



Causal Inference in Observational Studies

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Disclaimers:

- Sections and lines in brown correspond to content which is **very much** ‘under construction’.
- For all expressions whose simplification into a final expression is not detailed (either explicitly stated or by using “...”), the mathematical steps of the simplification are provided in the Appendix.

1 Definitions

1.1 Research design and identification strategy

Research design = working from the research question, the overall manner in which data will be gathered, assembled and assessed in order to draw conclusions.

In the applied economics literature, and only in the context of (1) *observational* studies that aim to (2) identify a *causal* effect, a subordinate notion is the “identification strategy”.¹

If one’s research goal is to identify the causal effect of a specific event or program (“treatment”), and sets internal validity as the priority,² then one wants a research design that may credibly identify causal effects.

One such design is a **randomized trial**: an experiment which randomly assigns the participants to either a treatment or a control group. This experiment is often considered as the “gold standard” against which to judge other research designs. In an observational study, one attempts to approximate the force of evidence generated by such an experiment. A key aspect of the research design is hence the identification strategy:

Identification (causal inference) strategy = how *observational* data are used to approximate a real experiment. It is the set of assumptions that will *identify* the causal effect of interest, including:

- = {
- a clear source of identifying variation in a causal variable,
- the use of a particular econometric technique to exploit this information.

1.2 Experiments, natural experiments, quasi-experiments

A true experiment is a study in which the researcher manipulates the level of a treatment (the independent variable of interest) and measures the outcome (the dependent variable of interest). All the important factors that might affect the phenomena of interest are controlled.

A natural experiment is an observational study in which a *randomization* of a treatment D or instrument Z has occurred naturally – mimicking the exogeneity of a randomized experiment. Researchers do not create natural experiments – they find them.

Ex: weather

A quasi experiment is a study of intentional treatment, that resembles a randomized field experiment but lacks full random assignment. Participants are *not* randomly assigned to the treatment or control group. The groups therefore differ in often unobservable ways, so one must control for as many of these differences as possible. The control group is rather called a “comparison” group.

Ex: In the 1990s, the U.S. Department of Housing and Urban Development (HUD) implemented a grant program to encourage resident management of low-income public housing projects. Housing projects were *selected* in 11 cities nationwide, so the treatment (the award of HUD funding) was not randomly assigned. But similar housing projects in the same cities provided a reasonably valid comparison, so the HUD was able to evaluate the program.

¹Angrist and Pischke (2010) use the notions of research design and identification strategy interchangeably.

²True experimental designs may be the “gold standard” of scientific research when considering only internal validity. However, the very methods used to increase internal validity may also limit the generalizability or external validity of the findings. Ex: a zoo is a controllable setting amenable to drawing causal inferences about the behavior of animals, but these inferences may not generalize to the behavior of animals in the wild.

2 Theory: a counterfactual approach to causality

2.1 The potential outcomes framework

2.1.1 The original selection bias problem and the CIA

We have a treatment of interest $D_i \in \{0, 1\}$ whose causal effect we want to estimate. Let Y_i be the realized outcome, Y_i^0, Y_i^1 the potential outcomes. The potential outcomes framework³ allows us to define quantities:

– Treatment effect (TE)	$Y_i^1 - Y_i^0$	<i>what we want to estimate</i>
– Average treatment effect (ATE)	$\mathbb{E}[Y_i^1 - Y_i^0]$	<i>what we ideally want to compute</i>
– Average treatment effect on the treated (ATET)	$\mathbb{E}[Y_i^1 - Y_i^0 D_i=1]$	<i>what we reasonably want to compute</i>
– Difference in average observed outcomes	$\mathbb{E}[Y_i D_i=1] - \mathbb{E}[Y_i D_i=0]$	<i>what we can compute</i>
– Difference in average observed outcomes for same X_i	$\mathbb{E}[Y_i D_i=1, X_i] - \mathbb{E}[Y_i D_i=0, X_i]$	<i>what we can compute</i>

The focus on identification is due to the **original selection bias problem**:

- To measure $TE = Y_i^1 - Y_i^0$, we need to see the same individual with and without treatment.
- This is impossible, as each individual has one existence. We cannot observe the counterfactual.⁴ We can only compute the difference in average observed outcomes:

$$\mathbb{E}[Y_i | D_i=1] - \mathbb{E}[Y_i | D_i=0] = \dots = \underbrace{\mathbb{E}[Y_i^1 - Y_i^0 | D_i=1]}_{\text{ATET}} + \underbrace{\mathbb{E}[Y_i^0 | D_i=1] - \mathbb{E}[Y_i^0 | D_i=0]}_{\text{selection bias}}$$

The “selection bias” is the average difference in Y_i^0 between the treated and untreated.⁵

- If treatment is randomly assigned, then potential outcomes are independent of it: $(Y_i^0, Y_i^1) \perp\!\!\!\perp D_i$, so there is no selection bias *in expectation*.⁶ The *independence assumption* identifies the TE, and $ATET=ATE$.
- In observational studies, $(Y_i^0, Y_i^1) \not\perp\!\!\!\perp D_i$. However, if we *match* treated and control individuals to be proper counterfactuals, i.e., if the potential outcomes are *conditionally* independent of the treatment $(Y_i^0, Y_i^1) \perp\!\!\!\perp D_i | X_i$, then we again eliminate selection bias. The *conditional independence assumption*⁷ (CIA) identifies the TE.

What makes our regression estimates causal is our **identifying assumption**:

- if we have the IA $(Y_i^0, Y_i^1) \perp\!\!\!\perp D_i \implies$ we can compute the ATE.
- if ~~IA~~ but we have the CIA $(Y_i^0, Y_i^1) \perp\!\!\!\perp D_i | X_i \implies$ we can compute the ATET.
- if ~~CIA~~ but \exists a relevant instrument Z_i that is an exogenous source of variation in D_i :
 - $\left\{ \begin{array}{l} \text{independent (new CIA)} \\ \text{relevant} \end{array} \right. (Y_i^0, Y_i^1) \perp\!\!\!\perp Z_i | X_i \implies$ we can compute a LATE.
 - $Z_i \not\perp\!\!\!\perp D_i | X_i$

So we need an **identification strategy** that convinces us that an IA holds.

³The potential outcomes framework for causal inference builds on [Neyman \(1923\)](#), was extended to observational studies by [Rubin \(1974\)](#), and became popular in econometrics around 1990. One strong assumption is that the treatment effect on one individual is independent of the treatment received by others. This excludes strategic interactions among agents.

⁴This is the ‘fundamental problem of causal inference’. Its implication: we *never* observe causal effects.

⁵For example: if individuals with low Y_i^0 choose treatment more frequently, then $\mathbb{E}[Y_i^0 | D_i=1] < \mathbb{E}[Y_i^0 | D_i=0]$. Comparing Y between treated and untreated underestimates the TE. Say we look at the effect of hospitalization; sick individuals go to the hospital (get treated) more often than healthy individuals. But they would also have been less healthy had they stayed at home.

⁶Independence removes selection bias *in expectation over all (hypothetical) trials*. Independence does not imply actual balance in any single trial ([Deaton and Cartwright, 2018](#)).

⁷The CIA is also referred to as the assumption of “selection on observables” (conditioning on observed characteristics X_i erases selection bias), unconfoundedness, or “ignorability” in statistics.

Econometric techniques or regression controls won't bring causality; econometrics and identifications strategies are complements in the production of causal estimates.⁸

2.1.2 Expressing TE as a linear regression

Suppose a heterogeneous TE, i.e., $Y_i^1 - Y_i^0 = \beta_i$. The relation between observed outcomes and potential outcomes (how we estimate our TE) can be written as a linear regression on the treatment:

$$\begin{aligned} Y_i &= Y_i^0 + (Y_i^1 - Y_i^0) D_i \\ &= \mathbb{E}[Y_i^0] + (Y_i^1 - Y_i^0) D_i + (Y_i^0 - \mathbb{E}[Y_i^0]) \\ &= \alpha + \beta_i D_i + u_i \end{aligned}$$

The OLS slope estimand $\beta_{OLS} \equiv \frac{cov[Y_i, D_i]}{Var[D_i]}$ simplifies to $\mathbb{E}[Y_i|D_i=1] - \mathbb{E}[Y_i|D_i=0]$: the difference in average observed outcomes,⁹ which is equal to $\beta + \mathbb{E}[u_i|D_i=1] - \mathbb{E}[u_i|D_i=0] = \dots = \beta + \mathbb{E}[Y_i^0|D_i=1] - \mathbb{E}[Y_i^0|D_i=0]$. Thus β_{OLS} equals the true β iff the error u_i is uncorrelated with D_i , or equivalently, iff there is no selection bias.

I.e., an identification problem (dependence) \implies a regression problem (endogeneity).

2.1.3 Why might the IA/CIA not hold? Endogeneity

In the simple (linear & univariate) regression model $y_i = \alpha + \beta x_i + e_i$, the variable x_i is

- **endogenous** if it is correlated with the error term: $cov[x_i, e_i] \neq 0$.
- **exogenous** if it is uncorrelated with the error term: $cov[x_i, e_i] = 0$.

If x is endogenous, the OLS slope estimator of β will comprise not only the partial derivative w.r.t. x (what we want) but also an indirect effect through e : $\beta_{OLS} = \frac{dy(x,e)}{dx} = \frac{\partial y}{\partial x} + \frac{\partial y}{\partial e} \frac{\partial e}{\partial x} = \beta + \frac{\partial e}{\partial x} \neq \beta$. The OLS estimator is therefore biased and inconsistent for β .

In our case of interest, if the treatment D_i is endogenous, i.e., $cov[D_i, e_i] \neq 0$, it means there is an imbalance in potential outcomes across the treatment groups. The CIA doesn't hold. Our estimate will be biased.

Sources of endogeneity

- reverse causality or simultaneity: If y also affects D , this is captured by e , making e correlated with D ;
- non-random measurement error in D — specifically, that is correlated with y ;
- omitted variable bias (OVB): All omitted variables¹⁰ are captured by e . Therefore, if an omitted variable w is correlated with D , e is correlated with D . w is a “confounding variable”.

→ In observational studies,

- excluding a confounding variable creates bias, so we must adjust for all *confounders*.
- with all confounders assumed to be measured, we estimate an unbiased causal effect.
- because we can rarely be certain to have measured all confounders,¹¹ we turn to alternative causal inference or “**identification**” strategies, that rely on other assumptions.

⁸However, even with a good identification strategy, one cannot simply compare means. There is no reason to expect balance for all relevant pre-treatment characteristics in *any single study*. In any observational study, one should therefore adjust for **all other** relevant pre-treatment variables. This will also increase precision; see section 4.1.

⁹A linear regression on an indicator variable is a comparison of averages, i.e., a simple difference estimate.

¹⁰An omitted variable is an explanatory variable not included in the regression but which is a determinant of y .

¹¹For instance, in cross-sectional approaches, we worry about time-invariant omitted variables. As a cross-section offers only inter-individual (across) variation, if y is affected by unobservable variables that systematically vary across groups, our estimate will be biased. With panel data, we have across variation and intra-individual (within) variation. Using individual fixed effects, we can focus on within variation only, which greatly reduces the threat of OVB.

2.2 The causal graph framework

Pearl (2009) proposes an alternative to the potential outcomes framework for thinking about causality: a causal graph framework.¹² We introduce it here on the basis of two important points:

1. The two frameworks are not opposed, they both define causality using counterfactuals. A causal effect is a comparison between two states of the world: a realized state as the intervention took one value, and a “counterfactual” state that would have happened had the intervention taken another value.
2. Each encodes these causal states differently, and as such elucidates different features of causal analysis.

The potential outcome and the causal graph frameworks are therefore **complementary** perspectives, and it can be useful to frame one’s causal inference in the language of each framework.¹³

2.2.1 Elements of directed acyclic graphs (DAGs)

Relationships are encoded with nodes and edges. In the context of analyzing the causal effect of a treatment variable D on an outcome variable Y , we introduce additional notions:

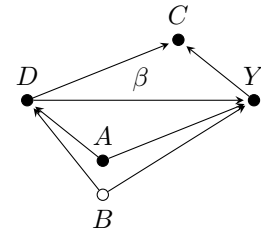
- a node represents a random variable; a solid circle if it is observed, hollow otherwise;
- all edges are directed and represent causal relationships;
- a path is any sequence of edges;
- a **back-door path** = any path between D and Y that begins with an arrow pointing to D .^a It is *closed* if at least one variable along the path is observed, *open* otherwise.
- a **confounder** = a variable that determines both D and Y along some path.
 \Rightarrow *Fluctuations in the confounder drive some of the association between D and Y ; the total association between D and Y is therefore not equal to β .*
- a **collider** = a variable that is determined by both D and Y along some path.
Colliders do not generate an unconditional association between D and Y , i.e., bias, so one need not adjust for them. On the contrary, including them would generate bias.

^aThis path is “entering A through the back door”.

Importantly, a DAG is a *complete* encoding of assumptions about causal relationships: those assumed to exist represented by arrows, and those assumed to not exist represented by missing arrows. I.e., the exclusion of an arrow is not the absence of an assumption, but the assumption that there is no direct relationship.

For example, the basic DAG on the right encodes:

- * explicitly, 4 paths linking D to Y :
 $D \xrightarrow{\beta} Y$: a direct (causal) path
 $D \leftarrow A \rightarrow Y$: a back-door confounding path, closed
 $D \leftarrow \cdots B \cdots \rightarrow Y$: a back-door confounding path, open
 $D \rightarrow C \leftarrow Y$: a colliding path
- * implicitly, 3 assumptions of no direct relationships between A , B and C .



¹²For a detailed presentation, see Morgan and Winship (2015, ch. 1.5 & 3), of which this section is (an attempt of) a summary.

¹³How directed graphs encode (potentially counterfactual) causal states is not detailed here. See sections 3.4 and 3.6 of Morgan and Winship (2015), or Pearl (2009), for a detailed presentation. Importantly, we also consider only the subset of directed *acyclic* graphs (DAGs), where no directed paths emanating from a causal variable also terminate at the same causal variable. This prohibition of cycles notably rules out representations of simultaneous causality and feedback loops. Section 3.2 of Morgan and Winship (2015) discusses the implications.

2.2.2 Two identification strategies: 1. blocking back-door paths; 2. instruments

We want to estimate the causal effect of a treatment D on Y . We represent in a DAG this causal relationship, and all other relationships relevant to the effect of D on Y . *Given the structure of the causal relationships, which variables must we observe and include to estimate the causal effect of D on Y ?*

- Strategy 1: blocking back-door paths

The most common concern with observational data is that D and Y are partly determined by a third variable, i.e., that there is a back-door path. **The total association between D and Y equals β iff there are no back-door paths.**

- In the previous basic DAG:

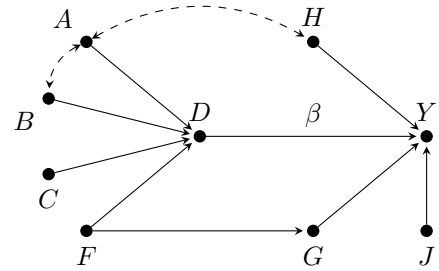
- * Assume B wasn't there. The only back-door path between D and Y is closed as we observe A . If we adjust for A , i.e., hold it fixed, we remove the association between D and Y that is driven solely by fluctuations in A , and recover the causal effect β . **We can recover β by blocking all back-door paths**, i.e., conditioning on one confounder along each path.
- * However the back-door path through B is *open*, as B is unobserved. → We therefore cannot recover β by blocking back-door paths.

- In the more complex DAG on the right, there are three back-door paths:¹⁴

$$\begin{aligned} D &\leftarrow A \leftrightarrow H \rightarrow Y \\ D &\leftarrow B \leftrightarrow A \leftrightarrow H \rightarrow Y \\ D &\leftarrow F \leftrightarrow G \rightarrow Y \end{aligned}$$

We can block all back-door paths by either:

- * conditioning on H and either F or G
- * conditioning on A and B , and either F or G



- Strategy 2: instruments

Instead of blocking back-door paths to estimate β directly, we can leverage an exogenous shock to D to estimate β indirectly. We use exogenous variation in an instrument Z ¹⁵ to isolate covariation in D and Y . In the DAG above, we can use as instrument for D either C , or F after conditioning on G .

To estimate the causal effect β of D on Y , we reach the same conclusion as with the potential outcomes framework:

- In observational studies,
- leaving a back-door unblocked, i.e., excluding a confounding variable, creates bias, so we must block all back-doors (adjust for all confounders).
- “Back-door criterion”: with all back-doors blocked, i.e., all confounders measured and conditioned on,¹⁶ we estimate an unbiased causal effect.
- because we can rarely be certain that we have measured all confounders, we turn to alternative causal inference or “identification” strategies, that rely on other assumptions.

¹⁴To show that two variables are mutually dependent on one or more unobserved common causes, instead of abiding by the definitions and showing it with U as in the left figure below, we can use a curved dashed bidirected edge as in the right figure as a shorthand. These bidirected edges should however not be interpreted as mere correlations between the two variables, they represent an unspecified set of unobserved common causes of the two variables that they connect.



¹⁵Instruments are formally introduced in the next section. In short, a variable Z is a valid instrument for D if it causes D but does not have an effect on Y except through its effect on D . We can then estimate consistently the effect of D on Y by taking the ratio of the relationships $Z \leftrightarrow Y$ and $Z \leftrightarrow D$.

¹⁶Using regression, matching, or another method.

Advantages of DAGs

- DAGs are helpful at clarifying the relationships between variables and guiding a research design that has a shot at identifying a causal effect. They force us to write all our assumptions, notably all the relationships that we assume are null between variables of importance. A DAG is telling two stories: what is happening, and *what (we assume) is not happening*.
- DAGs encode causal relationships that are completely nonparametric. When considering analysis strategies, it is thereby not necessary to make assumptions about the functional form of the dependence of Y on the variables that cause it. This notably means that all interactions between the effects of different variables on Y are implicitly permitted. No new arrows are needed to represent these interactions — where, for example, the effect of D on Y varies with the level of X — as the directed edges only signify inclusion in the structural function $f_Y(D, X, \dots)$.
- DAGs show that there is often more than one way to estimate a causal effect, and that “controlling for all other causes of Y ” can be misleading. In DAG #2, there were two completely different and relevant conditioning strategies (after conditioning for either F or G): conditioning either on H or on A and B . They also show clearly the importance of collider variables: endogenous variables that must be handled carefully — or they may create conditional dependence that can sabotage a causal analysis.
- They are helpful for communicating research designs; pictures do speak a thousand words.
- They provide a bridge between empirical schools, such as structural and reduced form.

2.3 Learning the causal structure vs the magnitude of effects given the structure

In the social sciences, from a given identification strategy, one cannot reliably learn the causal structure of relationships but only these relationships’ magnitudes given the model (Gelman, 2011).

3 Applied Identification Methods

3.1 Hierarchy of common identification methods

A contestable hierarchy of the most common identification methods in the ‘randomista’ toolkit,¹⁷ based on their capacity to mimic random assignment, is as follows:

0. Randomized experiment (RCT) — or direct natural randomization of treatment D
1. Instrumental Variables (IV) and regression discontinuity (RD)
If we fear that there is selection into treatment based on unobservables, we use an instrument or discontinuity that induces quasi-experimental variation in treatment status.
2. Difference-in-differences (DiD) and event-studies
If we have repeated observations and want to estimate the effect of an event, we use research designs that rely on the assumptions of time-invariant omitted variables and parallel trends.
3. Matching estimators
Strategies based solely on matching are considered much less credible – in terms of making us believe in the CIA, and thus their ability to recover a causal effect – than strategies based on some exogenous variation. However, matching is a type of procedure that can complement a natural-/quasi-experiment design. It is addressed in section 4.

The sections below present, for each method, in the canonical setup: (i) the assumed data generating process (DGP), (ii) the identifying assumptions, (iii) the estimand, i.e., the treatment effect of interest, (iv) the estimator used, and (v) some best practices, and strengths and weaknesses. Importantly, the **relation between the actual observed outcomes Y_i and the conceptual potential outcomes Y_i^0, Y_i^1** is made explicit. This relation underlies how our estimation recovers a causal treatment effect.

For simplification purposes, all methods are presented without the inclusion of exogenous controls X_i . However, the relationships hold when they are all conditional on covariates X_i .

¹⁷Term shamelessly copied from [Gibson \(2019\)](#).

3.2 Random assignment

Show:

- experimental: RCT
- observational but still random assignment: natural experiment. Ex: weather or other

3.3 IV

Context (DGP) $Y_i = \alpha + \beta_i D_i + u_i$, $cov[D_i, u_i] \neq 0$: D_i is endogenous. But \exists a binary instrument Z_i that is a random source of variation in D_i , it “assigns treatment” or changes the probability of treatment:¹⁸

$$\begin{array}{ccc}
 Z & \xrightarrow{\gamma} & D \xrightarrow{\beta} Y \\
 & \uparrow & \nearrow \\
 & u &
 \end{array}
 \quad
 \begin{aligned}
 D_i &= \delta + \gamma Z_i + v_i \\
 Y_i &= \alpha + \beta D_i + u_i, \quad cov[D_i, u_i] \neq 0
 \end{aligned}$$

In terms of potential outcomes:

We define the treatment assignment $Z_i \in \{0, 1\}$ and the treatment realization $D_i \in \{0, 1\}$. $Z_i = 0$ induces the potential treatment status D_i^0 , which will be realized as 0 if individuals comply, 1 if not. $Z_i = 1$ induces D_i^1 , realized as 1 if they comply, 0 if not. The compliance behavior defines 4 categories of participants — which the researcher *cannot* observe; they can only observe the assignment Z_i and the realization D_i .

	D_i^0	D_i^1
compliers	0	1
always-takers	1	1
never-takers	0	0
defiers	1	0

Identifying assumptions

- (A1) independence w.r.t. the potential outcomes, i.e., $cov[Z_i, v_i] = 0$
- (A2) exclusion restriction: $cov[Z_i, u_i] = 0$
- (A3) relevance: $cov[Z_i, D_i] \neq 0$
- (A4) monotonicity: the instrument does not discourage treatment (no defiers). This assumption is weaker (and therefore more realistic) than the assumption of homogenous effects.

Estimand We define the IV estimand: $\beta_{IV} \equiv \frac{cov[Y_i, Z_i]}{cov[D_i, Z_i]} = \dots = \frac{\mathbb{E}[Y_i | Z_i=1] - \mathbb{E}[Y_i | Z_i=0]}{\mathbb{E}[D_i | Z_i=1] - \mathbb{E}[D_i | Z_i=0]}$. Note that:

- The slope estimate $\widehat{\gamma}_{LS} = \frac{cov[D_i, Z_i]}{V[Z_i]}$ from regressing D on Z consistently estimates $\gamma = \frac{cov[D_i, Z_i]}{V[Z_i]}$
- The slope estimate $\widehat{\gamma} \cdot \widehat{\beta}_{LS} = \frac{cov[Y_i, Z_i]}{V[Z_i]}$ from regressing Y on Z consistently estimates $\gamma \cdot \beta = \frac{cov[Y_i, Z_i]}{V[Z_i]}$
- \implies Their ratio $\widehat{\beta}_{IV} \equiv \frac{\widehat{\gamma} \cdot \widehat{\beta}_{LS}}{\widehat{\gamma}_{LS}} = \dots = \beta + \frac{cov[u_i, Z_i]}{cov[D_i, Z_i]}$: is consistent but has a bias, which \searrow with Z_i 's strength.

The identifying assumptions reduce $\frac{\mathbb{E}[Y_i | Z_i=1] - \mathbb{E}[Y_i | Z_i=0]}{\mathbb{E}[D_i | Z_i=1] - \mathbb{E}[D_i | Z_i=0]}$ to $\underbrace{\mathbb{E}[Y_i^1 - Y_i^0 | D_i^0 = 0, D_i^1 = 1]}_{\text{LATE on the compliers}}$

Estimator Our natural choice of estimator is the sample analog $\widehat{\beta}_{IV} = \frac{cov[Y_i, Z_i]}{cov[D_i, Z_i]}$. It turns out to be numerically equivalent to the 2SLS estimator $\widehat{\beta}_{2SLS}$ obtained through the two-step procedure:¹⁹

$$\begin{aligned}
 \text{1st stage: } D_i &= \delta + \gamma \cdot Z_i + u_i \implies \widehat{D}_i = \widehat{\mathbb{E}}[D_i | Z_i] \\
 \text{2nd stage: } Y_i &= \alpha + \beta \cdot \widehat{D}_i + e_i
 \end{aligned}$$

¹⁸For more complicated treatment variables, we will need more complicated instruments. To identify *several* treatment variables, we will need at least as many instruments. To identify a *continuous* treatment, we can't use a binary instrument.

¹⁹The point estimates are equivalent, however the SEs of the 2nd stage would not give the correct SEs, as we need to adjust for the two stages of estimation. We must account for the estimation uncertainty from the first-stage (the first-stage is based on a sample, not the population, making \widehat{D}_i a random variable, instead of the usual fixed variable). Most 2SLS packages do the adjustment automatically — otherwise one can simply bootstrap the SEs manually.

Best practices

- Support the relevance assumption by showing a large F-statistic for the 1st stage (rule of thumb: $F > 10$). The bigger F , the “stronger” the instrument. Or run a test such as the Stock and Yogo test.
- Count and characterize the compliers to get more out of the LATE (see section on external validity).
- As in any observational study, adjust for **all other** relevant pre-treatment variables (include the same variables in both stages).

Strengths & weaknesses

- + Compelling identification strategy
- Strong assumptions
- The IV estimator will be less efficient than the OLS estimator if the instrument is weak.

3.4 RD (sharp)

Known assignment mechanism but no overlap

Context (DGP) Treatment D_i is not randomly assigned, it is deterministic, but *discontinuous* along a continuous X_i , s.t. there is “local randomization” around a cutoff c : $D_i = \mathbb{1}\{X_i \geq c\}$. Because D_i is a deterministic function of X_i , there are no confounding variables other than X_i . Noting the trend relation $\mathbb{E}[Y_i^0|X_i] = f(X_i, \phi)$, the DGP is:

$$Y_i = \alpha + \beta D_i + f(X_i, \phi) + u_i$$

△ There is zero overlap (no value of X_i with both treatment and control observations), so we must extrapolate across X_i . This means the RD estimate will be only as good as our model for $\mathbb{E}[Y_i^0|x_i]$: we can’t be that agnostic about functional form. By looking only at data in a small neighborhood around c , the TE estimate should not depend much on the correct specification of that model.

Identifying assumptions

(A1) *local continuity*: the expected potential outcomes $\mathbb{E}[Y_i^1|X_i]$ and $\mathbb{E}[Y_i^0|X_i]$ are continuous in X_i at c . I.e., the other determinants of Y don’t jump at c . \implies The average outcome of those right below the cutoff (who are denied the treatment) are a valid counterfactual for those right above (who receive it).

(A2) *relevance*: discontinuity in the dependence of D_i on X_i : $D_i = \mathbb{1}\{X_i \geq c\}$

I.e., if there appears to be no other reason for Y_i to be a discontinuous function of X_i , we can attribute a jump in Y_i at c to the causal effect of D_i .

Estimand $\beta_{RD} = \lim_{x \rightarrow c^+} \mathbb{E}[Y_i|X_i = x] - \lim_{x \rightarrow c^-} \mathbb{E}[Y_i|X_i = x] = \dots = \underbrace{\mathbb{E}[Y_i^1 - Y_i^0|X_i = c]}_{\text{LATE at the cutoff}}$

Estimator We can estimate β at the cutoff by running the centered regression below:²⁰

$$Y_i = \alpha + \beta D_i + f(X_i - c, \phi) + e_i$$

Best practices

- Choice of $f(\cdot)$: $f(\cdot)$ is unknown. This is a problem, as misspecification of the functional form of the DGP may bias the estimate. Estimation is therefore done with flexible functional forms, such as:
 - a local linear regression model: $Y_i = \alpha + \beta D_i + \gamma_1(X - c) + \gamma_2(X - c)D_i + e_i$ with $c - h \leq X \leq c + h$.²¹
 - a polynomial regression model: with a low-degree polynomial (e.g., quadratic).

In both cases, report the results of several specifications to assess the sensitivity to $f(\cdot)$.

- As in any observational study, adjust for **all other** relevant pre-treatment variables. Just because the treatment assignment depends on X , there is no reason to expect overlap and balance across other pre-treatment characteristics. We need to adjust for pre-treatment differences between the two groups.

Strengths & weaknesses

- + RDDs are similar to a local randomized experiment, and thereby require weak assumptions.
- + They have much potential in economic applications, as geographic boundaries or administrative or organizational rules (e.g., program eligibility thresholds) often create usable discontinuities.
- They risk being underpowered.
- The parameter estimates are very “local”, it may be hard to generalize from such a local result.

²⁰To allow for different trend functions for $\mathbb{E}[Y_i^0|X_i]$ and $\mathbb{E}[Y_i^1|X_i]$ (i.e., to let the regression model differ on each side of the cutoff), add interactions between D and X : $Y_i = \alpha + \beta D_i + f(X_i, \phi_l) + f(X_i, \phi_r)D_i + e_i$

²¹A larger bandwidth h increases precision but also bias. Choose the optimal h by estimating the model’s predictive accuracy for different values of h , for example using leave-one-out cross-validation: iteratively for each observation i , fit the model using only the observations $X_i - h \leq X < X_i < c$ when $X_i < c$, and only the observations $c < X_i < X \leq X_i + h$ when $X_i \geq c$.

3.5 RD (fuzzy)

Context (DGP) At $X_i \geq c$ there is a jump, not in treatment assignment (D_i going from 0 to 1), but in the *probability* of treatment assignment $P[D_i = 1|X_i]$. The discontinuity $Z_i \equiv \mathbb{1}\{X_i \geq c\}$ becomes an instrumental variable for treatment status D_i .

Estimand We define the IV estimand: $\beta_{IV} \equiv \frac{\lim_{x \rightarrow c^+} \mathbb{E}[Y_i|X_i=x] - \lim_{x \rightarrow c^-} \mathbb{E}[Y_i|X_i=x]}{\lim_{x \rightarrow c^+} \mathbb{E}[D_i|X_i=x] - \lim_{x \rightarrow c^-} \mathbb{E}[D_i|X_i=x]} = \dots = \underbrace{\mathbb{E}[Y_i^1 - Y_i^0|X_i = c]}_{\text{LATE at the cutoff}}$

Estimator Fuzzy RD leads naturally to a simple 2SLS estimation strategy. The sample analog $\widehat{\beta}_{IV}$ is numerically equivalent to the 2SLS estimator $\widehat{\beta}_{2SLS}$ obtained through the two-step procedure:

$$\text{1st stage: } D_i = \delta + \gamma \cdot Z_i + f(X_i) + u_i \implies \widehat{D}_i = \widehat{\mathbb{E}}[D_i|X_i]$$

$$\text{2nd stage: } Y_i = \alpha + \beta \cdot \widehat{D}_i + f(X_i) + e_i$$

As before, one can allow for treatment effects that change as a function of X_i by adding treatment-covariate interactions.

3.6 DiD

Context (DGP) We want to estimate the causal effect of *an event*, which occurs at time t_0 and affects one group of individuals in the population, on some outcome Y . Treatment assignment or exposure is a function of 2 dimensions: group (treatment/control) and period (pre/post event). We define the associated binary variables $G_i \equiv \mathbb{1}\{i \in \text{treatment group}\}$ and $P_t \equiv \mathbb{1}\{t \in \text{post period}\}$.

We define the potential *changes in* outcome Y_{it} between the pre- and post-exposure periods: $d_i^0 \equiv Y_{i1}^0 - Y_{i0}$ if the unit were never exposed to the treatment, and $d_i^1 \equiv Y_{i1}^1 - Y_{i0}$ under exposure.

Identifying assumptions

(A1) Same counterfactual trends across groups, i.e., same changes in outcomes in the absence of treatment:
 $\mathbb{E}[d_i^0 \mid G_i=1] = \mathbb{E}[d_i^0 \mid G_i=0]$

(A2) The sample composition does not vary over time.

Estimand

$$\begin{aligned}\beta_{\text{DiD}} &\equiv (\bar{Y}_{G_1 P_1} - \bar{Y}_{G_1 P_0}) - (\bar{Y}_{G_0 P_1} - \bar{Y}_{G_0 P_0}) \\ &\equiv (\mathbb{E}[Y_{i1} \mid G_i=1] - \mathbb{E}[Y_{i0} \mid G_i=1]) - (\mathbb{E}[Y_{i1} \mid G_i=0] - \mathbb{E}[Y_{i0} \mid G_i=0]) \\ &= \dots \\ &= \underbrace{\mathbb{E}[Y_{i1}^1 - Y_{i1}^0 \mid G_i=1]}_{\text{ATE}}\end{aligned}$$

Estimator The OLS estimator $\hat{\beta}_{\text{OLS}}$ of the following regression consistently estimates β_{DiD} :

$$\begin{aligned}Y_{it} &= \alpha + \beta_G G_i + \beta_P P_t + \beta G_i P_t + e_{it} \\ &= \lambda_G + \lambda_P + \beta G_i P_t + e_{it}\end{aligned}$$

If we have panel data (instead of merely repeated cross-sections), we can estimate this in a more direct way with a first difference approach, by regressing the change for each unit $Y_{i1} - Y_{i0}$ on G_i .

Best practices

- Support the assumption of parallel counterfactual trends by showing that pre-treatment trends coincide (if we have data for multiple pre-periods). Estimate the following regression model by OLS, and check that the coefficients β_τ where $\tau < t_0 - 1$ are 0:

$$y_{it} = \sum_{\tau \neq t_0 - 1} \beta_\tau G_i \mathbb{1}\{t = \tau\} + \lambda_i + \lambda_t + e_{it}$$

- The regression above also enables us to look at whether the effect of treatment actually *accumulates* over time: $\beta_{\tau, \tau \geq t_0} \uparrow$ in τ .
- If the composition of the groups changes over time, interact covariates with P_t .
- As in any observational study, adjust for **all other** relevant pre-treatment variables.

Strengths & weaknesses

- + DiD is a way of ruling out unobserved time-invariant confounders, by using repeated observations, thus creating comparable groups.
- + Pre-trends aren't a problem (unlike in event-studies) as long as that of the two groups are *parallel*.
- + Identification only requires repeated observations, so repeated cross-sectional data suffice, as long as the sample composition does not vary over time. Panel data satisfy this condition by construction.

3.7 DiDiD

Context (DGP) The treatment varies along a 3rd dimension or “subgroup” (in addition to time and group), such as gender, space... We define the binary variable $S_i \equiv \mathbb{1}\{i \in \text{treatment in dim \#3}\}$.

Identifying assumptions

(A1) Same counterfactual trends across ~~groups~~ subgroups, i.e., same changes in outcomes when no treatment:

$$\mathbb{E}[d_i^0 | G_1, S_1] - \mathbb{E}[d_i^0 | G_1, S_0] = \mathbb{E}[d_i^0 | G_0, S_1] - \mathbb{E}[d_i^0 | G_0, S_0]$$

(A2) The sample composition does not vary over time.

Estimand

$$\begin{aligned} \beta_{\text{DiDiD}} &\equiv \left[(\bar{Y}_{G_1 S_1 P_1} - \bar{Y}_{G_1 S_1 P_0}) - (\bar{Y}_{G_0 S_1 P_1} - \bar{Y}_{G_0 S_1 P_0}) \right] - \left[(\bar{Y}_{G_1 S_0 P_1} - \bar{Y}_{G_1 S_0 P_0}) - (\bar{Y}_{G_0 S_0 P_1} - \bar{Y}_{G_0 S_0 P_0}) \right] \\ &= \dots \\ &= \underbrace{\mathbb{E}[Y_{i1}^1 - Y_{i1}^0 | G_i=1, S_i=1]}_{\text{ATET}} \end{aligned}$$

Estimator The OLS estimator $\widehat{\beta}_{\text{OLS}}$ of the following regression consistently estimates β_{DiDiD} :

$$\begin{aligned} Y_{it} &= \alpha + \beta_G G_i + \beta_S S_i + \beta_P P_t + \beta_{GS} G_i S_i + \beta_{GP} G_i P_t + \beta_{PS} P_t S_i + \beta G_i S_i P_t + e_{it} \\ &= \beta G_i S_i P_t + \lambda_{GS} + \lambda_{GP} + \lambda_{PS} + e_{it} \end{aligned}$$

Best practices

- A triple differences makes for a very specific control group. Before doing an DiDiD, one must be able to answer why a double differences wasn't satisfactory (why the control group in double differences isn't good enough), and even the first differences.
- As in any observational study, adjust for **all other** relevant pre-treatment variables.

Strengths & weaknesses

- + A triple difference allows to difference out more confounding elements, it therefore gets harder to find a confounder.
- It requires more data and variation.

3.8 Event study

Context (DGP) We want to estimate the causal effect of *an event*,²² which occurs at different times τ_i for each unit i (“staggered adoption”) and affects *all units* in the population, on some outcome Y . Treatment assignment is a function of the period (pre/post event). We define the binary variable $P_t \equiv \mathbb{1}\{t \in \text{post period}\}$.

Identifying assumptions

(A1) exogeneity (random timing): the event is unpredictable, and not a result of the outcome Y . We can then reasonably use a unit’s past value to construct its counterfactual post-event value.

Estimand

$$\begin{aligned}\beta_{\text{ES}} &\equiv \mathbb{E}[Y_{it} \mid t = \tau_i] - \mathbb{E}[Y_{it} \mid t = \tau_i - 1] \\ &= \mathbb{E}[Y_{i,\tau_i}^1] - \mathbb{E}[Y_{i,\tau_i-1}] \\ &= \mathbb{E}[Y_{i,\tau_i}^1] - \mathbb{E}[Y_{i,\tau_i}^0] \\ &= \underbrace{\mathbb{E}[Y_{i\tau_i}^1 - Y_{i\tau_i}^0]}_{\text{ATET}}\end{aligned}$$

Estimator The OLS estimator $\widehat{\beta}_{\text{OLS}}$ of the following regression consistently estimates β_{ES} :

$$Y_{it} = \sum_{t=-K}^{\tau-1} [\beta_t \mathbb{1}\{t\}] + \beta \mathbb{1}\{\tau\} + \sum_{t=\tau+1}^L [\beta_t \mathbb{1}\{t\}] + \lambda_i + e_{it}$$

Best practices

- Report all β_t s, to check that they are not increasing up to the event. An increase would suggest the presence of pre-trends... which are a sign of endogeneity of the treatment variable, making it hard to interpret the event (unless there is a trend discontinuity). Provide a plot of pre-trends.
- As in any observational study, adjust for **all other** relevant pre-treatment variables.

Strengths & weaknesses

- It is difficult to rule out other things changing at the same time, i.e., unobserved confounders.

²²Like in DiD, we are estimating the causal effect of an event, thanks to observing units repeatedly over time. We need a model to estimate the counterfactual value (if the event had not occurred), s.t. the difference from the counterfactual is the causal effect. DiD and event studies are simply different models of the counterfactual. We use DiD when there are control units, that we can use to remove trends in the outcome of interest.

3.9 SCM

Summary of common identification methods

	Source of identification & identifying assumptions	Estimand β & corresponding TE	Chosen estimator $\widehat{\beta}$	Strengths / Weaknesses
RCT	(A) independence	$\beta_{\text{RCT}} \equiv \mathbb{E}[Y_i D_i=1] - \mathbb{E}[Y_i D_i=0] = \underbrace{\mathbb{E}[Y_i^1 - Y_i^0]}_{\text{ATE}}$	$\widehat{\beta}_{\text{OLS}}$ of the regression $Y_{it} = \alpha + \beta D_i + e_{it}$. Is consistent and unbiased .	+ Random assignment structurally guarantees (A) \implies RCT = “gold standard”
IV	Id. from the exogenous variation in D induced by Z . (A1) independence (A2) exclusion restriction (A3) relevance (A4) monotonicity	$\beta_{\text{IV}} \equiv \frac{\text{cov}[Y_i, Z_i]}{\text{cov}[D_i, Z_i]} = \dots$ $= \frac{\mathbb{E}[Y_i Z_i=1] - \mathbb{E}[Y_i Z_i=0]}{\mathbb{E}[D_i Z_i=1] - \mathbb{E}[D_i Z_i=0]} : \text{“Wald estimand”}$ $= \dots$ $= \underbrace{\mathbb{E}[Y_i^1 - Y_i^0 D_i^1=1, D_i^0=0]}_{\text{LATE, compliers}}$	$\widehat{\beta}_{\text{IV}} \equiv \frac{\widehat{\text{cov}}[Y_i, Z_i]}{\widehat{\text{cov}}[D_i, Z_i]} = \dots =$ numerically equivalent to $\widehat{\beta}_{\text{2SLS}}$ Is consistent , biased , but bias \downarrow with strength of Z_i .	+ compelling identification strategy – strong assumptions – less efficient than $\widehat{\beta}_{\text{OLS}}$ if instrument is weak
sharp RD	Id. from a discontinuous treatment assignment based on a cutoff in X . (A1) local continuity (A2) relevance	$\beta_{\text{RD}} \equiv \lim_{x \rightarrow c^+} \mathbb{E}[Y_i X_i = x] - \lim_{x \rightarrow c^-} \mathbb{E}[Y_i X_i = x]$ $= \dots$ $= \underbrace{\mathbb{E}[Y_i^1 - Y_i^0 X_i = c]}_{\text{LATE, at the cutoff}}$	$\widehat{\beta}_{\text{OLS}}$ of the regression $Y_i = \alpha_l + \beta D_i + f(X_i - c) + e_i$, w. choice of $f(\cdot)$: – local linear regression, bandwidth h – polynomial regression Is consistent , biased , bias \uparrow with h .	+ akin to a local randomized experiment + weak & testable assumption – risk being underpowered – “very local” estimates, hard to generalize
DiD	(A1) same counterfactual trends across groups (A2) same group composition over time	$\beta_{\text{DiD}} \equiv (\bar{Y}_{G_1 P_1} - \bar{Y}_{G_1 P_0}) - (\bar{Y}_{G_0 P_1} - \bar{Y}_{G_0 P_0})$ $= \dots$ $= \underbrace{\mathbb{E}[Y_{i1}^1 - Y_{i1}^0 G_i=1]}_{\text{ATET}}$	$\widehat{\beta}_{\text{OLS}}$ of the regression $Y_{it} = \beta G_i P_t + \lambda_G + \lambda_P + e_{it}$ Is consistent .	+ rules out unobserved time-invariant confounders
DiDiD	(A1) same counterfactual trends across subgroups (A2) same subgroup composition over time	$\beta_{\text{DiDiD}} \equiv [(\bar{Y}_{G_1 S_1 P_1} - \bar{Y}_{G_1 S_1 P_0}) - (\bar{Y}_{G_1 S_0 P_1} - \bar{Y}_{G_1 S_0 P_0})]$ $- [(\bar{Y}_{G_0 S_1 P_1} - \bar{Y}_{G_0 S_1 P_0}) - (\bar{Y}_{G_0 S_0 P_1} - \bar{Y}_{G_0 S_0 P_0})]$ $= \dots$ $= \underbrace{\mathbb{E}[Y_{i1}^1 - Y_{i1}^0 G_i=1, S_i=1]}_{\text{ATET}}$	$\widehat{\beta}_{\text{OLS}}$ of the regression $Y_{it} = \beta G_i S_i P_t + \lambda_{GS} + \lambda_{GP} + \lambda_{PS} + e_{it}$ Is consistent .	+ differences out more confounding elements than in DiD, so harder to find a confounder – requires more data & variation
Event-study	(A) random timing of the event	$\beta_{\text{ES}} \equiv \mathbb{E}[Y_{it} t = \tau_i] - \mathbb{E}[Y_{it} t = \tau_i - 1]$ $= \dots$ $= \underbrace{\mathbb{E}[Y_{i\tau_i}^1 - Y_{i\tau_i}^0]}_{\text{ATET}}$	$\widehat{\beta}_{\text{OLS}}$ of the regression $Y_{it} = \beta \mathbb{1}\{t = \tau_i\} + \sum_{t \neq \{\tau_i - 1, \tau_i\}} [\beta_t \mathbb{1}\{t\}] + \lambda_i + e_{it}$ Is consistent .	– difficult to rule out unobserved confounders

4 Analysis stage: Steps for stronger causal inferences

2-line summary: always use pre-treatment information to adjust for imbalance between the two groups, and do tests to support/reject modeling and identifying assumptions.

Identification strategies where all confounders are observed make the CIA hold, and thus give us an unbiased TE estimate. But:

1. Even if the TE estimator is unbiased, this does not guarantee that the estimate from any particular sample/randomization will be close to the true value of the estimand, especially with a small sample size. We might be interested in other properties of the estimator (e.g., efficiency).
2. We generally use regression models to estimate the TE, specifically, a regression of the outcome on the treatment indicator and the confounders (the nonparametric analysis by computing the difference in averages becomes too complicated with many covariates... so we use regression). Assuming the confounders are all observed and the CIA holds, accurate estimation is still not guaranteed. It comes down to:
 - (i) proper modeling (the coefficient on D corresponds to the ATE in the sample only if the model is properly specified, i.e., we need to be concerned with the classical regression assumptions. For ex, for the linear regression model, that the TE is additive),
 - (ii) the extent to which the model is forced to extrapolate beyond the support of the data (the more incomplete overlap in the data, the more we are forced to rely on model specification and less on direct support from the data, thus the least robust our inferences are to model misspecification).

4.1 *Estimation:* Regression controls and interactions

Good/bad regression controls We saw that to recover an unbiased TE estimate, we must adjust for all *confounding variables* (variables that correlated with both D and y). Adding confounders as covariates is part of the identification strategy. Separately from the identification strategy, which other covariates should we include (i.e., adjust for)?

- 👍 Adjusting for *pre*-treatment covariates that have a strong association with y can increase the efficiency of the estimate, i.e., reduce its standard error.
- 👎 Do not adjust for *post*-treatment variables! Covariates that may be affected by the treatment or that are highly correlated with it may introduce bias.

We must however be careful to avoid overfitting, and when having a large number of covariates, of finding a way to choose among them. Ways/criteria to penalize complexity in linear regressions and variable selection:

- Familiar: adjusted R²
- Elastic net regression: minimizes the sum of squared residuals plus a penalty term, to choose the regression coefficients $\{\beta_p\}$:

$$\{\beta_p\} = \underset{p}{\operatorname{argmin}} SSR + \lambda \sum_p [(1 - \alpha)|\beta_p| + \alpha|\beta_p|^2]$$

It overcomes the limitations of LASSO. If $\lambda = 0$, this is OLS; if $\alpha = 0$, this is LASSO.

Suresh Naidu suggests reporting robustness of estimated treatment effect of interest to different values of λ with LASSO; rather than arbitrary author-curated specifications across various columns of a table.

TE heterogeneity We expect some heterogeneity in the treatment effect, we might therefore want to look into it. In particular, if we have adjusted for a pre-treatment covariate X that has a large estimated effect, it is natural to look at how the TE varies with the level of that X (Gelman et al., 2020). A simple way of doing this is by interacting the treatment D_i with X .²³ Note that this implicitly assumes that the different treatment effects are perfectly independent. Another way of modeling the heterogeneity in TE is with a

²³Consider centering X , s.t. the treatment coefficient represents the TE for individuals with the mean X score for the sample.

multilevel or ‘partial pooling’ approach which relaxes this assumption, where group-level effects are assumed to belong to a common distribution and the degree of pooling is determined by the data.

4.2 *Pre-estimation:* Restructuring

Causal inference isn’t credible if the units in the treatment group aren’t comparable to those in the control group w.r.t. the observed confounders X . We can distinguish two forms of departures from comparability:

- Incomplete overlap: the *support* of the distribution of X differs across the groups. I.e., some observations have no empirical counterfactuals. Then in these zones of no overlap, the model is forced to extrapolate and inferences are based entirely on modeling assumptions rather than data.
- Imbalance: the *shape* of the distribution of X differs across the groups. The simple difference of group averages then isn’t a reliable estimate of the ATE.

Matching The least similar the distributions of X across the groups (the least overlap and balance), the more inferences will rely on the model (vs the data), thus the least robust they are to model misspecification. To alleviate this concern about needing to correctly specifying the form of the relationship, we can *restructure* our data sample prior to analysis: modify it such that it is analogous to one from a randomized trial. Indeed, if the treatment and control groups have sufficient overlap and balance, then, even if we misspecify the model, we should still get a reasonable estimate of the TE (Gelman et al., 2020). Matching procedures permit just that: we create matched groups to exhibit balance and overlap w.r.t. X .

Δ *Matching provides more overlap and balance, not identification. It is not an alternative to a design-based method.²⁴ It is merely a first step that reduces the reliance on parametric assumptions of the regression model. For matching to be able to capture by itself a causal effect, all the difference between the groups would need to be captured by X (assumption of selection on observables). This is a very strong assumption, that is not testable. Therefore a matching estimator by itself, i.e., an identification strategy based solely on matching, is considered much less credible than one based on some exogenous variation. We need exogenous variation to believe the CIA.²⁵ With both, i.e., if (i) the CIA is satisfied, and (ii) we have balance and overlap w.r.t. X , then the difference in average observed outcomes is an unbiased estimate of the true TE.*

Common matching methods

- Propensity score matching (PSM)
Units are matched based on their predicted probability of getting treated, called their “propensity score”. A logistic regression of D_i on X_i produces predicted probabilities of getting treated \hat{p}_i , which are then used to match each treated unit to non-treated units.

Δ *PSM ensures $\hat{p}(X^t) = \hat{p}(X^c)$, but not $X^t = X^c$.*

Add Algorithm for Estimating the Propensity Score (Doug’s lecture notes) & Gelman et al. (2020) p. 420

- Mahalanobis Distance Matching
Matching is based on a distance metric which can include multiple dimensions of “closeness” between observations: $\text{Distance}(X^c, X^t) = \sqrt{(X^c - X^t)' S^{-1} (X^c - X^t)}$ (whereas PSM reduces the dimensionality to 1). Each treated unit is matched to its nearest control unit, and control units are not reused.

This method gets as close as possible to: $X^c = X^c \implies \hat{p}(X^t) = \hat{p}(X^c)$.

²⁴Methods in which a feature in the setting approximates a randomized experiment, and we fit a model that adjusts for potential confounders: RDs, IVs... (the methods described in the previous section).

²⁵In other words, matching does not bring causality — nor do regression controls. Both are only adjustment strategies.

4.3 *Post-estimation*: Supporting assumptions

4.3.1 Diagnosis tests of modeling assumptions

4.3.2 Falsification tests of identifying assumptions

One can never directly *test* the identifying assumptions, i.e., prove that they hold. But one can do falsification analyzes that will either increase or decrease our confidence in them — and thus support the **internal validity** of the study.

“Falsification” or “placebo” tests are done almost automatically in RCTs — though rarely identified as such. In observational studies, the general approach is to estimate an alternative specification, which, under the identifying assumption, should not find an effect. An effect $\neq 0$ will suggest that the identifying assumption is violated, a confounder is probably driving the relationship.

Approach

- **RCT** The identifying assumption is random assignment (of each individual into the treatment vs control group). If treatment was indeed randomly assigned, then the sample means of explanatory variables should be the same across groups *in expectation*. RCT papers therefore typically show a “balance test” table of sample means of the X s by group.^{26,27}
- **IV** The two main identifying assumptions can be tested:
 - relevance (Z is strongly related to sorting into treatment D): directly observable in the 1st stage;
 - exclusion restriction (Z isn’t correlated with Y through some pathway other than D). The ideal falsification test is to estimate the reduced form effect of Z on Y in a situation where Z can’t affect D . Finding an effect means Z affects Y through another channel than D , falsifying the exclusion restriction. One can use an alternative population or an alternative outcome, that can’t be affected by the treatment but would be by potential confounders (unobserved characteristics correlated with Z and Y).
- **RD** The two main identifying assumptions can be tested:
 - continuity or “local randomization” (all other factors determining Y evolve “smoothly” w.r.t. Z). Test: do other covariates jump at the cutoff c ? Estimate the same model, but using covariates instead of Y , and plot the observations and the fitted curves. If none do, we can assume the unobservables don’t either.
 - relevance (discontinuity in the dependence of D on Z : $D = \mathbb{1}\{Z \geq c\}$). Test: do jumps occur at placebo cutoffs \tilde{c} ?
- **DiD** The two main identifying assumptions can be tested:
 - same counterfactual trends across groups. Tests: compare trends in the pre-period; use an alternative outcome that shouldn’t be affected by the treatment; use an alternative control group (the estimated effect should be the same); move the event to points earlier in time (falsely assume that the onset of treatment occurs before it actually does), if the estimated treatment effect is no

²⁶ \triangle One shouldn’t show t -tests (only balance tables) of baseline observables. t -tests in this context are conceptually unsound: they amount to assessing the probability of an event (a difference in averages) having occurred by chance, when we already know that it could only occur by chance, as the allocation between treatment arms was carried out randomly. Hayes and Moulton (2017) explain that “the point of displaying between-arm comparisons is not to carry out a significance test, but to describe in quantitative terms how large any differences were, so that the investigator and reader can consider how much effect this may have had on the trial findings.” t -tests are only sound in the sense of wanting to test empirically whether the randomization was carried out correctly.

²⁷ Doug Almond’s advice: even in observational settings, *always* show a balance test table. Andrew Gelman’s advice: to show (im)balance in averages of X across groups, plot the standardized and absolute differences in mean values for the continuous and binary X s, respectively.

longer be statistically significant (i.e., is statistically indistinguishable from 0.), suggests that the observed change is more likely due to the treatment (event) than to some alternative force.

- same group composition over time. Panel data satisfies this assumption by definition, but if we have instead repeated cross-sectional data, we can estimate covariate balance regressions.

Examples

DiD [Linden and Rockoff \(2008\)](#): *What is the hedonic price function for the local disamenity of crime risk (i.e., individuals' valuation of crime risk)?* Y_i = property value, D_i = a registered sex offender moves in nearby.

Falsification test of the “same counterfactual trends” assumption (if the prices of houses in offender areas are trending over time differently than the other houses in their neighborhood, they would estimate a spurious negative “impact” of the offender’s arrival): the authors estimate the DiD model using false arrival dates (2-3 years prior to an offender’s actual arrival), and find no effect.

Note: falsification tests are different from robustness checks, which consist in estimating alternative specifications that test the same hypothesis.

4.4 External validity

Validity of a statistical analysis

- **Internal validity** = the extent to which the causal effect *in the population being studied* is properly identified. It is determined by how well the study can rule out alternative explanations for its findings.
- **External validity** = the extent to which the study’s inferences can be generalized to other populations and settings.
 - △ Even in randomized trials, the experimental sample often differs from the population of interest. If participation decisions are explained by observed variables, such differences can be overcome by reweighting. But participation may depend on unobserved variables...

4.5 Which uncertainty matters? — Randomization inference (RI)

“In randomization-based inference, uncertainty arises naturally from the random assignment of the treatments, rather than from the hypothesized sampling from a large population.” ([Athey and Imbens, 2017](#))

The inference techniques we commonly use in regression analysis correspond to *sampling-based* inference. They consider variation in sampling: the uncertainty about population parameters is induced by random sampling from the population. These methods ask: *What would have occurred under a different random sample than the one sampled?*

In causal inference studies, there is also another type of variation at play: variation in *assignment of treatment*, i.e., *design-based* uncertainty corresponding to what the regression outcome would have been under alternative randomizations of treatment assignment. In “Randomization Inference”, introduced by [Fisher \(1935\)](#), the basis for inference is the distribution induced by the randomization of the treatment allocation. One takes “*a design-based perspective where the stochastic nature and properties of the estimators arises from the stochastic nature of the assignment of the treatments, rather than a sampling-based perspective where the uncertainty arises from the random*”²⁸ *sampling of units from a large population*” ([Athey and Imbens, 2018](#)). One asks:

²⁸At this point the term ‘randomization’ might seem confusing, as *both* approaches assume and build inference from randomness: in the traditional approach, that of the *sample*; in the design approach, of the *treatment assignment*. There is a subtle difference: in the first the sample isn’t *randomized* but simply *random*, i.e., taken randomly, whereas in the second, because assignment is made in a random fashion, the resulting treatment is first randomized, and therefore random. RI is aptly named.

What would have occurred under a different random assignment of treatment among units than the assignment observed?

RI is a method for calculating p-values for hypothesis tests. RI may also be used for construction of confidence intervals, but this application requires stronger assumptions.

Application to hypothesis testing Both sampling-based and design-based inference follow the same approach to hypothesis testing: we formulate a null hypothesis that represents a fact about the data we'll try to refute. In causal inference, it is generally a hypothesis of no effect. We then derive a test statistic T s.t. when H_0 is true, T has a specific distribution, and we look at where the value of T for our observed data \hat{T}_{obs} lies within that distribution. The further in the tails, the less likely these observed data were under the null hypothesis, therefore the higher the confidence against it.

In randomization inference, considering the *sharp* null hypothesis of no effect for any unit,²⁹ we can simply use $\hat{\beta}$ as the test-statistic and obtain its empirical distribution under H_0 . Indeed:

- If there is no effect for any unit, then a unit's potential outcomes are the same: the observed outcome is also the counterfactual. Under H_0 , our data therefore represent the outcomes of all possible experiments.
- If we construct all possible random assignments, estimate $\hat{\beta}$ for each, the resulting distribution of $\hat{\beta}$ is therefore a reference distribution under H_0 .
- We look at where our actual $\hat{\beta}_{\text{obs}}$ falls in the reference distribution; if in the tails, e.g., such that only 2% of all random assignments produce a $\hat{\beta} \geq \hat{\beta}_{\text{obs}}$, our one-tailed p-value is 0.02.

Sampling-based inference	Randomization inference
H_0	
No average effect: $\mathbb{E}[Y_i^1] - \mathbb{E}[Y_i^0] = 0$	“Sharp” no effect: $Y_i^1 - Y_i^0 = 0, \forall i$
Distribution of \hat{T} under H_0	
Under H_0 , the distribution of \hat{T} across all random samples converges (as $n \rightarrow \infty$) to a known distribution: usually t or normal. → We compute the parameters of this distribution. → The asymptotic distribution of \hat{T} (across random samples) = the “sampling distribution”.	Under H_0 , however the treatment was randomly assigned wouldn't change the observed outcomes; but it would change the value of \hat{T} . → We compute \hat{T} for many simulated assignments. → The distribution of \hat{T} (across random treatment assignments) = the “randomization distribution”.
2-sided p-value = $\Pr [\text{observing a } \hat{T} > \hat{T}_{\text{obs}}] \text{ under } H_0$ = share of the distribution that is $> \hat{T}_{\text{obs}}$	
= $\Pr[\text{the observed difference between groups would have been observed}]$ if they had been drawn from underlying sampling frames with no mean difference.	= $\Pr[\text{the observed difference between groups would have been observed}]$ if they had received a different treatment assignment.
\implies Given e.g. a rejection threshold $\alpha = 0.05$, the test will erroneously reject $H_0 < 5\%$ of the time	

In practice: simulation We repeat a large number of times (e.g., 10000) the following procedure:³⁰

1. Re-assign treatment randomly, i.e., draw from the “randomization set”³¹ (respecting the structure of the original assignment mechanism, e.g., within strata), thus generating fake treatment statuses.
2. Estimate the regression model using these fake treatments, and store the $\hat{\beta}$ s.

We obtain a distribution for the $\hat{\beta}$ s.

²⁹Note that this is substantially different from the usual null hypothesis in sampling-based inference of *no average effect*.

³⁰RI is a simulation approach, like Bootstrap, however Bootstrap considers variation from sampling. A Bootstrap procedure resamples observations from our actual sample (which is fair, as we assumed it was representative of the population), with replacement, to simulate how *sampling* variation would affect our results.

³¹Rubin (1974) defines the “randomization set” as “the set of allocations that were equally likely to be observed given the randomization plan”. Ex: for a completely randomized experiment of $2N$ trials, where N is assigned to each treatment arm, there are $\binom{2N}{N}$ possible allocations.

Why choose randomization-based inference instead of sampling-based inference?

- Conceptually, there is sometimes no true sampling variation to speak of. Suppose we observed the universe of y outcomes, then there is no sampling from a large population, making sampling-based p -values meaningless, $SE = 0$.³² The core uncertainty within a causal study is not based on sampling uncertainty, but rather on the fact that we do not know the counterfactual.
- RI allows us to make inferences about causal effects without having to appeal to large samples, i.e., without relying on the asymptotic (large sample) properties of an estimator. In situations such as when there is a small number of treatment units, assuming an infinite number of units may not be credible.
 - When all possible random assignments can be simulated, the reference distribution is known, thus RI produces exact p -values.
 - When the set of possible random assignments is so large that a complete census of possible random assignments is infeasible, the reference distribution can be approximated by randomly sampling from the randomization set many times. We compute approximate p -values.
- RI salvages inference with particular clustered designs
 - *Small number of assignment clusters:* When the number of clusters is small, cluster-robust standard errors are downwardly biased. RI circumvents this problem as the reference distribution is calculated based on the set of possible clustered assignments, which takes into account the sampling variability associated with clustered assignment.
 - *Assignment clusters without well-defined boundaries:* if the assignment clustering isn't within well-defined boundaries, one can't rely on common methods to estimate correct standard errors (clusters can't be defined; other sandwich-type covariance matrix estimators require additional modeling assumptions...). Ex: weather variables such as rainfall are often used as a strategy for causal inference, as rainfall shocks are as-if randomly assigned. However, the assignment of rainfall is highly correlated across space in an unformalizable structure. [Cooperman \(2017\)](#) uses national draws of historical rainfall patterns as potential randomizations, allowing her to preserve patterns of spatial dependence while remaining agnostic about the specific form of the clustering.³³

³²While it is indeed possible to observe the value of a variable for all the units in a population (e.g., the eye colors of the 50 U.S. senators), one rarely observes all the possible range of values that units could have taken. Thinking of that universe of values as the relevant population alleviates the conceptual concern.

³³Note that the use of historical data is disputable if climate change changes the distribution across years.

5 Presentation

5.1 Characterizing the empirical strategy

The empirical strategy for any econometric analysis aiming for causal inference should contain – to some degree, explicitly – the following items:

1. Research question – *What causal effect of interest are we trying to estimate?*
2. Ideal experiment – *What ideal experiment would capture the causal effect?*
3. Identification strategy – *How are the observational data at hand used to make comparisons that approximate such an experiment? Specifying notably: the identifying assumptions, what makes them satisfied, the specific effect estimated (ATET, LATE...).*
 - Show a balance test table (table of sample means of the covariates X by treatment and control group), to check that the X are balanced across the treatment and control group, i.e. that X is uncorrelated with treatment.
4. Estimation method
5. Falsification tests that bring confidence in the identifying assumptions.

All these items can be characterized before opening the dataset.

5.2 Putting the paper in perspective

In addition to the paper’s empirical strategy, one may want to discuss:

- Contributions to the literature on the topic or research question
- Methodological contributions
- Internal validity of the statistical analysis
 - Are the identifying assumptions plausible (are there stories under which the assumptions would not hold?) Could there be measurement error? Are there unexplained results?*
- External validity of the statistical analysis
 - w.r.t. policy: is there a gap between policy questions and the analyses performed?
 - w.r.t. the literature: how does the paper account for its results compared to other results in the literature?
 - w.r.t. other settings: are the results generalizable to other populations and settings?

Counting and characterizing compliers to get more out of a LATE Compliers are rarely representative, due to selective uptake. While we cannot identify individual compliers in the data, we can estimate the size of the complier group: $P[D_{i1} > D_{i0}] = \mathbb{E}[D_{i1} - D_{i0}] = \mathbb{E}[D_i|Z_i = 1] - \mathbb{E}[D_i|Z_i = 0]$, and characterize them in terms of their distribution of observed covariates (see [Kowalski \(2018\)](#), [Abadie \(2003\)](#)). Different valid instruments will yield different estimates because they correspond to different estimands, as each selected a specific set of compliers. Think of the group of compliers selected, to make sure the instrument is relevant w.r.t. the policy of interest.

6 Other branches of causal modeling

6.1 Structural Equation Models (SEMs)

Structural Equation Models are probabilistic models that unite multiple predictor and response variables in a single causal network.

SEMs are increasingly popular in ecological research. They are often represented using path diagrams, a.k.a. directed acyclic graphs (DAG), where arrows indicate directional relationships between observed variables.

Implicit assumptions — what separate SEMs from traditional modeling approaches:

1. SEMs implicitly assume that the relationships among variables (paths) are causal. This is a big leap from the traditional statistics' "correlation does not imply causation". By using pre-existing knowledge of the system, one makes an informed hypothesis about the causal structure of the variables, and the SEM explicitly tests this supposed causal structure.³⁴
2. Variables can be both predictors and responses. A SEM is thereby useful for testing and quantifying indirect (cascading) effects that would otherwise go unrecognized by any single model.

Traditional SEM

Estimation: Coefficients are estimated simultaneously in a single variance-covariance matrix of all variables; typically by MLE.

Goodness-of-fit: = discrepancy between the observed and predicted covariance matrices. χ^2 test: the χ^2 statistic describes the agreement between the 2 matrices.

Assumptions

- Independent errors (no underlying structure)
- Normal errors

Limits

- *Assumptions often violated in ecological research: e not independent (spatial or temporal correlation in observational studies), distribution not normal (count data \sim Poisson)...*
- computationally intensive (depending on the sizes of the variance-covariance matrix);
- if variables are nested, then the sample size is limited to the use of variables at the highest level of the hierarchy. Can shrink our sample and reduce the power of the analysis...

Piecewise SEM

Estimation: Decompose the network and estimate each relationship separately (estimate m separate vcov matrices). Then piece the m paths together for inferences about the entire SEM.

- \implies Much easier to estimate than a single vcov matrix \rightarrow can estimate large networks
- \implies Flexible: can incorporate many model structures, distributions... using extensions of linear reg (random effects, hierarchical models, non-normal responses, spatial correlation...)

Goodness-of-fit: No formal χ^2 test. Instead: "tests of directed separation": are any paths missing from the model?

The 'basis set' = all k pair relationships unspecified in the model (i.e., independence claims). Test whether are indeed not significant (controlling for variables on which these paths are conditional), keep the p-value. From the k p-values, calculate Fisher's C statistic $C = -2 \sum_{i=1}^k \ln(p_i) \sim \chi^2(2k)$. If C's p-value > 0.05 , accept the model. This approach is vulnerable to model misspecification.

Rmk: we can compute an AIC score for the SEM, for model comparisons: $AIC = C + 2k \frac{n}{n-k-1}$

³⁴Causality is central: SEM is designed to test competing hypotheses about complex relationships. On causality in SEMs: Judea Pearl (2012) and Kenneth Bollen & Judea Pearl (2013).

A Maths of potential outcomes

The steps overlooked in the main document are provided here in blue.

2.1.1 The original selection bias problem

$$\begin{aligned}
 \mathbb{E}[Y_i|D_i=1] - \mathbb{E}[Y_i|D_i=0] &= \mathbb{E}[Y_i^1|D_i=1] - \mathbb{E}[Y_i^0|D_i=0] \quad (\text{definition of potential outcomes}) \\
 &= \mathbb{E}[Y_i^1|D_i=1] - \mathbb{E}[Y_i^0|D_i=1] + \mathbb{E}[Y_i^0|D_i=1] - \mathbb{E}[Y_i^0|D_i=0] \\
 &= \underbrace{\mathbb{E}[Y_i^1 - Y_i^0 | D_i=1]}_{\text{ATE}} + \underbrace{\mathbb{E}[Y_i^0 | D_i=1] - \mathbb{E}[Y_i^0 | D_i=0]}_{\text{selection bias}}
 \end{aligned}$$

2.1.2 Expressing TE as a linear regression

Consider the simple linear regression $Y_i = \alpha + \beta D_i + u_i$.

- The OLS slope estimand simplifies to the difference in average observed outcomes:

$$\begin{aligned}
 \beta_{\text{OLS}} &= \frac{\text{cov}[Y_i, D_i]}{\text{Var}[D_i]} = \frac{\mathbb{E}[Y_i D_i] - \mathbb{E}[Y_i]\mathbb{E}[D_i]}{\mathbb{E}[D_i^2] - \mathbb{E}[D_i]^2} \\
 &= \frac{\mathbb{E}[Y_i \times 1 | D_i=1]P(D_i=1) - \left(\mathbb{E}[Y_i | D_i=0]P(D_i=0) + \mathbb{E}[Y_i | D_i=1]P(D_i=1) \right) \left(\frac{1}{2} \times 1 + \frac{1}{2} \times 0 \right)}{\left(\frac{1}{2} \times 1^2 + \frac{1}{2} \times 0^2 \right) - \left(\frac{1}{2} \times 1 + \frac{1}{2} \times 0 \right)^2} \\
 &= \frac{\mathbb{E}[Y_i | D_i=1] \times \frac{1}{2} - \left(\mathbb{E}[Y_i | D_i=0] \times \frac{1}{2} + \mathbb{E}[Y_i | D_i=1] \times \frac{1}{2} \right) \times \frac{1}{2}}{\frac{1}{2} - \frac{1}{4}} \\
 &= \frac{\mathbb{E}[Y_i | D_i=1] - \mathbb{E}[Y_i | D_i=0] \times \frac{1}{2} - \mathbb{E}[Y_i | D_i=1] \times \frac{1}{2}}{\frac{1}{2}} \\
 &= \mathbb{E}[Y_i | D_i=1] - \mathbb{E}[Y_i | D_i=0]
 \end{aligned}$$

- However this is equal to the true β only if the error term is uncorrelated with the treatment:

$$\left. \begin{aligned} \mathbb{E}[Y_i | D_i=1] &= \alpha + \beta + \mathbb{E}[u_i | D_i=1] \\ \mathbb{E}[Y_i | D_i=0] &= \alpha + \mathbb{E}[u_i | D_i=0] \end{aligned} \right\} \implies \mathbb{E}[Y_i | D_i=1] - \mathbb{E}[Y_i | D_i=0] = \beta + \mathbb{E}[u_i | D_i=1] - \mathbb{E}[u_i | D_i=0]$$

As $u_i \equiv Y_i^0 - \mathbb{E}[Y_i^0]$, we have $\mathbb{E}[u_i | D_i=1] - \mathbb{E}[u_i | D_i=0] = \mathbb{E}[Y_i^0 | D_i=1] - \mathbb{E}[Y_i^0 | D_i=0]$: the average difference in potential outcome Y_i^0 between the treated and the untreated, or “selection bias”.

3.3 IV

The IV estimand is defined as:

$$\begin{aligned}
 \beta_{\text{IV}} &\equiv \frac{\text{cov}[Y_i, Z_i]}{\text{cov}[D_i, Z_i]} = \frac{\mathbb{E}[Y_i Z_i] - \mathbb{E}[Y_i]\mathbb{E}[Z_i]}{\mathbb{E}[D_i Z_i] - \mathbb{E}[D_i]\mathbb{E}[Z_i]} \\
 &= \frac{\mathbb{E}[Y_i | Z_i=1]P(Z_i=1) - \left(\mathbb{E}[Y_i | Z_i=1]P(Z_i=1) + \mathbb{E}[Y_i | Z_i=0]P(Z_i=0) \right)P(Z_i=1)}{\mathbb{E}[D_i | Z_i=1]P(Z_i=1) - \left(\mathbb{E}[D_i | Z_i=1]P(Z_i=1) + \mathbb{E}[D_i | Z_i=0]P(Z_i=0) \right)P(Z_i=1)} \\
 &= \frac{\mathbb{E}[Y_i | Z_i=1](1 - P(Z_i=1)) - \mathbb{E}[Y_i | Z_i=0]P(Z_i=0)}{\mathbb{E}[D_i | Z_i=1](1 - P(Z_i=1)) - \mathbb{E}[D_i | Z_i=0]P(Z_i=0)} \\
 &= \frac{\mathbb{E}[Y_i | Z_i=1] - \mathbb{E}[Y_i | Z_i=0]}{\mathbb{E}[D_i | Z_i=1] - \mathbb{E}[D_i | Z_i=0]}
 \end{aligned}$$

The identifying assumptions then reduce it to the LATE on the compliers:

- Numerator: $\mathbb{E}[Y_i|Z_i=1] - \mathbb{E}[Y_i|Z_i=0] =$

$$\begin{aligned}
&= \mathbb{E}[Y_i|Z_i=1, D_i^0=0, D_i^1=0]P(D_i^0=0, D_i^1=0) - \mathbb{E}[Y_i|Z_i=0, D_i^0=0, D_i^1=0]P(D_i^0=0, D_i^1=0) \\
&\quad + \mathbb{E}[Y_i|Z_i=1, \text{---}0, \text{---}1]P(\text{---}0, \text{---}1) - \mathbb{E}[Y_i|Z_i=0, \text{---}0, \text{---}1]P(\text{---}0, \text{---}1) \\
&\quad + \mathbb{E}[Y_i|Z_i=1, \text{---}1, \text{---}0]P(\text{---}1, \text{---}0) - \mathbb{E}[Y_i|Z_i=0, \text{---}1, \text{---}0]P(\text{---}1, \text{---}0) \\
&\quad + \mathbb{E}[Y_i|Z_i=1, \text{---}1, \text{---}1]P(\text{---}1, \text{---}1) - \mathbb{E}[Y_i|Z_i=0, \text{---}1, \text{---}1]P(\text{---}1, \text{---}1) \\
&= \mathbb{E}[Y_i^0|D_i^0=0, D_i^1=0]P(D_i^0=0, D_i^1=0) - \mathbb{E}[Y_i^0|D_i^0=0, D_i^1=0]P(D_i^0=0, D_i^1=0) \\
&\quad + \mathbb{E}[Y_i^1|\text{---}0, \text{---}1]P(\text{---}0, \text{---}1) - \mathbb{E}[Y_i^0|\text{---}0, \text{---}1]P(\text{---}0, \text{---}1) \\
&\quad + \mathbb{E}[Y_i^0|\text{---}1, \text{---}0]P(\text{---}1, \text{---}0) - \mathbb{E}[Y_i^1|\text{---}1, \text{---}0]P(\text{---}1, \text{---}0) \\
&\quad + \mathbb{E}[Y_i^1|\text{---}1, \text{---}1]P(\text{---}1, \text{---}1) - \mathbb{E}[Y_i^1|\text{---}1, \text{---}1]P(\text{---}1, \text{---}1) \\
&= \mathbb{E}[Y_i^1 - Y_i^0|D_i^0=0, D_i^1=1]P(D_i^0=0, D_i^1=1) - \mathbb{E}[Y_i^1 - Y_i^0|D_i^0=1, D_i^1=0]P(D_i^0=1, D_i^1=0) \\
&= \mathbb{E}[Y_i^1 - Y_i^0|D_i^0=0, D_i^1=1]P(D_i^0=0, D_i^1=1) \text{ as the probability of defiers is 0}
\end{aligned}$$
- Denominator:
$$\begin{aligned}
\mathbb{E}[D_i|Z_i=1] - \mathbb{E}[D_i|Z_i=0] &= \mathbb{E}[D_i^1 - D_i^0] \\
&= 1 \times P(D_i^1 - D_i^0=1) + 0 \times P(D_i^1 - D_i^0=0) - 1 \times P(D_i^1 - D_i^0=-1) \\
&= P(D_i^0=0, D_i^1=1) \text{ as the probability of defiers is 0}
\end{aligned}$$

$$\Rightarrow \frac{\mathbb{E}[Y_i|Z_i=1] - \mathbb{E}[Y_i|Z_i=0]}{\mathbb{E}[D_i|Z_i=1] - \mathbb{E}[D_i|Z_i=0]} = \underbrace{\mathbb{E}[Y_i^1 - Y_i^0 | D_i^0=0, D_i^1=1]}_{\text{LATE on the compliers}}$$

3.4 Sharp RD

The sharp RD estimand is defined as:

$$\begin{aligned}
\beta_{\text{RD}} &\equiv \lim_{x \rightarrow c^+} \mathbb{E}[Y_i|X_i=x] - \lim_{x \rightarrow c^-} \mathbb{E}[Y_i|X_i=x] \\
&= \lim_{x \rightarrow c^+} \mathbb{E}[Y_i^1|X_i=x] - \lim_{x \rightarrow c^-} \mathbb{E}[Y_i^0|X_i=x] \\
&= \mathbb{E}[Y_i^1|X_i=c] - \mathbb{E}[Y_i^0|X_i=c] \\
&= \underbrace{\mathbb{E}[Y_i^1 - Y_i^0 | X_i=c]}_{\text{LATE at the cutoff}}
\end{aligned}$$

3.5 Fuzzy RD

The fuzzy RD estimand is defined as:

$$\beta_{\text{IV}} \equiv \frac{\lim_{x \rightarrow c^+} \mathbb{E}[Y_i|X_i=x] - \lim_{x \rightarrow c^-} \mathbb{E}[Y_i|X_i=x]}{\lim_{x \rightarrow c^+} \mathbb{E}[D_i|X_i=x] - \lim_{x \rightarrow c^-} \mathbb{E}[D_i|X_i=x]} = \lim_{\delta \rightarrow 0} \frac{\mathbb{E}[Y_i|c < X_i < c + \delta] - \mathbb{E}[Y_i|c - \delta < X_i < c]}{\mathbb{E}[D_i|c < X_i < c + \delta] - \mathbb{E}[D_i|c - \delta < X_i < c]}$$

$$\begin{aligned}
\mathbb{E}[Y_i|c < X_i < c + \delta] - \mathbb{E}[Y_i|c - \delta < X_i < c] &\simeq \gamma\beta \\
\mathbb{E}[D_i|c < X_i < c + \delta] - \mathbb{E}[D_i|c - \delta < X_i < c] &\simeq \gamma
\end{aligned}$$

$$\text{Therefore, } \beta_{\text{IV}} = \frac{\gamma\beta}{\gamma} = \beta$$

3.6 DiD

The DiD estimand is defined as:

$$\begin{aligned}
\beta_{\text{DiD}} &\equiv (\bar{Y}_{G_1 P_1} - \bar{Y}_{G_1 P_0}) - (\bar{Y}_{G_0 P_1} - \bar{Y}_{G_0 P_0}) \\
&\equiv (\mathbb{E}[Y_{i1} | G_i=1] - \mathbb{E}[Y_{i0} | G_i=1]) - (\mathbb{E}[Y_{i1} | G_i=0] - \mathbb{E}[Y_{i0} | G_i=0]) \\
&= (\mathbb{E}[Y_{i1}^1 | G_i=1] - \mathbb{E}[Y_{i0} | G_i=1]) - (\mathbb{E}[Y_{i1}^0 | G_i=0] - \mathbb{E}[Y_{i0} | G_i=0]) \\
&= \mathbb{E}[d_i^1 | G_i=1] - \mathbb{E}[d_i^0 | G_i=0] \\
&= \mathbb{E}[d_i^1 | G_i=1] - \mathbb{E}[d_i^0 | G_i=1] \\
&= \mathbb{E}[d_i^1 - d_i^0 | G_i=1] \\
&= \underbrace{\mathbb{E}[Y_{i1}^1 - Y_{i1}^0 | G_i=1]}_{\text{ATET}}
\end{aligned}$$

3.7 DiDiD

The DiDiD estimand is defined as:

$$\begin{aligned}
\beta_{\text{DiDiD}} &\equiv [(\bar{Y}_{G_1 S_1 P_1} - \bar{Y}_{G_1 S_1 P_0}) - (\bar{Y}_{G_1 S_0 P_1} - \bar{Y}_{G_1 S_0 P_0})] - [(\bar{Y}_{G_0 S_1 P_1} - \bar{Y}_{G_0 S_1 P_0}) - (\bar{Y}_{G_0 S_0 P_1} - \bar{Y}_{G_0 S_0 P_0})] \\
&\equiv (\mathbb{E}[Y_{i1} - Y_{i0} | G_1, S_1] - \mathbb{E}[Y_{i1} - Y_{i0} | G_1, S_0]) - (\mathbb{E}[Y_{i1} - Y_{i0} | G_0, S_1] - \mathbb{E}[Y_{i1} - Y_{i0} | G_0, S_0]) \\
&\equiv (\mathbb{E}[d_i^1 | G_1, S_1] - \mathbb{E}[d_i^0 | G_1, S_0]) - (\mathbb{E}[d_i^0 | G_0, S_1] - \mathbb{E}[d_i^0 | G_0, S_0]) \\
&\equiv (\mathbb{E}[d_i^1 | G_1, S_1] - \cancel{\mathbb{E}[d_i^0 | G_1, S_0]}) - (\mathbb{E}[d_i^0 | G_1, S_1] - \cancel{\mathbb{E}[d_i^0 | G_1, S_0]}) \\
&\equiv \mathbb{E}[d_i^1 - d_i^0 | G_1, S_1] \\
&= \underbrace{\mathbb{E}[Y_{i1}^1 - Y_{i1}^0 | G_1, S_1]}_{\text{ATET}}
\end{aligned}$$

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