

Causal Inference Methods and Case Studies

STAT24630

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Lecture 6

Topic: Regression for complete randomized experiment

- Using regression with no covariates
- Using regression with covariates adjustments
- Using regression with covariates adjustments and interactions
- The LRC-CPPT cholesterol data example

Linear regression and causality

- Linear regression:

$$\mathbb{E}(Y_i | \mathbf{X}_i) = f(\mathbf{X}_i) = \alpha + \boldsymbol{\beta}^T \mathbf{X}_i$$

- Question:

- When can we interpret the coefficient(s) as causal effect?
- How can we do correct inference if we take into account the randomization procedure of treatment assignments?

- Benefit of using linear regression in randomized experiments

- Provides a straightforward and familiar way to incorporate covariates
- More accurate estimator if covariates are predictive of potential outcomes

- Some critiques

- In complete randomized experiments, covariates are not confounders
- Why do we want to assume a linear model if we don't need to?

“Experiments should be analyzed as experiments, not as observational studies”

---- David A. Freedman, 2006

The LRC-CPPT cholesterol data

- An experiment to evaluate the effect of the drug cholestyramine on reducing cholesterol levels
- $N = 337$ patients are completely randomized
- **Pre-treatment covariates:** two cholesterol measurements before and after a suggestion of low-cholesterol diet, both measurements taken prior to the random assignment
 - Does $\text{chol2} - \text{chol1}$ reflect the average causal effect of suggestion? Not necessarily
 - $\text{cholp} = 0.25 \text{chol1} + 0.75 \text{chol2}$

Table 7.1. Summary Statistics for PRC-CPPT Cholesterol Data

	Variable	Control ($N_c = 172$)		Treatment ($N_t = 165$)		Min	Max
		Average	Sample (S.D.)	Average	Sample (S.D.)		
Pre-treatment	chol1	297.1	(23.1)	297.0	(20.4)	247.0	442.0
	chol2	289.2	(24.1)	287.4	(21.4)	224.0	435.0
	cholp	291.2	(23.2)	289.9	(20.4)	233.0	436.8
Post-treatment	cholf	282.7	(24.9)	256.5	(26.2)	167.0	427.0
	chold	-8.5	(10.8)	-33.4	(21.3)	-113.3	29.5
	comp	74.5	(21.0)	59.9	(24.4)	0	101.0

The LRC-CPPT cholesterol data

- An experiment to evaluate the effect of the drug cholestyramine on reducing cholesterol levels
- $N = 337$ patients are completely randomized
- **Post-treatment outcomes:**
 - cholf: post-treatment average cholesterol level
 - chold = cholf – cholp
 - comp: compliance rate, the percentage of individuals follow the treatment assignment

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The LRC-CPPT cholesterol data

- Can we evaluate the drug effect by simply look at whether chold is positive or negative?
 - **No!** The before-after comparison is NOT necessarily causal
 - Even for the control group, chold is significantly negative
- The patient's post-treatment cholesterol should be highly correlated with his/her pre-treatment cholesterol level
- **How do we evaluate the causal effect after “adjusting for the pre-treatment cholesterol”?**

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What does
“adjust for”
exactly mean
here?

The LRC-CPPT cholesterol data

A bit explanation about compliance

- If we compare between control and treatment group, we are evaluating the causal effect of “being assigned”, not the causal effect of actually taking the drug
- Compliance lower in the treatment group possibly due to the side effect of the drug
- Can we just throw away individuals who do not follow the treatment and estimate the causal effect of taking the drug based on the rest individuals? **No**
- Will discuss more about compliance in later lectures

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Linear regression with no covariates

- Causal model on the potential outcomes

$$Y_i(w) = \alpha + \tau_i w + \varepsilon_i^* = \alpha + \tau w + \varepsilon_i(w)$$

where $\mathbb{E}(\varepsilon_i^*) = 0$ and $\varepsilon_i(w) = \varepsilon_i^* + (\tau_i - \tau)w$

- Assume that there is a super-population and the potential outcomes are random
 - Individual-level causal effect $\tau_i = Y_i(1) - Y_i(0)$ is also treated as random (as individuals are randomly sampled), and are allowed to be heterogenous
 - Define PATE: $\tau = \mathbb{E}(\tau_i) = \mathbb{E}(Y_i(1) - Y_i(0))$
 - $\alpha = \mathbb{E}(Y_i(0))$ and $\mathbb{E}(\varepsilon_i(w)) = 0$
 - If the treatment is binary ($w = 0, 1$), then the above model essentially has no assumption on $Y_i(0)$ and $Y_i(1)$
 - If the treatment is continuous, the model assumes a linear but heterogenous causal effect on each individual
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- How to estimate τ from observed data?
 - When does the above model imply the linear regression model on observed data?

$$Y_i^{\text{obs}} = \alpha + \tau W_i + \varepsilon_i$$

Linear regression with no covariates

$$Y_i(w) = \alpha + \tau_i w + \varepsilon_i^* = \alpha + \tau w + \varepsilon_i(w)$$

We assume the following identification conditions

- **Randomization of the treatment:**

$$(\mathbf{Y}(0), \mathbf{Y}(1)) \perp \mathbf{W}$$

- Satisfied in complete randomized experiments
- Then, $\mathbb{E}(Y_i(w)) = \mathbb{E}(Y_i^{\text{obs}} | W_i = w) = \alpha + \tau w$ Regression model for the observed Y_i^{obs}
- So this implies a regression model $Y_i^{\text{obs}} = \alpha + \tau W_i + \varepsilon_i$ and $\varepsilon_i = \varepsilon_i(W_i)$
- In the regression model, we treat assignment vectors as fixed
- Random sampling of the units
 - $(\varepsilon_i(0), \varepsilon_i(1))$ are independent across i
 - This implies that ε_i in the linear regression model are **independent** as W_i are treated as fixed (the regression model is conditional on W_i)

Least square estimator

$$(\hat{\tau}^{\text{ols}}, \hat{\alpha}^{\text{ols}}) = \arg \min_{\tau, \alpha} \sum_{i=1}^N \left(Y_i^{\text{obs}} - \alpha - \tau \cdot W_i \right)^2,$$

with solutions

$$\hat{\tau}^{\text{ols}} = \frac{\sum_{i=1}^N (W_i - \bar{W}) \cdot (Y_i^{\text{obs}} - \bar{Y}^{\text{obs}})}{\sum_{i=1}^N (W_i - \bar{W})^2}, \quad \text{and} \quad \hat{\alpha}^{\text{ols}} = \bar{Y}^{\text{obs}} - \hat{\tau}^{\text{ols}} \cdot \bar{W},$$

where

$$\bar{Y}^{\text{obs}} = \frac{1}{N} \sum_{i=1}^N Y_i^{\text{obs}} \quad \text{and} \quad \bar{W} = \frac{1}{N} \sum_{i=1}^N W_i = \frac{N_t}{N}.$$

Simple linear algebra shows that

$$\hat{\tau}^{\text{ols}} = \bar{Y}_t^{\text{obs}} - \bar{Y}_c^{\text{obs}} = \hat{\tau}^{\text{dif}},$$

- $\hat{\tau}^{\text{ols}}$ is unbiased for the estimation of τ
- How to estimate the variance of $\hat{\tau}^{\text{ols}}$?

Homoscedastic error assumption

Homoscedastic error assumption: $\mathbb{V}(\varepsilon_i(0)) = \mathbb{V}(\varepsilon_i(1)) = \sigma^2 = \mathbb{V}(Y_i^{\text{obs}}|W_i)$

- OLS estimates of the variance is

$$\hat{\sigma}_{Y|W}^2 = \frac{1}{N-2} \sum_{i=1}^N \hat{\varepsilon}_i^2 = \frac{1}{N-2} \sum_{i=1}^N (Y_i^{\text{obs}} - \hat{Y}_i^{\text{obs}})^2,$$

where the estimated residual is $\hat{\varepsilon}_i = Y_i^{\text{obs}} - \hat{Y}_i^{\text{obs}}$, and the predicted value \hat{Y}_i^{obs} is

$$\hat{Y}_i^{\text{obs}} = \begin{cases} \hat{\alpha}^{\text{ols}} & \text{if } W_i = 0, \\ \hat{\alpha}^{\text{ols}} + \hat{\tau}^{\text{ols}} & \text{if } W_i = 1. \end{cases}$$

- Then from OLS, estimate of the variance of $\hat{\tau}^{\text{ols}}$

$$\hat{\mathbb{V}}^{\text{homosk}} = \frac{\hat{\sigma}_{Y|W}^2}{\sum_{i=1}^N (W_i - \bar{W})^2}$$

Heteroscedastic errors

- If we don't want to assume $\mathbb{V}(\varepsilon_i(0)) = \mathbb{V}(\varepsilon_i(1))$, then the homoscedastic error assumption fails
- Robust variance estimation of $\hat{\tau}^{\text{ols}}$ allowing any heterogeneity of $\mathbb{V}(Y_i^{\text{obs}}|W_i)$ across i

$$\hat{\mathbb{V}}^{\text{hetero}} = \frac{\sum_{i=1}^N \hat{\varepsilon}_i^2 \cdot (W_i - \bar{W})^2}{\left(\sum_{i=1}^N (W_i - \bar{W})^2 \right)^2}$$

- If we replace $\hat{\varepsilon}_i^2$ by $\hat{\sigma}_{Y|W}^2$, then we get back the OLS variance estimation of $\hat{\tau}^{\text{ols}}$
- This is also called the Sandwich estimator that is robust to the violation of the homoscedastic noise assumption in linear regression
- The robust variance estimator can be rewritten as
- This is the same variance estimator as from Neyman's approach, or our two-sample testing approach

$$\hat{\mathbb{V}}^{\text{hetero}} = \frac{s_c^2}{N_c} + \frac{s_t^2}{N_t}.$$

Linear regression with covariates adjustment

To summarize the logic

- We build a (linear) model on the potential outcomes
- This model implies a linear regression model on the observed outcome if $(Y(0), Y(1)) \perp W$
- The coefficient on W_i in the linear regression model is the average causal effect (PATE)
- The linear regression model treat W as fixed so it works for any randomization assignment mechanism that satisfy $(Y(0), Y(1)) \perp W$
- Noise in the linear regression model are independent as long as potential outcomes are independent across units
- For statistical inference
 - The OLS estimator estimator is always unbiased
 - We can apply standard linear regression inference results if we assume $V(\varepsilon_i(0)) = V(\varepsilon_i(1))$
 - If $V(\varepsilon_i(0)) \neq V(\varepsilon_i(1))$, we need to use the robust variance estimator

Linear regression with covariates adjustment

- Regress $Y_i(0)$ on the pre-treatment covariates \mathbf{X}_i

$$Y_i(w) = \alpha + \tau_i w + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i^* = \alpha + \tau w + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i(w)$$

where $\mathbb{E}(\varepsilon_i^* | \mathbf{X}_i) = 0$ and $\varepsilon_i(w) = \varepsilon_i^* + (\tau_i - \tau)w$

- We assume that $\mathbb{E}(Y_i(0) | \mathbf{X}_i) = \alpha + \boldsymbol{\beta}^T \mathbf{X}_i$
- Individual-level causal effect is $\tau_i = Y_i(1) - Y_i(0)$
- Assume CATE $\tau(\mathbf{x}) = \mathbb{E}(\tau_i | \mathbf{X}_i = \mathbf{x}) \equiv \tau = \text{PATE}$ constant across levels of \mathbf{X}_i
- We can allow for heterogeneous causal effect but need $\mathbb{E}(\tau_i - \tau | \mathbf{X}_i) = 0$
(individual causal effects are independent from the pre-treatment covariates)
- The above implies that $\mathbb{E}(\varepsilon_i(w) | \mathbf{X}_i) = 0$
- The above also implies that $\mathbb{E}(Y_i(w) | \mathbf{X}_i) = \alpha + \tau w + \boldsymbol{\beta}^T \mathbf{X}_i$

When does the above model imply the linear regression model on observed data?

$$Y_i^{\text{obs}} = \alpha + \tau W_i + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i$$

Linear regression with covariates adjustment

$$Y_i(w) = \alpha + \tau w + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i(w)$$

We assume the following identification conditions

- (Conditional) randomization of the treatment:

$$(\mathbf{Y}(0), \mathbf{Y}(1)) \perp \mathbf{W} \mid \mathbf{X}$$

- Always satisfied in randomized experiments
- $\mathbb{E}(Y_i(w)|\mathbf{X}_i = \mathbf{x}) = \mathbb{E}(Y_i^{\text{obs}}|W_i = w, \mathbf{X}_i = \mathbf{x}) = \alpha + \tau w + \boldsymbol{\beta}^T \mathbf{X}_i$

Regression model for the observed Y_i^{obs}

- So this implies a regression model $Y_i^{\text{obs}} = \alpha + \tau W_i + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i$ and $\varepsilon_i = \varepsilon_i(W_i)$
- Both \mathbf{X}_i and W_i are treated as fixed
- Random sampling of the units
 - $(\varepsilon_i(0), \varepsilon_i(1))$ are independent across i
 - This implies that $\varepsilon_i = \varepsilon_i(W_i)$ are independent across units

OLS with covariates adjustment

$$(\hat{\alpha}^{\text{ols}}, \hat{\tau}^{\text{ols}}, \hat{\beta}^{\text{ols}}) = \arg \min_{\alpha, \tau, \beta} \sum_{i=1}^N \left(Y_i^{\text{obs}} - \alpha - \tau \cdot W_i - X_i \beta \right)^2$$

- The estimator $\hat{\tau}^{\text{ols}}$ is unbiased for the causal estimand τ
- Even if the model is incorrect (either the violation of $\mathbb{E}(Y_i(0)|X_i) = \alpha + \beta^T X_i$ or $\tau \equiv \mathbb{E}(\tau_i|X_i = x)$), $\hat{\tau}^{\text{ols}}$ still converges to the PATE $\mathbb{E}(\tau_i)$ under complete randomization

Efficiency gain from regression

- If the model is correct, we have

$$\mathbb{V}(\hat{\tau}^{\text{ols}}) \approx \frac{\mathbb{E}\{\mathbb{V}(Y_i(1)|X_i)\}}{N_t} + \frac{\mathbb{E}\{\mathbb{V}(Y_i(0)|X_i)\}}{N_c} \leq \frac{\sigma_c^2}{N_c} + \frac{\sigma_t^2}{N_t}$$

- If X_i is predictive of the (potential) outcomes, we have a more accurate estimator
- If the linear model is incorrect, the efficiency might be lost
(Freedman 2008, *Adv. Appl. Math.*)

Estimate of the variance of $\hat{\tau}^{\text{ols}}$ with covariates adjustment

- Assume homoscedastic error assumption:

$$\mathbb{V}(\varepsilon_i(0)) = \mathbb{V}(\varepsilon_i(1)) = \sigma^2 = \mathbb{V}(Y_i^{\text{obs}} | W_i, X_i)$$

We can follow standard linear regression inference and estimate variance of $\hat{\tau}^{\text{ols}}$ as

$$\hat{\mathbb{V}}_{\text{sp}}^{\text{homo}} = \frac{1}{N(N-1-\dim(X_i))} \cdot \frac{\sum_{i=1}^N (Y_i^{\text{obs}} - \hat{\alpha}^{\text{ols}} - \hat{\tau}^{\text{ols}} - X_i \hat{\beta}^{\text{ols}})^2}{\bar{W} \cdot (1 - \bar{W})}$$

- The robust variance estimator (Sandwich estimator) without assuming homoscedasticity

$$\begin{aligned} \hat{\mathbb{V}}_{\text{sp}}^{\text{hetero}} = & \frac{1}{N(N-1-\dim(X_i))} \\ & \cdot \frac{\sum_{i=1}^N (W_i - \bar{W})^2 \cdot (Y_i^{\text{obs}} - \hat{\alpha}^{\text{ols}} - \hat{\tau}^{\text{ols}} - X_i \hat{\beta}^{\text{ols}})^2}{(\bar{W} \cdot (1 - \bar{W}))^2} \end{aligned}$$

Linear regression with covariates adjustment and interactions

What if the assumption $\tau \equiv \tau(\mathbf{x}) = \mathbb{E}(\tau_i | \mathbf{X}_i = \mathbf{x})$ constant across levels of \mathbf{X}_i is incorrect?

- $Y_i(w) = \alpha + \tau_i w + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i^* = \alpha + \tau w + \boldsymbol{\beta}^T \mathbf{X}_i + \varepsilon_i(w)$ where $\mathbb{E}(\varepsilon_i^* | \mathbf{X}_i) = 0$ and $\varepsilon_i(w) = \varepsilon_i^* + (\tau_i - \tau)w$
- Assume CATE $\tau(\mathbf{x}) = \mathbb{E}(\tau_i | \mathbf{X}_i = \mathbf{x}) = \tau + \boldsymbol{\gamma}^T (\mathbf{x} - \bar{\mathbf{X}})$
- τ is still the population average treatment effect
- Then $\mathbb{E}(\varepsilon_i(w) | \mathbf{X}_i) = \boldsymbol{\gamma}^T (\mathbf{X}_i - \bar{\mathbf{X}})w$
- The above also implies that $\mathbb{E}(Y_i(w) | \mathbf{X}_i) = \alpha + \tau w + \boldsymbol{\beta}^T \mathbf{X}_i + \boldsymbol{\gamma}^T (\mathbf{X}_i - \bar{\mathbf{X}})w$
- When does the above model imply the linear regression model with interactions on observed data?

$$Y_i^{\text{obs}} = \alpha + \tau W_i + \boldsymbol{\beta}^T \mathbf{X}_i + \boldsymbol{\gamma}^T (\mathbf{X}_i - \bar{\mathbf{X}})W_i + \varepsilon_i$$

- Same assumptions as before (slide 15)
- We can still use least square estimators

Results on the LRC-CPPT cholesterol data

- We estimate the PATE for both the post-treatment cholesterol level cholf and compliance
 - A considerable reduction of the variance of $\hat{\tau}^{\text{ols}}$ for cholf when we add the pre-treatment cholesterol levels in the regression
 - Our goal is always estimating PATE even after “covariates adjustment”
 - In randomized experiments satisfying $(Y(0), Y(1)) \perp W$, adjusting for covariates or not, our estimate of PATE is always valid, we only change the efficiency of our estimate

Covariates	Effect of Assignment to Treatment on			
	Post-Cholesterol Level		Compliance	
	$\hat{\tau}$	(s. e.)	$\hat{\tau}$	(s. e.)
No covariates	−26.22	(3.93)	−14.64	(3.51)
cholp	−25.01	(2.60)	−14.68	(3.51)
chol1, chol2	−25.02	(2.59)	−14.95	(3.50)
chol1, chol2, interacted with W	−25.04	(2.56)	−14.94	(3.49)

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- We estimate the PATE for both the post-treatment cholesterol level cholf and compliance
 - A considerable reduction of the variance of $\hat{\tau}^{\text{ols}}$ for cholf when we add the pre-treatment cholesterol levels in the regression
 - Our goal is always estimating PATE even after “covariates adjustment”
 - In randomized experiments satisfying $(Y(0), Y(1)) \perp \mathbf{W}$, adjusting for covariates or not, our estimate of PATE is always valid, we only change the efficiency of our estimate
 - **Which variables are “significantly” contributing to the variance reduction of $\hat{\tau}^{\text{ols}}$ for cholf ?**

Covariates	Model for Levels	
	Est	(s. e.)
Assignment	−25.04	(2.56)
Intercept	−3.28	(12.05)
chol1	0.98	(0.04)
chol2-chol1	0.61	(0.08)
chol1 × Assignment	−0.22	(0.09)
(chol2-chol1) × Assignment	0.07	(0.14)
R-squared	0.63	

Why do we use linear regression in randomized experiments?

- Covariate adjustment can be used to improve efficiency in randomized experiments
- Under various experimental designs, linear regression models are useful methods for this purpose
- Randomization of treatment assignment protects researchers from misspecification
 - independence between treatment and covariates
 - linear regression estimators are often consistent even when the model is incorrect