treatment until after data collection is complete.

Placebo Effect: When Belief Causes Change

- The **placebo effect** occurs when improvement happens because a person believes they're receiving effective treatment.
- This demonstrates how psychological factors can create real physiological changes.
- The placebo effect is a legitimate causal relationship (belief $\rightarrow$ improvement).
- Controlling for the placebo effect is essential in determining whether treatments have effects beyond psychological expectations.

Important Note

The placebo effect is not "fake" or "all in the mind" but a real phenomenon with measurable biological effects, including changes in brain chemistry and immune response.

Natural Experiments: When Nature Does the Work for Us

- **Natural experiments** occur when circumstances create comparison groups without researcher intervention.
- These situations allow us to study causes when deliberate experiments would be impossible or unethical.
- Natural experiments approximate Mill's methods in real-world settings.
- They provide valuable causal insights when controlled experiments aren't feasible.

Example

After a flood in 1993, some schools in Chicago were damaged and closed, forcing students to transfer to better-performing schools. Researchers tracked these students to study the effect of school quality on academic achievement, finding significant improvements compared to similar students who stayed in their original schools.

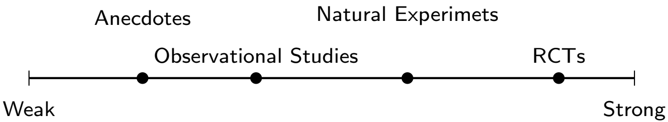
Case Studies vs. Controlled Experiments: Strengths and Weaknesses

- **Case studies** examine a single instance or small group in great depth.
- They provide rich detail but may not generalize to other situations.
- Controlled experiments offer stronger causal evidence but often sacrifice context and detail.
- Both approaches have complementary roles in establishing causal knowledge.

Aspect	**Case Studies**	**Controlled Experiments**
Depth	Rich, detailed information	Limited information on many cases
Breadth	Limited to few cases	Many subjects/observations
Causal evidence	Suggestive, exploratory	Strong, confirmatory
Context	Preserved	Often removed

Observational Studies: Finding Patterns in the Wild

- **Observational studies** examine existing data without manipulating variables.
- Researchers look for patterns and associations that suggest causal relationships.
- Statistical techniques help control for confounding variables after data collection.
- These studies are valuable when experiments are impractical but provide weaker causal evidence.



Counterfactuals: Thinking About What Didn't Happen

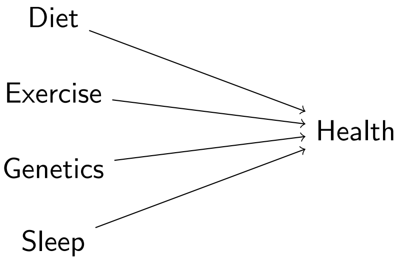
- A **counterfactual** is a "what if" scenario that didn't actually occur but could have.
- Causal claims implicitly involve counterfactuals: "If A hadn't happened, B wouldn't have happened."
- Controlled experiments create real-world counterfactuals through control groups.
- Counterfactual thinking helps us understand the logic behind causal reasoning.

The Counterfactual Definition of Causation

Event A causes event B if and only if, had A not occurred, B would not have occurred either (assuming all else remained the same).

The Problem of Multiple Causes

- Most effects in the real world have multiple causes working together.
- A single cause may be necessary but not sufficient to produce an effect.
- Multiple causal pathways may lead to the same outcome.
- Understanding how causes interact is essential for accurate causal reasoning.



When Causes Are Probabilistic, Not Deterministic

- **Deterministic causation** means that if A occurs, B must occur.
- **Probabilistic causation** means that if A occurs, B becomes more likely but isn't guaranteed.
- Most real-world causes are probabilistic rather than deterministic.
- Statistical methods help us identify causes that increase the probability of effects.

Example

Smoking causes lung cancer, but not every smoker develops lung cancer, and some non-smokers do. Smoking increases the probability of lung cancer by about 15-30 times compared to non-smokers.

Causal Chains: From Dominos to Complex Systems

- **Causal chains** are sequences where one event causes another, which causes another, and so on.
- Understanding these chains helps identify root causes and intervention points.
- Longer chains have more potential breaking points, making predictions less reliable.
- In complex systems, causal chains may include feedback loops and interactions.

Drought → Crop Failure → Food Shortage → Price Increase → Social Unrest

Political instability affects drought response

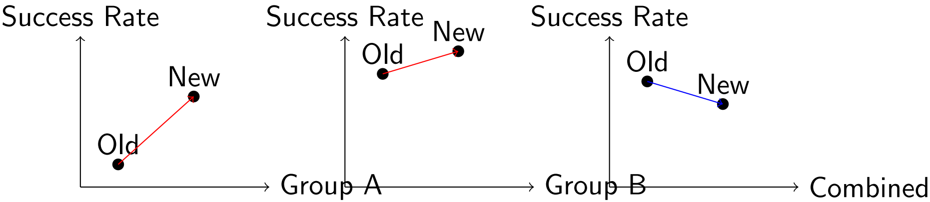
Necessary vs. Sufficient Causes: Different Types of "Because"

- A **necessary cause** must be present for the effect to occur (without A, no B).
- A **sufficient cause** guarantees the effect will occur (if A, then B).
- Some causes are both necessary and sufficient; others are neither.
- Understanding these distinctions helps clarify what we mean when we say "A causes B."

	Necessary	**Not Necessary**
Sufficient	Oxygen for fire (both necessary and sufficient)	Match strike for fire (sufficient but not necessary - can use lighter)
Not Sufficient	Exposure to virus for infection (necessary but not sufficient)	Red hair for sunburn (neither necessary nor sufficient)

Simpson's Paradox: When Groups Tell Different Stories Than Individuals

- **Simpson's Paradox** occurs when a trend appears in separate groups but disappears or reverses when the groups are combined.
- This paradox demonstrates how aggregating data can obscure or misrepresent causal relationships.
- It highlights the importance of considering subgroup differences when analyzing data.
- Simpson's Paradox is a warning against drawing hasty causal conclusions from statistical summaries.



Common Causal Fallacies in Everyday Reasoning

- The **post hoc fallacy** assumes that if B follows A, then A caused B (confusing sequence with causation).
- The **correlation fallacy** mistakes correlation for causation without considering alternative explanations.
- The **single-cause fallacy** assumes complex phenomena have simple, single causes.
- The **reversing causation fallacy** gets the direction of causality backward.

Warning Signs of Causal Fallacies

Be cautious of causal claims that:

- Involve only two variables in a complex system
- Are based on a few anecdotes or small samples
- Don't consider alternative explanations
- Align suspiciously well with someone's agenda

Critical Thinking About Causality in News and Social Media

- News headlines often imply causation when only correlation has been established.
- Social media can spread causal claims without the context needed to evaluate them.
- Understanding research methods helps evaluate the strength of causal claims.
- Critical questions about sample size, confounders, and alternative explanations are essential.

Example

Headline: "Study Finds Coffee Drinkers Live Longer"
Critical questions to ask: Was this a controlled experiment or an observational study? Did researchers control for other lifestyle factors? Could the relationship be reversed (do healthier people drink more coffee)? How large was the sample size and how significant was the effect?

Ethics in Causal Research: When We Can't Do Certain Experiments

- Many important causal questions cannot be studied through controlled experiments due to ethical constraints.
- It would be unethical to deliberately expose people to potential harms, even for knowledge.
- Researchers must use alternative methods like natural experiments and observational studies.
- Ethical considerations shape how we acquire causal knowledge about human behavior and health.

Examples of Ethical Boundaries

We cannot ethically conduct experiments to determine:

- Whether smoking causes cancer by assigning people to smoke
- The effects of abuse or neglect on children's development
- Long-term effects of illegal drugs by giving them to participants
- How pollution affects health by deliberately exposing communities

Modern Causal Inference: Beyond Mill's Methods

- **Causal inference** is the modern field that develops mathematical and statistical tools for establishing causation.
- **Directed Acyclic Graphs (DAGs)** provide visual representations of causal relationships in complex systems.
- **Propensity score matching** helps simulate experimental conditions with observational data.
- **Instrumental variables** exploit natural randomization to establish causal effects.

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Data Science and Causality: New Frontiers

- Big data and machine learning are creating new opportunities and challenges for causal reasoning.
- Correlation-focused algorithms can find patterns but struggle to establish causation.
- **Causal machine learning** combines traditional experimental design with modern computational methods.
- These approaches help us move from "what happened" to understanding "why it happened."

Important Distinction

"Machine learning provides the power to predict but not necessarily to understand. Causal reasoning provides the understanding necessary for meaningful intervention."
– Judea Pearl, Computer Scientist and Causality Researcher

Causality in Your Life: Making Better Decisions

- Understanding causal reasoning helps you evaluate claims in media, advertising, and politics.
- Causal thinking improves personal decision-making by distinguishing between correlation and causation.
- Seeking evidence for causal claims protects against manipulation and misinformation.
- The principles of causal inference apply to everything from personal health choices to policy decisions.

Summary: From Mill to Modern Experiments

- Mill's methods provide a foundation for systematic causal reasoning
- Controlled experiments strengthen causal evidence through randomization and controls
- Understanding causal complexity helps us navigate an increasingly complicated world
- Critical thinking about causality is an essential skill for informed citizenship