

Counterfactual Framework of Causal Inference

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Outline

Missing Data

Counterfactual Framework of Causal Inference

Random Experiments

Identification

- We have learned how to use **samples** to estimate and make statistical inference over some population quantity (e.g., $P(X)$ or $E(Y|X)$)
- What if we cannot observe some random variables?
- Statistical **identification**: use some **observed** random variables to infer properties about **unobserved** random variables.
- And statisticians call it **identification problem**
- To address identification problem, we need additional assumptions about our data

Missing Data

- **Missing data** is one common identification problem
- Let us work with the simplest case: we are interested in only one random variable Y .
- And we draw a sample of n points, Y_1, \dots, Y_n from population Y .
- Define R_i be an indicator for whether or not we observe Y_i
- General solutions:
 1. Bounds: possible ranges of Y
 2. Deletion: discard missing ones
 3. Imputation: predict missing Y

Missing data: bounds

- Assume we are interested in $E(Y)$
- How do we estimate $E(Y)$ in the presence of missing data?
- Suppose we see a data that looks like the below

Unit	Y_i	R_i
1	1	1
2	?	0
3	1	1
4	0	1
5	1	1
6	?	0

(1)

- And we know that Y can take values in between $[0, 1]$ (Y can be continuous)
- What is the maximum possible value of $E(Y)$?

Missing data: bounds

- The largest value of Y is 1. We just fill in them, and calculate the largest possible value of $E(Y)$

Unit	Y_i	R_i
1	1	1
2	1	0
3	1	1
4	0	1
5	1	1
6	1	0

(2)

- The largest possible $E(Y)$ is $5/6$
- Likewise, we plug in the smallest value of Y
- The smallest possible value of $E(Y)$ is $3/6$
- We obtained bounds for $E(Y|X)$: $[3/6, 5/6]$; this is known as Manski bounds.
- Note that bounds are not confidence intervals. WHY?

Missing data: deletion

- Bounds can often be very wide, making them not that useful
- We can make stronger assumption to obtain more meaningful **point** estimation of $E(Y)$

Definition (MCAR: Missing Complete at Random, Rubin, 1976)

Y is missing completely at random if:

1. The missing $Y \perp\!\!\!\perp R$ (Response is **independent** of the missing Y we are interested in).
2. $P(R = 1) > 0$ (non-zero response probability)

Missing data: deletion

- MCAR assumption implies that

$$E(Y) = E(Y|R = 1) \quad (3)$$

- The right hand side is something we can estimate: the sample mean for those we can observe (apply plug-in principle)
- **Practical implication:** if MCAR holds, we can safely delete missing Y , and $E(Y|R = 1)$ is an unbiased estimates of $E(Y)$

Missing data: imputation

- We can also impute missing values to estimate $E(Y)$

Unit	Y_i	R_i
1	1	1
2	?	0
3	1	1
4	0	1
5	1	1
6	?	0

- Instead of deleting missing rows, we can fill in values

Imputation Method 1: Unconditional Mean Imputation

- Unconditional mean imputation fill in missing Y by the **sample mean of observed Y**

Unit	Y_i	R_i
1	1	1
2	$\hat{E}[Y R=1] = \frac{3}{4}$	0
3	1	1
4	0	1
5	1	1
6	$\hat{E}[Y R=1] = \frac{3}{4}$	0

- After unconditional mean imputation, the sample mean of imputed Y is an unbiased estimate of Y
 - Note: this is not the only way to make $E(Y) = E(Y|R=1)$
- Deletion and imputation all lead to unbiased estimate of $E(Y)$
- Their variance estimates are usually different!
 - $\hat{V}_{deletion}(Y) = 0.25$
 - $\hat{V}_{imputation}(Y) = 0.15$

MACR in multivariate case

- When we have multiple variables, we can extend MACR assumptions: each variable is independent of response.
- And with MACR assumptions, we can perform **listwise deletion** by removing any row that has missing entries.

Unit	Y_i	R_i	X_i
1	1	1	0
2	?	0	0
3	1	1	0
4	0	1	0
5	1	1	1
6	?	0	1

(4)

- Or taking the imputation perspective, we can perform **unconditional mean imputation** for each variables

MAR

- MACR is often too strong in multivariate case
 - If there are many variables, we can delete a lot of observations
 - Often these variable are correlated with each other;
- One weaker assumption is **MAR**, also known as **ignorability**

Definition (MAR: Missing at Random, Rubin, 1976)

Y is missing at random if:

1. $Y \perp\!\!\!\perp R | X$ (Response is **independent** of Y , given some other variables X).
 2. $P(R = 1) > 0$ (non-zero response probability)
- That is, Y is missing at random, once we **condition on some control variables** X .

Post-stratification estimator of sample mean

- Under MAR, we can estimate the mean of Y using **post-stratification** estimator

$$E(Y) = \sum_x E(Y|R = 1, X = x)p(X = x) \quad (5)$$

- In other words, we estimate $E(Y)$ as the weighted mean of the conditional expectation of Y given X in observed data, with weights $P(X = x)$
- Both terms on the right hand side can be estimated from samples (plug-in sample analog)
- Note: post-stratification estimator does not impute; directly estimate $E(Y)$

MAR vs MACR

- Under MACR: $\hat{E}[Y_i] = 3/4$

Unit	Y_i	R_i	X_i
1	1	1	0
2	?	0	0
3	1	1	0
4	0	1	0
5	1	1	1
6	?	0	1

- Under MAR, with stratification estimator, $\hat{E}[Y_i] = 7/9$

$$\begin{aligned}\hat{E}[Y] &= \hat{E}[Y|R=1, X=0] \hat{P}[X=0] + \hat{E}[Y|R=1, X=1] \hat{P}[X=1] \\ &= \frac{2}{3} \cdot \frac{4}{6} + 1 \cdot \frac{2}{6} = \frac{7}{9}\end{aligned}$$

- MACR and MAR will yield different estimates of $E(Y)$
- Each estimate is unbiased estimate * only if the corresponding assumption is true*

Imputation method 2: Conditional Mean Imputation

- With MAR, we can also impute Y using **conditional mean imputation**: use the conditional mean of Y as our guesses of the missing Y
- $Y_i = \hat{E}(Y|R = 1, X = X_i)$

Unit	Y_i	R_i	X_i
1	1	1	0
2	$\hat{E}[Y_i X_i = 0] = \frac{2}{3}$	0	0
3	1	1	0
4	0	1	0
5	1	1	1
6	$\hat{E}[Y_i X_i = 1] = 1$	0	1

(6)

- Then we can calculate **sample mean** over imputed Y
- Under conditional mean imputation, $\hat{E}(Y)$ is again 7/9
- The below two gives the same estimate of $E(Y)$:
 - conditional mean imputation of Y , and then take sample mean of imputed Y
 - post-stratification estimator

Conditional Mean Imputation using linear regression

- If we further assume all assumptions of linear regression are correct: $E(Y|R = 1, X = x)$ is linear in X
- Then conditional mean imputation just uses predicted values of linear regression as imputed values

Unit	Y_i	R_i	$X_{[1]i}$	$X_{[2]i}$
1	1	1	0	3
2	?	0	0	7
3	1	1	0	9
4	0	1	0	5
5	1	1	1	4
6	?	0	1	3

(7)

Conditional Mean Imputation using regression

Unit	Y_i	R_i	$X_{[1]i}$	$X_{[2]i}$
1	1	1	0	3
2	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 0 + \hat{\beta}_2 \cdot 7$	0	0	7
3	1	1	0	9
4	0	1	0	5
5	1	1	1	4
6	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 1 + \hat{\beta}_2 \cdot 3$	0	1	3

(8)

Conditional Mean Imputation using other methods

- The interpretation advantage of linear regression is not relevant now; we do not care about interpreting β ; we want our predictions of $E(Y|R = 1, X = x)$ to be more precise
- So you can use machine learning methods we have learned to predict $E(Y|R = 1, X = x)$
 - GLAM
 - CART
 - Random forest
- These options are all provided in R package `mice`

Imputation Method 3: hot-deck imputation

- Hot-deck imputation uses nearest-neighbor **matching**
- For unit i with missing Y_i , and non-missing X_i
 - Find the X_j that has the smallest distance to/is closet X_i
 - Use the Y_j associated with j as the imputed Y value for i

Unit	Y_i	R_i	X_i
1	1	1	4
2	?	0	8
3	1	1	1
4	0	1	12
5	1	1	20
6	?	0	3

- Example: unit 6's X is closest to unit 1's X . So we impute Y_6 as $Y_1 = 1$

Hot-deck imputation using propensity scores

- When we have multivariate X , it is not easy to calculate their distances
- Instead, it is popular to estimate **propensity score of response**

$$P(R = 1|X) \tag{9}$$

- Propensity score of response provides an single-number summary of multivariate X
- Hot-deck imputation based on **nearest propensity score**, not based on original distances between X
 - In other words, you want to match units whose response propensity are similar
- Estimation of propensity scores
 - Logistic regression is the default choice
 - But apparently other machine learning methods are acceptable

Hot-deck example

Unit	Y_i	R_i	$X_{[1]i}$	$X_{[2]i}$	$P(R_i = 1 X_i)$
1	2	1	0	3	0.33
2	?	0	0	7	0.14
3	3	1	0	9	0.73
4	10	1	0	5	0.35
5	12	1	1	4	0.78
6	?	0	1	3	0.70

(10)

- Unit 6's propensity score of response is closest to unit 3's propensity score. Thus Y_6 is imputed as $Y_3 = 3$

Deletion vs Imputation

- In practice, assume we want to run a regression based on Y and 10 predictors X
- Solution 1: Listwise deletion
 - Both R and Stata uses this strategy by default
 - Pros: simple; unbiased if **MAR is true**
 - Cons: **large** standard errors (since you will drop many cases)
- Solution 2: mean imputation (unconditional or conditional)
 - Pros:
 - give you more cases to work with
 - also unbiased if **MCAR/MAR is true**
 - Cons: **small** standard errors. Why?
 - Artificially fix the missing Y to its mean.
- Solution 3: hot-deck imputation
 - Pros: preserve the support of original data
 - Bear similarity to **propensity score matching**
 - Cons: how to estimate propensity scores?

Stochastic Imputation

- Problem of mean imputation: small standard error issues when we use sample mean for imputation
- A workaround—stochastic imputation—add some random noise to the sample mean
 - Say, we still use regression to impute Y , but add some random noises to your predicted Y
 - If we are working with complex machine learning models, there may be some inherent stochastic component (results are not the same every time)
- Problem: stochastic imputation also have some uncertainty, based on what noises you use
 - These random noises are not added to your final analysis, thus still producing **small** standard error estimates

Multiple Imputation

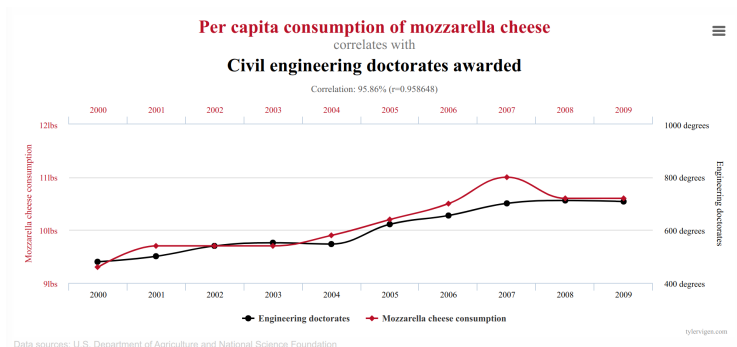
- Rubin, 1977, Multiple Imputation
 - **Stochastic imputation** for m times; ending up with m imputed datasets.
 - **Analysis**: Run your model (regression Y on X) m times
 - **Pooling**: parameter estimates for m different models can be used for estimation and inference:
 - The final parameter estimates of β is the mean of β across m models
 - The standard error of final β is more complex in math
 - basically it's the (within model standard error of β) + (between model standard error of β)
 - Or use bootstrap if m is large enough

Missing data by Chained Equations

- In practice, more than one X can have missing values
- Assume we have 5 X ; we use 1, 2, 3, 4 to impute the 5th variable, and then use 1, 2, 3, 5 to impute the 4th variable, and so on and so forth
 - Imputed values are allowed to use in the next step

Prediction vs Causation

- Correlation \neq causation
- We can use X to predict Y , and use Y to predict X
- $Y = g(X) \iff X = g^{-1}(Y)$
- This does not capture the intuitive idea that X causes Y



Counterfactual

- Does college education lead to higher wages?
- **Observed (Factorial)**: on average, college graduates indeed earn more than people with only high school education
- Critique:
 - people who can go to college have higher ability
 - even if they did not go to education, they could still earn more
 - Therefore, correlation does not mean causation
- Counterfactual thinking:
 - Guess the (**counterfactual**) earning of college graduates if they did not go to college
 - If the counterfactual earning equals to the factual earning, then college education does not matter; there is no causal effect
 - Alternatively, if the factual earning is higher than counterfactual earning, then college education indeed lead to increase in wages

Neyman-Rubin Causal Model: potential outcomes

- Neyman-Rubin Causal Model formally write down the counterfactual idea
- We have a binary treatment D ; $D = 1$ if treated and 0 otherwise
- For a person i in the population, her outcome Y_i is assumed to be:

Definition (Neyman-Rubin model)

$$Y_i = \begin{cases} Y_i^0 & : D_i = 0 \\ Y_i^1 & : D_i = 1 \end{cases}$$

$$= Y_i^0 + D_i(Y_i^1 - Y_i^0)$$

- Y_i is observed outcome
- Y_i^0 is the **potential** outcome if i is not treated
- Y_i^1 is the **potential** outcome if i is treated

Individual Level Treatment Effect

Definition (Unit-Level Treatment Effect)

For i in the population, the causal effect of treatment for unit i is :

$$\rho_i = Y_i^1 - Y_i^0$$

- $Y_i = Y_i^0 + D_i(Y_i^1 - Y_i^0)$
- So the Neyman Rubin model suggests that the observed Y for a treated unit i are the two sums:
 - counterfactual outcome if i were not treated
 - individual level treatment effect

Counterfactual Outcome as Missing Data Problem

Unit	Y_i	D_i
1	1	1
2	1	0
3	1	1
4	0	1
5	1	1
6	0	0

(11)

Unit	Y_i^0	Y_i^1	D_i
1	?	1	1
2	1	?	0
3	?	1	1
4	?	0	1
5	?	1	1
6	0	?	0

(12)

Fundamental Problem of Causal Inference

Definition (Fundamental Problem of Causal Inference, Holland, 1986)

At any given time, we only observe one of the potential outcomes for unit i — either Y_i^1 or Y_i^0 —but not both. Thus unit-level treatment effect ρ_i is not identified.

- Similar to missing data problems, we have to make assumptions (here, assumptions about potential outcomes) to allow identification.
 - In particular, identification of the average of treatment effect ρ_i because identifying the effect for every unit can be extremely hard

ATE and ATT

Definition (Average Treatment Effect (ATE))

$$ATE = E(\rho) = E(Y^1 - Y^0) = E(Y^1) - E(Y^0)$$

- ATE is the mean of unit-level treatment effect
- ATE is the difference between the mean of two **potential** outcomes

Definition (Average Treatment Effect on the Teated (ATT))

$$ATT = E(\rho|D = 1) = E(Y^1 - Y^0|D = 1) = E(Y^1|D = 1) - E(Y^0|D = 1)$$

- ATT is the mean of unit-level treatment effect for treated units

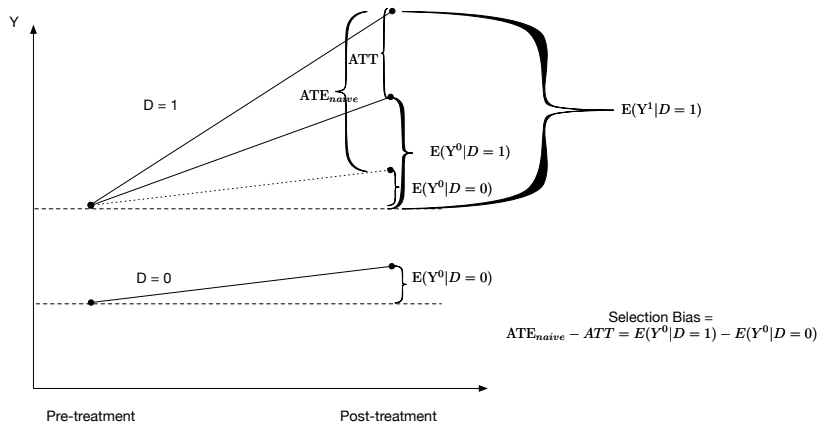
Naive estimate of ATE

- Naive estimate of ATE is just the difference in means of **observed** data

$$ATE_{naive} = E[Y|D = 1] - E[Y|D = 0] \quad (13)$$

- For instance, $D = 1$ for college education and $D = 0$ for less than college education
- ATE_{naive} is the mean earning of college education - mean earning of non-college educated
- In general, $ATE \neq ATT \neq ATE_{naive}$; what is their connection?

Selection Bias



Selection bias

- ATE_{naive} neither estimates ATE nor ATT
- ATE_{naive} differs from ATT by **selection bias**

$$\text{selection bias} = ATE_{naive} - ATT = E(Y^0|D=1) - E(Y^0|D=0)$$

- Intuitively, this is the **counterfactual** earning of college educated if they did not go to college, minus the **factual** earning of non-college educated
 - This selection bias could be caused by ability, for example
- If selection bias is 0, $ATE_{naive} = ATT$

Random Assignment

- In randomized controlled experiments, we randomly assign subjects into treatment and control groups; we have **random assignment**

Definition ((Completely) Random Assignment)

- $Y_i^0, Y_i^1 \perp\!\!\!\perp D_i$ (Potential outcome is **independent** of treatment assignment)
- $P(D = 1) > 0$ (non-zero treatment probability)
- **Cautions:**
 - Observed outcome Y is not independent of treatment assignment.

Random Assignment Solves the Identification Problem

- Under random assignment of D , we have:

$$ATE_{naive} = E[Y|D = 1] - E[Y|D = 0] = ATE \quad (14)$$

- Proof (the first line to second line is due to independence between D and Y^0, Y^1)

$$\begin{aligned} E[Y|D = 1] - E[Y|D = 0] &= E[Y^1|D = 1] - E[Y^0|D = 0] \\ &= E[Y^1|D = 1] - E[Y^0|D = 1] \\ &= E[Y^1 - Y^0|D = 1] \\ &= E[Y^1 - Y^0] \\ &= E[Y^1] - E[Y^0] \end{aligned} \quad (15)$$

Non-parametric estimator: difference-in-means

- With random assignment, estimating ATE is very simple: ATE_{naive} , which is just the difference in mean outcome of the treatment and the control group
- This is a **non-parametric** estimator
- Another important observation: $ATT = ATE$ for randomized experiments

Experiment as Imputation

Unit	Y_i^0	Y_i^1	D_i
1	?	1	1
2	1	?	0
3	?	1	1
4	?	0	1
5	?	1	1
6	0	?	0

(16)

- Random assignment implies that we can impute the missing values using observed sample mean; similar to the MCAR assumption in missing data
 - But here, random assignment is a fact, not an assumption

Unit	Y^0	Y^1	D
1	$\hat{E}[Y D=0] = \frac{1}{2}$	1	1
2	1	$\hat{E}[Y D=1] = \frac{3}{4}$	0
3	$\hat{E}[Y D=0] = \frac{1}{2}$	1	1
4	$\hat{E}[Y D=0] = \frac{1}{2}$	0	1
5	$\hat{E}[Y D=0] = \frac{1}{2}$	1	1
6	0	$\hat{E}[Y D=1] = \frac{3}{4}$	0

(17)

Regression estimator of ATE

- We can rewrite Y_i in the following way (MHE, 2.3.1)

$$\begin{aligned} Y_i &= E(Y_i^0) + (Y_i^1 - Y_i^0) D_i + Y_i^0 - E(Y_i^0) \\ &= \alpha + \rho_i D_i + \eta_i \end{aligned} \quad (18)$$

- This equation looks like linear regression! But each individual has its own regression coefficient ρ_i , which is the individual-level treatment effect
- Constant treatment assumption:** assume that ρ_i is the same for every one, ρ , $ATE = E(\rho_i) = \rho$

$$\begin{aligned} E[Y_i | D_i = 1] &= \alpha + \rho + E[\eta_i | D_i = 1] \\ E[Y_i | D_i = 0] &= \alpha + E[\eta_i | D_i = 0] \end{aligned} \quad (19)$$

$$\begin{aligned} ATE_{naive} &= E[Y_i | D_i = 1] - E[Y_i | D_i = 0] \\ &= \underbrace{\rho}_{ATE} + \underbrace{E[\eta_i | D_i = 1] - E[\eta_i | D_i = 0]}_{\text{selection bias}} \quad (20) \end{aligned}$$

Regression estimator of ATE

- Selection bias is 0, since $Y^0 \perp\!\!\!\perp D$ under random assignment
- Therefore,

$$ATE_{naive} = E[Y_i | D_i = 1] - E[Y_i | D_i = 0] = \underbrace{\rho}_{ATE}$$

- Therefore, if you are running a random experiment,
 - Non-parametric estimator: the difference in mean outcome of treated and control units
 - Parametric estimator:
 - assume **constant treatment effect**
 - run a regression of observed outcome on treatment D , and use coefficient of D as the estimate of ATE

Regression as Imputation

- The regression estimator of ATE is implicitly making counterfactual imputation using linear regression:

Unit	Y_i^0	Y_i^1	D_i	$X_{[1]i}$	$X_{[2]i}$
1	?	2	1	1	7
2	5	?	0	8	2
3	?	3	1	9	3
4	?	10	1	3	1
5	?	2	1	5	2
6	0	?	0	7	0

Regression as Imputation

- Run a regression as $Y = \beta_0 + \beta_1 D_i + \beta_2 X_{[1]i} + \beta_3 X_{[2]i}$, and impute counterfactual outcome using the linear regression:

Unit	Y_i^0	Y_i^1	D_i	$X_{[1]i}$	$X_{[2]i}$
1	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 0 + \hat{\beta}_2 \cdot 1 + \hat{\beta}_3 \cdot 7$	2	1	1	7
2	5	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 1 + \hat{\beta}_2 \cdot 8 + \hat{\beta}_3 \cdot 2$	0	8	2
3	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 0 + \hat{\beta}_2 \cdot 9 + \hat{\beta}_3 \cdot 3$	3	1	9	3
4	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 0 + \hat{\beta}_2 \cdot 3 + \hat{\beta}_3 \cdot 1$	10	1	3	1
5	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 0 + \hat{\beta}_2 \cdot 5 + \hat{\beta}_3 \cdot 2$	2	1	5	2
6	0	$\hat{\beta}_0 + \hat{\beta}_1 \cdot 1 + \hat{\beta}_2 \cdot 7 + \hat{\beta}_3 \cdot 0$	0	7	0

(21)

- Then ATE and ATT can be easily calculated as the difference in means of Y^1 and Y^0

Inference: Neyman Variance Estimator

- If we are running experiments, ATE can be estimated easily by taking the differences between $E(Y|D = 1)$ and $E(Y|D = 0)$
- What about statistical inference?
- Neyman Variance Estimator

1. assume **constant treatment effect**

2. Then

$$V(ATE) = \frac{V_t}{N_t} + \frac{V_c}{N_c}$$

3. V_t is variance of Y for treated users, and N_t is number of treated users

- If treatment effect is not constant, true variance is usually smaller than $\frac{V_t}{N_t} + \frac{V_c}{N_c}$

Inference: Linear regression

- If we regress Y on D ($Y = \alpha + \rho D$), it can be shown that the regression estimates of the standard error of regression coefficient is exactly same as the Neyman Variance estimator

$$V(\rho) = V(ATE) = \frac{V_t}{N_t} + \frac{V_c}{N_c}$$

- See Imbens and Rubin (chapter 7) for proof

Inference: Randomization Test

- Null distribution: D has no causal effect on Y
 - then if we **shuffle** the outcome, $E(Y|D = 1) - E(Y|D = 0) = 0$
- Randomization test
 - Calculate ATE based on experimental data
 - Shuffle your observed Y , and recalculate $ATE_{shuffle}$ based on the shuffled data
 - Say you shuffled 1000 times, and have 1000 $ATE_{shuffle}$.
 - Then you can easily calculate 95% confidence interval/standard errors of ATE estimates
 - The p value for observing ATE is just the probability that your shuffled $ATE_{shuffle}$ is larger than ATE : $p\text{-value} = P(ATE_{shuffle} > ATE)$
- Pros: do **not** need to assume constant treatment effect
- Cons: time consuming

Additional Covariates

- Researchers often collect some additional covariates (i.e., **pre-treatment** variables)
- With additional variables, it is easier to work with regression estimator

$$Y_i = \alpha + \rho D_i + \beta X_i + \epsilon_i \quad (22)$$

- $\hat{\rho}^{adj}$: covariate-adjusted estimate of treatment effect
- $\hat{\rho}$: difference-in-means of outcome variables across treatment and control (or regression coefficient by regressing Y on D without covariates)
- $\hat{\rho}_X$: difference-in-means of X across treatment and control

Additional Covariates

- It can be shown that (Li and Ding, 2019, J. R. Stat. Soc, or Imbens and Rubins, Chapter 7):

$$\hat{\rho}^{adj} = \hat{\rho} - \hat{\beta}^T \hat{\rho}_X$$

- $\hat{\rho}_X$: difference-in-means of X across treatment and control
 - With completely randomized experiments
 - $\hat{\rho}^{adj}$ is **biased**; $\hat{\rho}$ is **unbiased**
 - $\hat{\rho}_X$ are usually not exactly 0, especially when the data size is not that large
 - Both are consistent
 - because with more and more data, $\hat{\rho}_X$ approaches 0; this is called **covariate balance**
- Be careful if your treatment and control groups are not balanced; in that case, the treatment effect estimates without and with covariates can differ a lot in finite sample

Additional Covariates

- Another classical justification to add covariates in regression is that $\hat{\rho}^{adj}$ has smaller standard error than $\hat{\rho}$
- For instance, MHE (p. 23): “Inclusion of the variable $X \dots$ generate more precise estimates of the causal effect)”
- David A. Freedman, *On regression adjustments to experimental data*, *Advances in Applied Mathematics* **40** (2008), no. 2, 180–193
- It is not necessarily true!

Additional Covariates

- Winston Lin, *Agnostic notes on regression adjustments to experimental data: Reexamining Freedman's critique*, The Annals of Applied Statistics **7** (2013), no. 1, 295–318. MR3086420
- adding covariate lead to smaller standard error estimates, only if **full interaction** is added:
- And robust standard errors are used

$$Y_i = \alpha + \rho D_i + \beta X_i + \gamma D_i X_i + \epsilon_i$$

Recommended practice

- Always present two treatment effects: with and without covariates
- David A. Freedman, *On regression adjustments to experimental data*, *Advances in Applied Mathematics* **40** (2008), no. 2, 180–193
- “Regression estimates... should be deferred until rates and averages have been presented”
- Always check pre-treatment covariate balance
- Add interactions if covariance-balance is passed
- not only guarantees smaller standard error, but also detects treatment effect heterogeneity (next week)