Causal Identification

The Causal Graph Perspective

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Outline

1 The graph terminology

2 Causal graph

3 The do-operator
- Interventions: the secret sauce
- Understanding the do $(\cdot)$

4 Understanding do-calculus

5 Causal identification
- Defining causal identification
- Four identification strategies

RSM Erasmus

Causation $\neq$ correlation

- Try to explain how causation and correlation are different.
- You know the differences but it is difficult to verbalize.
- We lack a sort of “language” to explain the differences.

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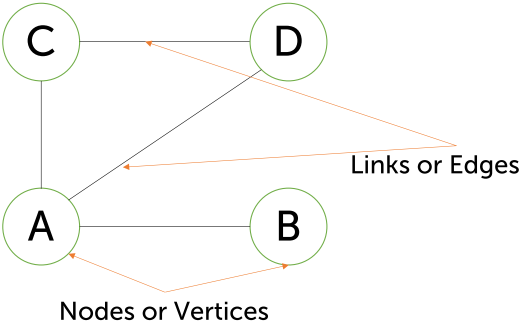
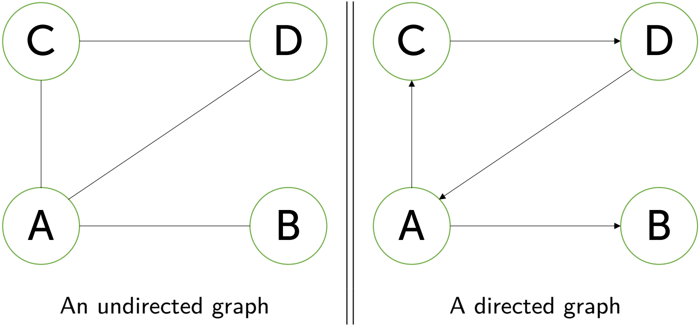
The atoms of a graph



- Nodes: any entity, e.g., people, organizations, charging stations, internet routers
- Links: any relationship or connectedness

Directed vs. undirected graphs



- Undirected graph: no directions, e.g., Facebook friends
- Directed graph: with directions, e.g., Twitter followers

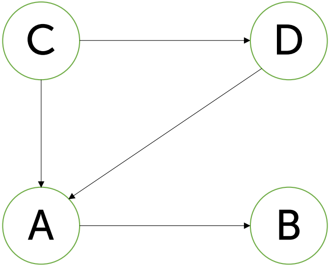
Paths in directed graphs

- Between two nodes X and Y in a directed graph:
  - Adjacent: $X \rightarrow Y$ or $Y \rightarrow X$
  - Non-adjacent: $X \qquad Y$
- If $X \rightarrow Y$, X is a parent of Y and Y is a child of X.
  - If $X \rightarrow \cdots \rightarrow Y$, X is an ancestor of Y, and Y is a descendant of X.

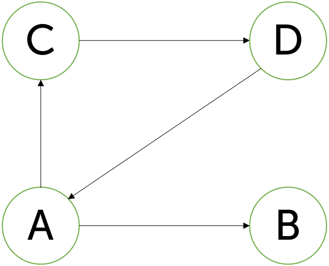
Definition (Paths in directed graphs)

A path in a directed graph is any sequence of adjacent nodes, regardless of the direction of the links that join them.

Cycles in directed graphs



A acyclic directed graph



An cyclic directed graph

Definition (Cycles in directed graphs)

A cycle is a particular type of path that starts from a node and links back to the same node, i.e., $X \to \cdots \to X$.

Basis: Bayesian networks

- A Bayesian network is a **directed acyclic graph (DAG)** that represents **joint probabilities (or a probabilistic graphical model)** of a series of variables.
  - **Nodes**: variables.
  - **Links**: directed and represent the flow of association.

- Causal graphs inherit most the the properties of Bayesian networks.
  - Causal graphs are Bayesian networks with additional causal assumptions.

Bayesian networks: an example

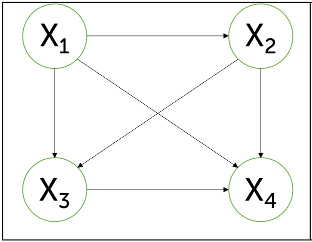
The joint probability $P(X_1, X_2, X_3, X_4)$

- If all variables are **binary**, how many parameters we need to have the joint probability?
- Answer: 15 parameters.

$$
\begin{aligned}
P(X_1, X_2, X_3, X_4) \quad = \quad & \underbrace{P(X_1)}_{1 \text{ parameter}} \\
& \times \underbrace{P(X_2 \mid X_1)}_{2 \text{ parameters}} \\
& \times \underbrace{P(X_3 \mid X_2, X_1)}_{4 \text{ parameters}} \\
& \times \underbrace{P(X_4 \mid X_3, X_2, X_1)}_{8 \text{ parameters}}
\end{aligned}
$$

Bayesian networks: an example

- We can represent the joint distribution with a Bayesian network, given some knowledge of the flow of association.
  - The graph efficiently represents $P\left(X_1, X_2, X_3, X_4\right)$!
  - Bridging theories and empirics (joint probability).



$$\begin{array}{cc} & \begin{matrix} X_1 & X_2 & X_3 & X_4 \end{matrix} \\ \begin{matrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{matrix} & \begin{bmatrix} 0 & a_{12} & a_{13} & a_{14} \\ 0 & 0 & a_{23} & a_{24} \\ 0 & 0 & 0 & a_{34} \\ 0 & 0 & 0 & 0 \end{bmatrix} \end{array}$$

The DAG	The adjacency matrix

Bayesian networks: the Markov assumption

- The complexity of graphs $\uparrow^{\text{Exponentially}}$ the no. of nodes (variables).
- Intractable to study with even a moderate no. of nodes.

Local Markov Assumption

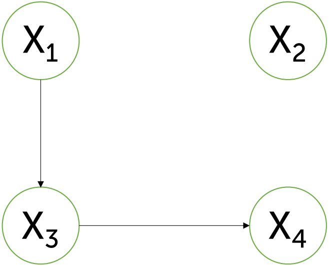
Given its parents in the DAG, a node X is independent of all its non-descendants.

- **Implications: to study the association flow into X**
  - **Only need a node X and its parents!**

Bayesian networks: the Markov assumption

How to apply the local Markov assumption?

- Joint probability
- $P(X_1, X_2, X_3, X_4) =$
  $P(X_1) \times P(X_2 \mid X_1) \times P(X_3 \mid X_2, X_1) \times P(X_4 \mid X_3, X_2, X_1)$



$$P(X_1) = P(X_1)$$
$$P(X_2 \mid X_1) = P(X_2)$$
$$P(X_3 \mid X_2, X_1) = P(X_3 \mid X_1)$$
$$P(X_4 \mid X_3, X_2, X_1) = P(X_4 \mid X_3)$$

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What is a causal graph?

Simply put it: a causal graph is a Bayesian network where the links are causal.

- What is a causal link?

Definition (Causal Links)

*A variable X is said to be the cause of a variable Y, if an **exogenous** change in X can **flow** on the graph to Y.*

The change in X must be exogenous

It is a parent of X and non-adjacent to Y or other variables in the system.

3 Axioms of causal graphs

3 axioms of causal graphs

For a directed acyclic graph to be a causal graph, we must have:

1. (**Causal Links Assumption or the Existence of Causal Graph**) In a DAG, every parent is a direct cause of all its children.
2. (**Local Markov Assumption**) Given its parents in a DAG, a node is independent of all its non-descendants.
3. (**Faithfulness or No Conspiracy**) The correlation patterns are always implied by the causal Markov property.

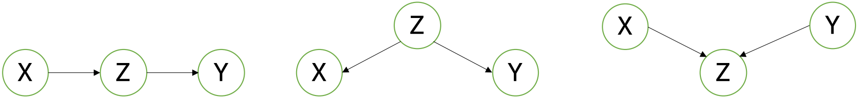
Causal graphs must be acyclic

No cycle exists in a causal graph. In econometrics, this is called "no simultaneity," which implies the policy effects are from a "partial equilibrium."

Starting with motifs: 3 motifs

Graphs are complex, and how to analyze it?

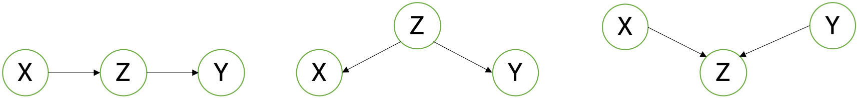
- We focus on motifs - repeated structures on graphs.
- Three-node motifs: chains, forks, and collisions (or immorality)



(a) Chain (b) Fork (c) Collision

Starting with motifs: some observations

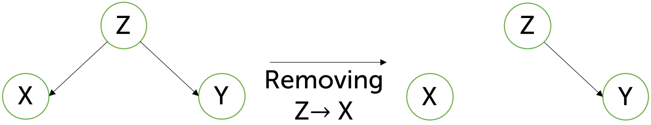
…between X and Y	Chains	Forks	Collisions
Association	> 0	> 0	$= 0$
Causation	> 0	$= 0$	$= 0$



(a) Chain (b) Fork (c) Collision

Starting with motifs: blocking paths

- For a fork $X \leftarrow Z \rightarrow Y$, X and Y are correlated but $X \nrightarrow Y$.
- But how do we know this if we only observe data or $\gamma(X, Y)$?
- Solution: What if we remove the arrow into X ($Z \rightarrow X$)?



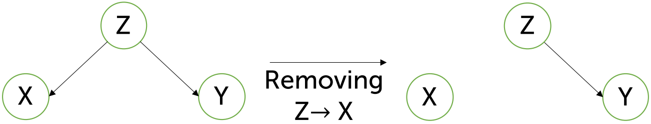
Starting with motifs: blocking paths

If we want to know the effect of X on Y, we must remove all "redundant paths."

- In formal terms, we "block" all unwanted paths.

How to block paths between X and Y?

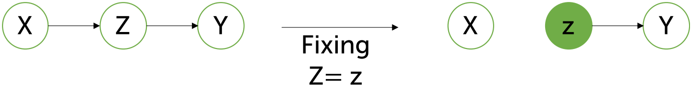
- Let's look at the motifs one by one.



Blocking paths: chains

Chains (front-door paths)

To block a chain $X \rightarrow Z \rightarrow Y$, we fix the value of Z (a.k.a. the mediator) or set $Z = z$.



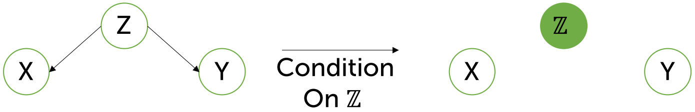
Testing with causal links assumption

A change in ΔX cannot pass through to Y.

Blocking paths: forks

Forks (back-door paths)

To block a fork $X \leftarrow Z \rightarrow Y$, we condition on the full support of $Z \in \mathbb{Z}$ (a.k.a. the moderator).



Testing with causal links assumption

Given Z, the value of X and Y are pre-determined.
A change in ΔX therefore does not pass over to Y.

Blocking paths: collisions

Collisions (immoral paths)

A collision path $X \rightarrow Z \leftarrow Y$ is already blocked.

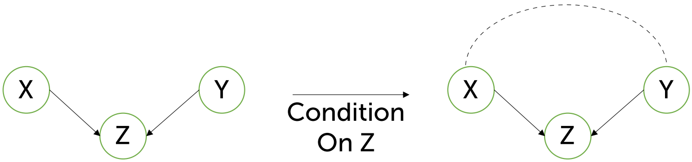
Testing with causal links assumption

A change in ΔX changes Z, but NOT Y.

Blocking paths: more on collisions

Do not condition on collider Z

It is tempting, but conditioning on Z creates spurious correlation between X and Y!



An example

In the general population, gender and age are independent.
In the sub-population of CEOs, more older males.
In the sub-population of nurses, more younger females.

D-separation: the general rules of path-blocking

Definition (Blocked Paths)

A path between nodes X and Y is blocked by a node W along the path if either of the following is true:

1. *For a chain along the path, $\cdots \to W \to \cdots$, W is fixed.*
2. *For a fork along the path, $\cdots \leftarrow W \to \cdots$, W is conditioned on.*
3. *For a collision along the path $\cdots \to W \leftarrow \cdots$, W is not conditioned on, as well as all descents of W.*

D-separation

Two nodes X and Y are d-separated by a set of nodes Z, if all paths between X and Y are blocked by Z.

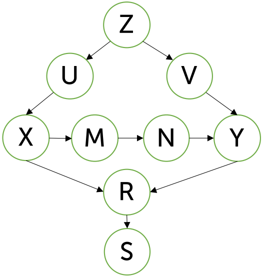
D-separation: an application

First, we find all the three types of paths:

1. Backdoor paths: $X \leftarrow U \leftarrow Z \rightarrow V \rightarrow Y$.
2. Frontdoor paths: $X \rightarrow M \rightarrow N \rightarrow Y$.
3. Collision paths: $X \rightarrow R$ (de(R)) $\leftarrow Y$.

Second, we construct a blocking set that:

1. Includes one or two or three of$\{U, V, Z\}$.
2. Includes one or two of $\{M, N\}$
3. Does NOT include R and S (the descendant of R)



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Interventions or Manipulations

When they are infeasible...

- Randomized control experiments - **the golden standard**.
- However, not everything can be intervened (ethically).
  - Example: age, gender, or some medical treatments etc.
- In business or economics studies:
  - Something is simply too costly to intervene.
  - e.g., lowering price of electricity? Tax cuts?

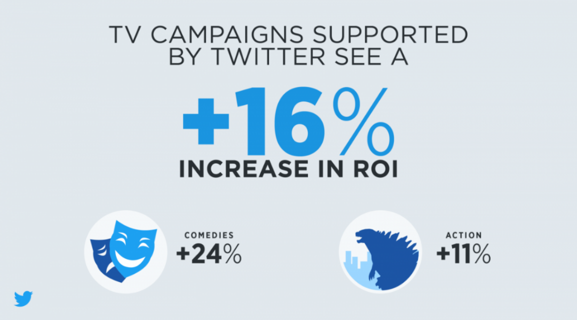
What then?

- People turn to observational data.
  - "Conditional on..." or "adding control variables..."
- Difficult to untangle causation from correlation.
- What's worse: we are causal animals.
  - We see patterns and are drawn towards causality.
  - So, causal interpretations seem more "intuitive."

Twitter example

New movie marketing research reveals Twitter Ads deliver increased ticket sales (LINK)

- "The research team used multivariate regression analysis (a process that measures and predicts the sales impact of various media channels) to understand the effects of changes in Twitter media for movies."



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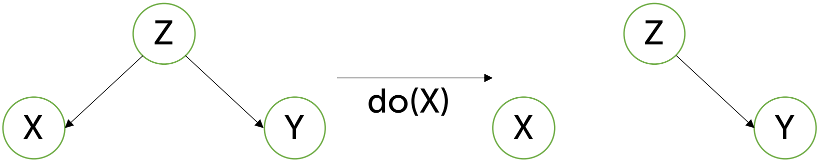
The do-operator: illustration

- Intervention on X: $\text{do}\,(X) = x$ or fixing $X = x$.
- Graphical interpretation: removing all arrows into X.



$P(Y \mid X = x)$ vs. $P(Y \mid \mathrm{do}(X) = x)$

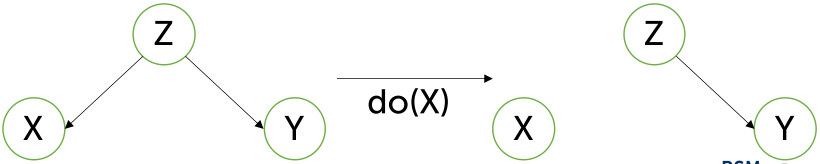
Comparing $P(Y \mid X = x)$ vs. $P(Y \mid \mathrm{do}(X) = x)$

$\mathbf{P(Y \mid X = x)}$	$\mathbf{P(Y \mid \mathrm{do}(X) = x)}$
Conditioning	Intervening
Purely Statistical	Beyond statistics
Select a subgroup	Create a population
Always calculable	Not always calculable
In the full DAG	In a surgically-altered DAG (subgraph)

How to obtain $P(Y \mid \mathrm{do}(X) = x)$?

Procedure to obtain $P(Y \mid \mathrm{do}(X) = x)$

1. Do **a surgery on the full DAG** by removing all arrows into X
2. Transform the conditional probability with **the new DAG**
    1. i.e., $P(Y \mid \mathrm{do}(X) = x) = P(Y \mid X)$
3. Calculate the conditional probability $P(Y \mid X) = P(Y)$



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The definition of do-calculus

Definition (Do-calculus)

The do-calculus is an axiomatic system for replacing probability formulas containing the do operator with ordinary conditional probabilities.

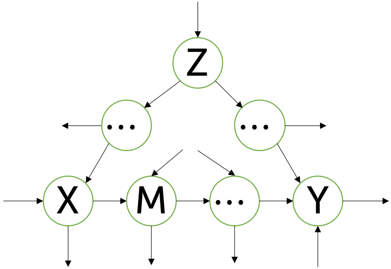
- The normal reaction to the definition is "**say what?**"
- Let's look at the intuitions behind it!

The intuition behind do-calculus

- To know causal effects, we need $P(Y \mid do(X))$.
  - e.g., Average Treatment Effect: $P(Y \mid do(X) = 1) - P(Y \mid do(X) = 0)$.
- But, we do not have $P(Y \mid do(X))$, unless we intervene on X.
  - In many cases, we cannot intervene X (see above).
  - We can have $P(Y \mid X)$, but $P(Y \mid X) \neq P(Y \mid do(X))$.
- Question: **under what conditions** $P(Y \mid X) = P(Y \mid \mathbf{do}(X))$**?**

Illustrating the intuition

- In practice, the DAG may be much more complex.
  - Many interventions or do($\cdot$)'s are needed for $P(Y \mid do(X))$.
- Do-calculus: rules of which interventions are essential.
  - Without the essential do($\cdot$)'s, $P(Y \mid do(X))$ is unknown.



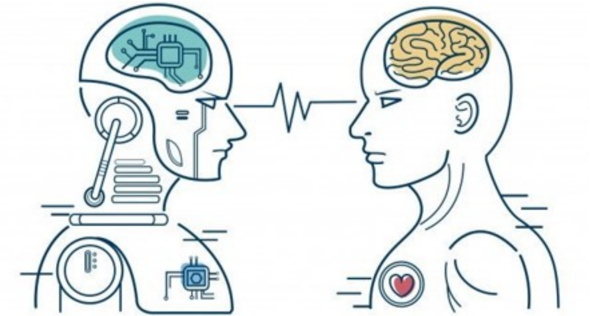
Three rules of do-calculus

- Omitted here. Please see [1, Pearl 1995] for more details.
- Proved by [2, Shpitser and Pearl 2006], the rules are complete.
  - That is, the three rules are sufficient to transform $P\left(Y \mid \mathrm{do}\left(X\right), \cdots\right) \mapsto P\left(Y \mid X, \cdots\right)$.
  - If the rules are not met, $P\left(Y \mid \mathrm{do}\left(X\right), \cdots\right)$ may not be known from the DAG.
- For us: **causal identification for business research**.
  - The implications from the three rules of do-calculus.

To sum up: Where do DAGs come from?

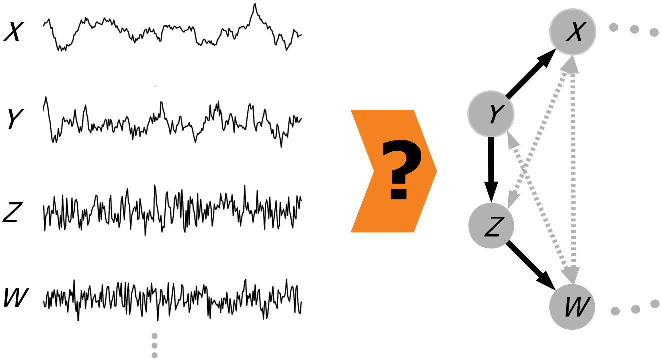
- Rules of do-calculus $\Rightarrow$ whether a causal relationship is knowable from a DAG.

- Where do DAGs come from?
  - Human minds or “theories”
  - Machine or Causal Learning



To sum up: Causal graph is for causal learning

- The do-calculus and the follow-up algorithms are for causal learning (or discovery).



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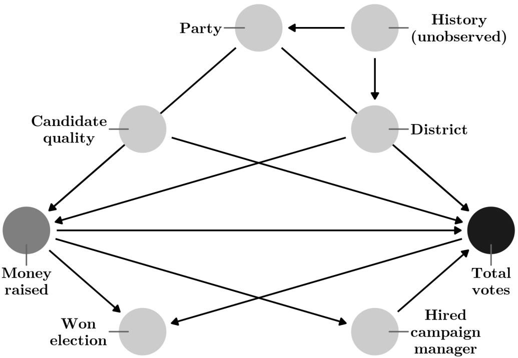
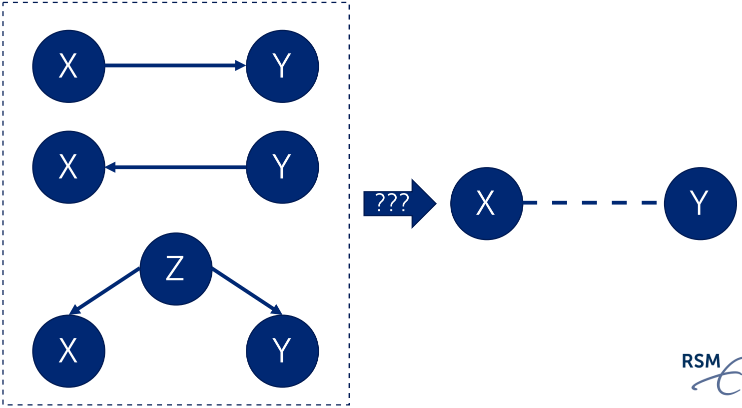
Two types of causal inference

- Type 1: Given data of a system, to find its causal structure.
- **Type 2: Given a causal structure, measure the effect of one variable on another.**



Explaining "Correlation $\neq$ Causation"

- Correlation is produced by causation
- Multiple causal structures (DAGs) can produce same correlation pattern

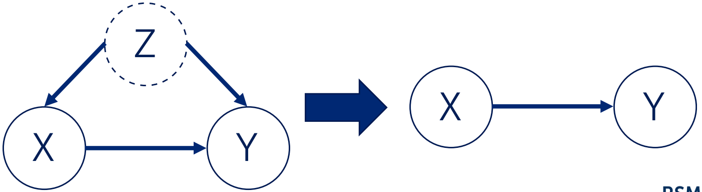


The core problem of causal inference

Definition (The Core Problem)

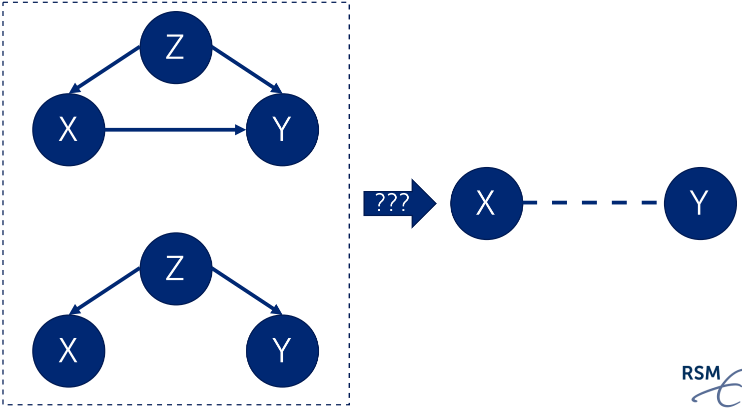
Suppose we want to quantify the effect of X on Y from the DAG below and we perfectly observe X and Y. However, the set of confounders Z is partially or unobserved.

- Z has many names: lurking variables, omitted variables, unobservable etc.



The core problem is an identification problem

In almost all business research, obtaining $P(Y \mid do(X))$ boils down to distinguishing two observation-equivalent DAGs.



Defining the identification problem

Definition (The identification problem)

Multiple assumed data-generating processes can result in the same patterns in data.

- **Data-generating processes**: models or theories or assumptions.
- **Patterns in data**: information in data or statistics of data (e.g., correlations).

Endogeneity issue in linear regression $Y = \beta X + \varepsilon$

$P(Y \mid X) = P(\beta X + \varepsilon \mid X) = \beta X + P(\varepsilon \mid X)$ with $P(\varepsilon \mid X) \neq 0$.

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The complex concept of identification

We stick to the core problem of causal identification for clarity.

Over-identification

Parametric identification

Partial identification

Identification by construction

Exact identification

Essential identification

Structural identification

First-order identification

Point identification

Identification of bounds

Sampling identification

Identification at infinity

Set identification

Nonparametric identification

Non-robust identification

Causal identification

Strong identification

Bayesian identification

Generic identification

Ill-posed identification

Global identification

Weak identification

Irregular identification

Thin-set identification

Nonstandard weak identification

Eventual identification

Frequentist identification

Local identification

Semi-strong identification

Semiparametric identification

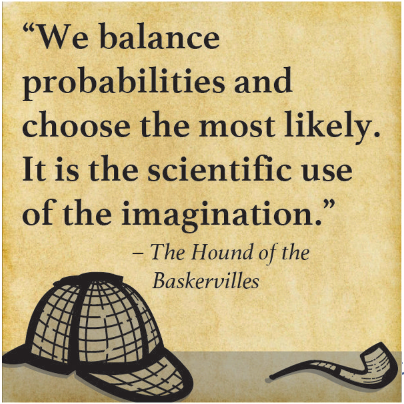
Nearly-weak identification

Identification arrangement

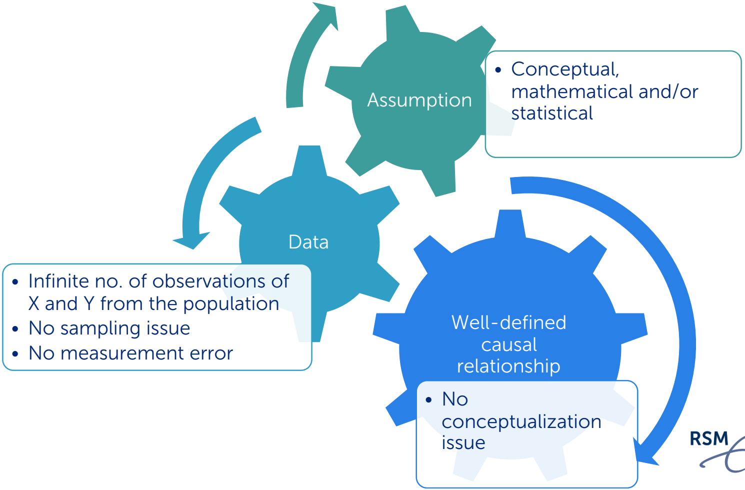
Bayesian identification

Identification strategies

- A well-defined causal relationship ($X \rightarrow Y$)
- An action plan to solve the core problem of causal inference
- An integration of data and assumptions



3 pillars of an identification strategy



Identification vs. estimation

Proposition (Identification vs. Estimation)

The relationship between identification and estimation is as such: first, identification logically precedes estimation; and second, one does not logically imply the other.

Two examples

Estimable but not identifiable: $\text{Sales} = \beta\text{Price} + \varepsilon$.
Identifiable but not estimable: Static discrete game with multiple equilibria.

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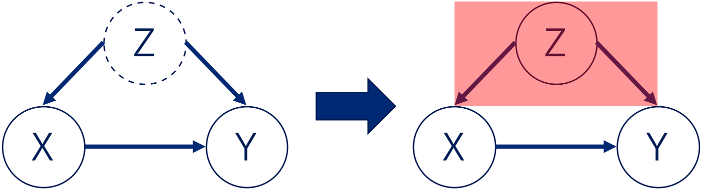
Identification by conditioning



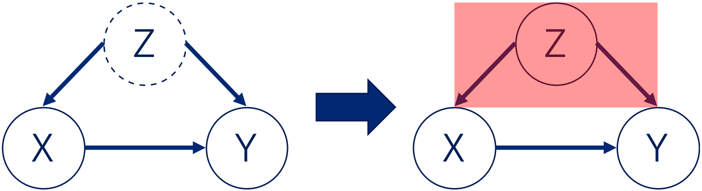
- A.k.a. "killing lurking variables" or "adding control variables."
- Guaranteed by the backdoor criterion.

Definition (Backdoor Criterion)

A set of variables Z satisfies the backdoor criterion relative to X and Y if the following are true:

1. *Z block ALL backdoor paths from X to Y.*
2. *Z does NOT contain any common descendants (colliders) of X and Y.*

Identification by conditioning

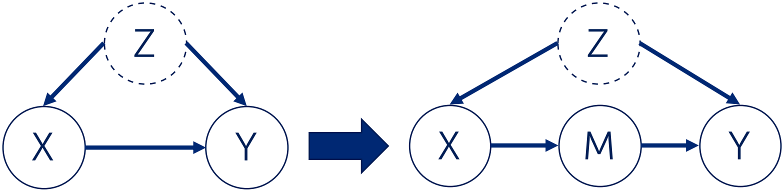


- If backdoor criterion is satisfied, we have $P(Y \mid \mathrm{do}(X)) = \sum_z P(Y \mid X, Z)\, P(Z)$.

Checklist of Conditioning

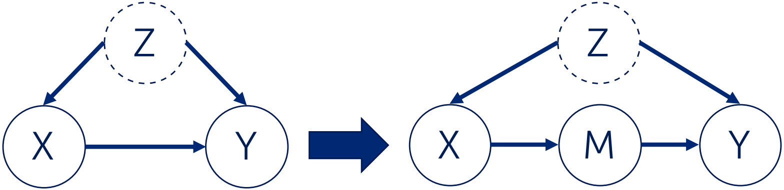
- *Z contain (at least) all common parents of X and Y.*
- *Z do not contain any common descendants of X and Y.*
  - *In practice, do NOT use post-treatment variables as controls!*

Identification by mechanism



- Guaranteed by the front-door criterion (the front-door path $X \to M \to Y$).
- A strategy found by studying the DAG.

Identification by mechanism

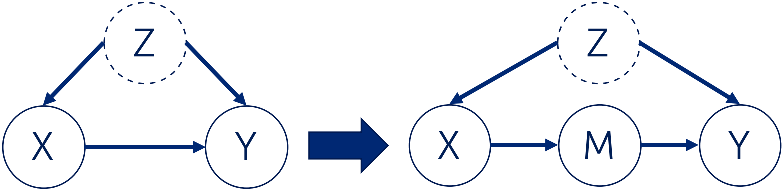


Definition (Front-door Criterion)

A set of variables M satisfies the front-door criterion relative the the DAG of $\{X, Y, Z\}$ if the following are true:

1. *All backdoor paths between X and M are blocked.*
2. *All backdoor paths between M and Y are blocked by X.*
3. *M complete intercept all the front-door paths between X and Y (i.e., full mediation).*

Identification by mechanism: the intuition

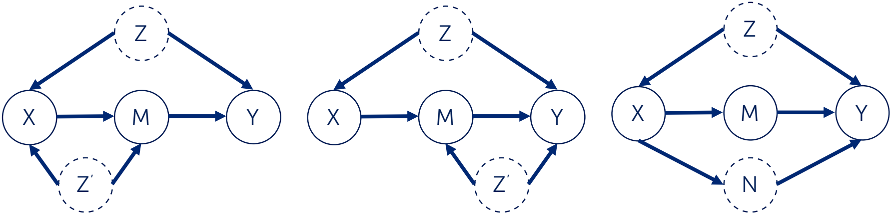


From the DAG:

- Do we know $P(M \mid do(X))$?
- Do we know $P(Y \mid do(M))$?
- Can we integrate $P(M \mid do(X))$ and $P(Y \mid do(M))$ to get $P(Y \mid do(X))$?

RSM Erasmus

Front-door criterion illustrated in DAGs



Condition 1 :
M is isolated from X

Condition 2 :
M is isolated from Y

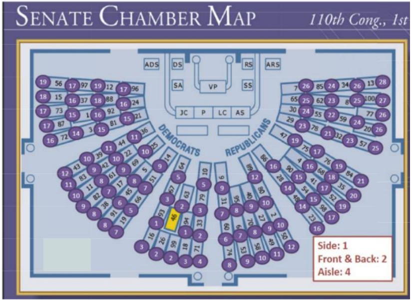
Condition 3 :
M is exhaustive

Under the front-door criterion, we have:

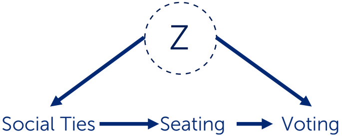
- $P(Y \mid do(X)) = \sum_m \left[P(M \mid X) \sum_{\tilde{X}} \left[P\left(Y \mid M, \tilde{X}\right) P\left(\tilde{X}\right) \right] \right]$

RSM Erasmus

Identification by mechanism: Cohen and Malloy 2014



Congressional Seating



The DAG

- Social ties and congressional voting
  - "Logrolling": quid pro quo in bill voting
  - Social ties: college alumni

Identification by instruments: the origin

"Exogenous shocks/variation"

- An inventions of economists
- Wide adoption outside of economics
- The origin can be traced back to 1920's

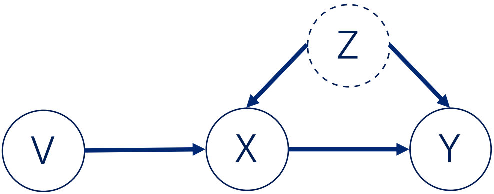
One of the early contributors: Jan Tinbergen (1930)

- Bestimmung und Deutung von Angebotskurven Ein Beispiel
- Determination and Interpretation of Supply Curves: An Example

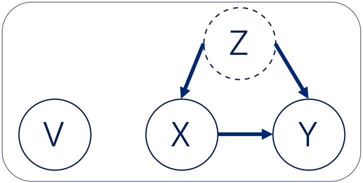
Identification by instruments: how

Instead of mutilating the DAG, we expand it!

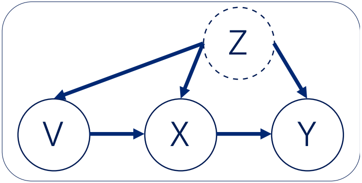
- $P(Y \mid \text{do}(V)) = P(Y \mid V)$: identified.
- $P(X \mid \text{do}(V)) = P(X \mid V)$: identified.
- To have $P(Y \mid \text{do}(X))$, we solve this equation:
  $P(Y \mid \text{do}(V)) = \sum_X P(Y \mid \text{do}(X))\, P(X \mid \text{do}(V))$.



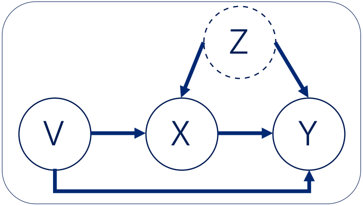
Identification by instruments: assumptions



Relevance



Exogeneity

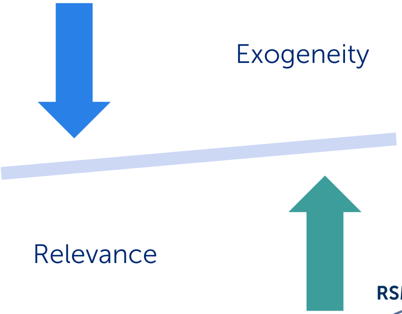


Exclusion

Is any assumption testable on its own right?

The sources of valid instruments

- Natural occurrences or uncontrollable events (the problem of weak instruments).
- Policy or regulation changes (for partial equilibrium).
- Random assignment (as in experiments).



Identification by set

Instead of focusing on a specific value, we try to have a "bound" or "set."

- "Half-baked" as compared to point identification.
- a.k.a. partial identification, identification by bounds, or interval identification etc.
- Conceptually insightful but empirically less attractive.

Think of this example:

- An experiment with liking of a brand as outcome
- Measured with $0-9$ points scale (0−dislike and 9−like)
- Treatment effects must $[-9, +9]$ ("no data bound")

The law of credibility

Quote Manski 2003(Chapter 1):

"Empirical researchers should be concerned with both the logic and the credibility of their inferences. Credibility is a subjective matter, yet I take there to be wide agreement on a principle I shall call: ***The Law of Decreasing Credibility: The credibility of inference decreases with the strength of the assumptions maintained.*** *This principle implies that empirical researchers face a dilemma as they decide what assumptions to maintain: Stronger assumptions yield inferences that may be more powerful but less credible."*

Application of the law of credibility

Set 1

- No assumptions

Sharper Set 2

- More or stronger assumptions

…Sharper Set…

- …Even more or stronger assumptions…

Points

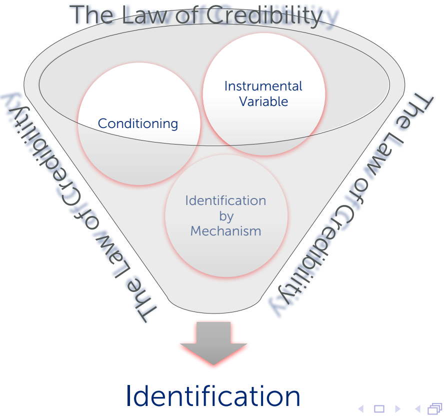
- “Minimal sufficient assumptions”

- **An example**: Sensitivity analysis (see Rosenbaum 2014)

Summary I

In my own experience, identification strategies:

- Go beyond data, and need institutional knowledge and/or theoretical understanding.
- "Break it until you probably make it."



Summary II

The identification-estimation flowchart

The "faithfulness" assumption

- The causal link assumption is not sufficient to have a unique DAG. We need the faithfulness assumption to deal with tricky scenarios.

An example

- Consider a DAG, with $X \to Y \leftarrow Z$, and we further assume $Y = X + Z$, without the loss of generality.
- Conditional on $Y = y$, the covariance between X and Z should be **non-zero**.
  - $cov\left(X, Z \mid Y = y\right) = cov\left(X, y - X\right) = yE\left(X\right) - E\left(X^2\right)$.
- If $yE\left(X\right) - E\left(X^2\right)$ is always 0, then $cov\left(X, Z \mid Y = y\right) = 0$.
- If $cov\left(X, Z \mid Y = y\right)$ is always 0, then the DAG $X \to Y \leftarrow Z$ cannot be right. But it is the true DAG.
- We therefore have the assumption to rule the situation.

Do-operator: some formality

Definition (Do-operator)

If we intervene on a set of nodes S on a DAG, then for all nodes X_i, we have the following:

1. *For $X_i \notin S$, $P(X_i \mid pa(X_i))$ remains unchanged.*
2. *For $X_i \in S$, if $x_i = do(X_i)$, then $P(X_i = x_i \mid pa(X_i)) = 1$, and otherwise $P(X_i = x_i \mid pa(X_i)) = 0$.*

Do-operator: some formality

Corollary (Truncated Factorization)

We assume that P and G satisfy the Markov and causal links assumption. Given a set of intervened nodes S, we have,

$$P\left(X_1, X_2, \cdots, X_n \mid do\left(S = s\right)\right) = \prod_{X_i \notin S} P\left(X_i \mid pa\left(X_i\right)\right)$$

The three rules of do-calculus

For a DAG G, let $G\left(\nrightarrow_X\right)$ denote the graph G with all incoming links to X removed. Similarly, $G\left(\nleftarrow_X\right)$ denote the graph G with all outgoing links from X removed. Combining these two, the graph G with incoming links to X and outgoing links from Z removed is denoted as $G\left(\nrightarrow_X \nleftarrow_Z\right)$. In addition, I will use $\perp_G$ to represent d-separation on the graph.

Theorem (The Rules of Do-calculus)

Given a DAG G, an associated distribution P, and disjoint set of variables Y, X, Z and W, the following rules hold:

1. $P\left(Y \mid do\left(X\right), Z, W\right) = P\left(Y \mid do\left(X\right), W\right)$, *if* $Y \perp_{G\left(\nrightarrow_X\right)} Z \mid X, W$.
2. $P\left(Y \mid do\left(X\right), do\left(Z\right), W\right) = P\left(Y \mid do\left(X\right), Z, W\right)$, *if* $Y \perp_{G\left(\nrightarrow_X \nleftarrow_Z\right)} Z \mid X, W$.
3. $P\left(Y \mid do\left(X\right), do\left(Z\right), W\right) = P\left(Y \mid do\left(X\right), W\right)$, *if* $Y \perp_{G\left(\nrightarrow_X \nrightarrow_{Z \setminus Ancestor(W)}\right)} Z \mid X, W$, *where* $Z \setminus Ancestor\left(W\right)$ *denotes non-ancestors of* W *in set* Z.

The intuition for the 1st rule

To get the intuition for Rule 1, we may simply remove the intervention $do(X)$. The removal of $do(X)$ reverses the manipulated graph $G(\nrightarrow_X)$ to the original graph G. We also remove any other X from the picture. Thus, we have

$$P(Y \mid Z, W) = P(Y \mid W), \text{ if } Y \perp_G Z \mid W$$

This simply implied if Y and Z are d-separated, then Y is independent from Z, conditional on W. This is from the very definition of d-separation.

The intuition for the 2nd rule

Similar to Intuition for Rule 1, we remove the $do(X)$, and get

$$P(Y \mid do(Z), W) = P(Y \mid Z, W), \text{ if } Y \perp_{G(\nleftarrow_Z)} Z \mid W$$

This is the backdoor criterion, where W blocks all backdoor path between Z and Y. The operation $G(\nleftarrow_Z)$ serves to block all frontdoor paths from Z, and thus all frontdoor paths between Z and Y are blocked, and only the backdoor paths remain which are all blocked by conditioning on W.

The intuition for the 3rd rule

Again, we remove the $do(X)$, and get

$$P(Y \mid do(Z), W) = P(Y \mid W), \text{ if } Y \perp_{G\left(\nrightarrow_{Z \setminus \text{Ancestor}(W)}\right)} Z \mid W$$

This implies if we remove the do-operation $do(Z)$ by reintroducing the links that come into Z, we would not cause flow of association into Y. Because $do(Z)$ removes all incoming links to Z give us $G(\nrightarrow_Z)$, the main pathways for the flow of association between Z and Y are the frontdoor paths from Z to Y in $G(\nrightarrow_Z)$. If W contain all chain nodes, naturally Y and Z will be d-separated. However, if W also contains colliders (i.e., nodes that are descendants of Z), conditioning would lead to non-causal association flow between Y and Z. Therefore, we have to modify the set of Z and limit the set of manipulated nodes in Z to those that are not ancestors of W. By doing so, W would not contain colliders or descendants of colliders. Simply put, Rule 3 applies the do-separation criterion on colliders.

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