

Instrumental Variables

EC 421, Set 11

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Prologue

Schedule

Last Time

Causality

Today

- Review: Causality
- New: Instrumental variables

Upcoming

Assignment soon.

Causality

Review

Causality

Review

In our last lecture, we returned to the concept of **causality**.

We worked through the *Rubin causal model*, in which we defined

- y_{1i} : the outcome for individual i if she had received treatment
- y_{0i} : the outcome for individual i if she had not received treatment

and we referred to individuals who did not receive treatment as *control*.

If we were able to know both y_{1i} **and** y_{0i} , we could calculate the causal effect of treatment for individual i , i.e.,

$$\tau_i = y_{1i} - y_{0i}$$

Causality

Review

Fundamental problem of causal inference:

We cannot simultaneously know y_{1i} and y_{0i} .

Either we observe individual i in the treatment group, i.e.,

$$\tau_i = y_{1i} - ?$$

or we observe i in the control group, i.e.,

$$\tau_i = ? - y_{0i}$$

but never both at the same time.

Causality

Review

If we want to know τ_i (or at least $\bar{\tau}$), what can we do?

Idea: Estimate the **average treatment effect** as the difference between the average outcomes in the treatment group and the control group, *i.e.*,

$$Avg(y_i \mid D_i = 1) - Avg(y_i \mid D_i = 0)$$

where $D_i = 1$ if i received treatment, and $D_i = 0$ if i is in the control group.

Causality

Review

Result: We showed that even when the treatment effect is constant (meaning $\tau_i = \tau$ for all i),

$$\begin{aligned} & \text{Avg}(y_i | D_i = 1) - \text{Avg}(y_i | D_i = 0) \\ &= \tau + \underbrace{\text{Avg}(y_{0,i} | D_i = 1) - \text{Avg}(y_{0,i} | D_i = 0)}_{\text{Selection bias}} \end{aligned}$$

which says that the difference in the groups' means will give us a **biased estimate** for the causal effect of treatment **if we have selection bias.**

Causality

Review

Q: What is this **selection bias**?

A: (Informal) We have selection bias when our control group doesn't offer a good comparison for our treatment group.

Specifically, the control group doesn't give us a good **counterfactual** for what our treatment group would have looked like if the members had not received treatment. Basically, the groups are different.

A: (Formal) The *average untreated outcome* for a member of our **treatment group** (which we cannot observe) differs from the *average untreated outcome* for a member of our **control group**, i.e.,

$$Avg(y_{0,i} \mid D_i = 1) - Avg(y_{0,i} \mid D_i = 0)$$

Causality

Review

Practical problem: Selection bias is also difficult to observe

$$\underbrace{\text{Avg}(y_{0,i} \mid D_i = 1) - \text{Avg}(y_{0,i} \mid D_i = 0)}_{\text{Unobservable}}$$

(back to the *fundamental problem of causal inference*)

Bigger problem: If selection bias is present, our estimate for τ is biased, preventing us from understanding the causal effect of treatment.

Sounds a bit like omitted-variable bias, right? Our *treatment* variable is correlated with something that makes the two groups different.

Causality

Review

Example: Imagine we have two people—Al and Bri—and a single binary treatment, college. We interested in the effect of college on earnings.

$$\text{Earn}_{1,\text{Al}} = \$60\text{K}$$

$$\text{Earn}_{0,\text{Al}} = \$30\text{K}$$

$$\text{Earn}_{1,\text{Bri}} = \$140\text{K}$$

$$\text{Earn}_{0,\text{Bri}} = \$110\text{K}$$

They both have the same treatment effect (return to college)

$$\tau_{\text{Al}} = \text{Earn}_{1,\text{Al}} - \text{Earn}_{0,\text{Al}} = \$60\text{K} - \$30\text{K} = \$30\text{K}$$

$$\tau_{\text{Bri}} = \text{Earn}_{1,\text{Bri}} - \text{Earn}_{0,\text{Bri}} = \$140\text{K} - \$110\text{K} = \$30\text{K}$$

but any real-world estimate would have serious selection issues since $\text{Earn}_{0,\text{Al}} \neq \text{Earn}_{0,\text{Bri}}$.

Causality

Review

Example: Imagine we have two people—Al and Bri—and a single binary treatment, college. We interested in the effect of college on earnings.

$$\text{Earn}_{1,\text{Al}} = \$60\text{K}$$

$$\text{Earn}_{0,\text{Al}} = \$30\text{K}$$

$$\text{Earn}_{1,\text{Bri}} = \$140\text{K}$$

$$\text{Earn}_{0,\text{Bri}} = \$110\text{K}$$

The selection bias...

If Bri attended college ($D_{\text{Bri}}=1$) and Al did not ($D_{\text{Al}}=0$):

$$\hat{\tau} = \text{Earn}_{1,\text{Bri}} - \text{Earn}_{0,\text{Al}} = \$140\text{K} - \$30\text{K} = \$110\text{K}$$

If Al attended college ($D_{\text{Al}}=1$) and Bri did not ($D_{\text{Bri}}=0$):

$$\hat{\tau} = \text{Earn}_{1,\text{Al}} - \text{Earn}_{0,\text{Bri}} = \$60\text{K} - \$110\text{K} = -\$50\text{K}$$

Causality

Review

We have (at least) two problems...

1. Selection bias is difficult to observe
2. If selection bias is present, our estimate for τ is biased, preventing us from understanding the causal effect of treatment.

Solution: Eliminate/minimize selection bias.

- **Option 1: Distribute treatment** in a way such that the treatment and control groups are essentially identical (experiments).
- **Option 2: Build a control** group that *matches* the treatment group (life with observational data).

Instrumental variables

Instrumental variables

Intro

Instrumental variables (IV) is one route econometricians often take toward estimating the causal effect of a treatment/program.

Recall: **Selection bias** means our **treatment** and **control** groups differ on some unobserved/omitted dimension. (**Endogeneity**)

Instrumental variables attempts to separate out

- the **exogenous** part of x , which gives us unbiased estimates
- the **endogenous** part of x , which biases our results

If we use only the exogenous (*good*) variation in x , then we can avoid selection bias/omitted-variable bias.

Instrumental variables

Introductory example

Example: If we want to estimate the effect of veteran status on earnings,

$$\text{Earnings}_i = \beta_0 + \beta_1 \text{Veteran}_i + u_i \quad (1)$$

We would love to calculate $\text{Earnings}_{1i} - \text{Earnings}_{0i}$, but we can't.

And OLS will likely be biased for (1) due to selection/omitted-variable bias.

Instrumental variables

Introductory example

Imagine that we can split veteran status into an exogenous part and an endogenous part...

$$\begin{aligned}\text{Earnings}_i &= \beta_0 + \beta_1 \text{Veteran}_i + u_i & (1) \\ &= \beta_0 + \beta_1 \left(\text{Veteran}_i^{\text{Exog.}} + \text{Veteran}_i^{\text{Endog.}} \right) + u_i \\ &= \beta_0 + \beta_1 \text{Veteran}_i^{\text{Exog.}} + \underbrace{\beta_1 \text{Veteran}_i^{\text{Endog.}} + u_i}_{w_i} \\ &= \beta_0 + \beta_1 \text{Veteran}_i^{\text{Exog.}} + w_i\end{aligned}$$

We could use this exogenous variation in veteran status to consistently estimate β_1 .

Q: What would exogenous variation in veteran status mean?

Instrumental variables

Introductory example

Q: What would exogenous variation in veteran status mean?

A₁: Choices to enlist in the military that are essentially random—or at least uncorrelated with omitted variables and the disturbance.

A₂: No selection bias:

$$Avg(\text{Earnings}_{0i} \mid \text{Veteran}_i = 1) - Avg(\text{Earnings}_{0i} \mid \text{Veteran}_i = 0) = 0$$

Instrumental variables

Instruments

Q: How do we isolate this *exogenous variation* in our explanatory variable?

A: Find an instrument (an instrumental variable).

Q: What's an instrument?

A: An **instrument** is a variable that is

1. **correlated** with the **explanatory variable** of interest (**relevant**),
2. **uncorrelated** with the **disturbance** (**exogenous**).

Instrumental variables

Instruments

Q: What's an instrument?

A: An **instrument** is a variable that is

1. **correlated** with the **explanatory variable** of interest (**relevant**),
2. **uncorrelated** with the **disturbance** (**exogenous**).

So if we want an instrument z_i for endogenous veteran status in

$$\text{Earnings}_i = \beta_0 + \beta_1 \text{Veteran}_i + u_i$$

1. **Relevant:** $\text{Cov}(\text{Veteran}_i, z_i) \neq 0$
2. **Exogenous:** $\text{Cov}(z_i, u_i) = 0$

Instrumental variables

Instruments: Relevance

Relevance: We need the instrument to cause a change in (correlate with) our endogenous explanatory variable.

We can actually test this requirement using regression and a t test.

Example: For the [veteran status](#), consider three potential instruments:

1. Social security number
2. Physical fitness
3. Vietnam War draft

Probably not relevant

uncorrelated with military service

Potentially relevant

service may correlate with fitness

Relevant

being draw led to service

Instrumental variables

Instruments: Exogeneity

Exogeneity: The instrument to be independent of omitted factors that affect our outcome variable—as good as randomly assigned.

z_i must be uncorrelated with our disturbance u_i . **Not testable.**

Example: For the **veteran status**, consider three potential instruments:

1. Social security number
2. Physical fitness
3. Vietnam War draft

Exogenous

Indep. of other factors of service

Not exogenous

fitness correlates with many things

Exogenous

the lottery was random

Instrumental variables

Instrumental review

Let's recap...

- Our instrument must be **correlated with our endogenous variable**.
- Our instrument must be **uncorrelated with any other variable that affects the outcome**.

In other words:

The instrument only affects our outcome through the endogenous variable.

Instrumental variables

Back to our example

For **veteran status** we considered three potential instruments:

1. Social security number

Not relevant

Exogenous

2. Physical fitness

Probably relevant

Not exogenous

3. Vietnam War draft

Relevant

Exogenous

Thus, only the Vietnam War's draft lottery appears to be a **valid instrument**.

If we have a *valid* instrument (e.g., the draft lottery), how do we use it?

Instrumental variables

Estimation

Recall: We want to estimate the effect of veteran status on earnings.

$$\text{Earnings}_i = \beta_0 + \beta_1 \text{Veteran}_i + u_i$$

Let's consider two related effects:

1. The effect of the **instrument** on the **endogenous variable**, e.g.,

$$\text{Veteran}_i = \gamma_0 + \gamma_1 \text{Draft}_i + v_i$$

2. The effect of the **instrument** on the **outcome variable**, e.g.,

$$\text{Earnings}_i = \pi_0 + \pi_1 \text{Draft}_i + w_i$$

Instrumental variables

Estimation

Recall: We want to estimate the effect of veteran status on earnings.

$$\text{Earnings}_i = \beta_0 + \beta_1 \text{Veteran}_i + u_i$$

and we know that the draft affected veteran status.

Draft → **Veteran status** → **Earnings**

Using our assumptions on independence and exogeneity:

(Effect of **the draft** on **earnings**) =

(Effect of **the draft** on **veteran status**) ×

(Effect of **veteran status** on **earnings**)

Instrumental variables

Estimation

We just wrote out an expression for the effect of **the draft** on **earnings**, i.e.,

$$\begin{aligned} \text{(Effect of } \textbf{the draft} \text{ on } \textbf{earnings}) &= \\ &\text{(Effect of } \textbf{the draft} \text{ on } \textbf{veteran status}) \times \\ &\text{(Effect of } \textbf{veteran status} \text{ on } \textbf{earnings}) \end{aligned}$$

but we want to know the effect of **veteran status** on **earnings**. Rearrange!

$$\begin{aligned} \text{(Effect of } \textbf{veteran status} \text{ on } \textbf{earnings}) &= \\ &\frac{\text{(Effect of } \textbf{the draft} \text{ on } \textbf{earnings})}{\text{(Effect of } \textbf{the draft} \text{ on } \textbf{veteran status})} \end{aligned}$$

Our **instrument** consistently estimates both parts of this fraction!

Instrumental variables

Estimation: Bring it all together

By estimating two regressions involving our **instrument**,

1. The effect of the **instrument** on the **endogenous variable**, e.g.,

$$\text{Veteran}_i = \gamma_0 + \gamma_1 \text{Draft}_i + v_i$$

2. The effect of the **instrument** on the **outcome variable**, e.g.,

$$\text{Earnings}_i = \pi_0 + \pi_1 \text{Draft}_i + w_i$$

we can estimate our desired effect:

(Effect of **veteran status** on **earnings**) =

$$\frac{\text{(Effect of } \text{the draft} \text{ on } \text{earnings})}{\text{(Effect of } \text{the draft} \text{ on } \text{veteran status})}$$

Instrumental variables

Estimation: Bring it all together

By estimating two regressions involving our **instrument**,

1. The effect of the **instrument** on the **endogenous variable**, e.g.,

$$\text{Veteran}_i = \gamma_0 + \gamma_1 \text{Draft}_i + v_i$$

2. The effect of the **instrument** on the **outcome variable**, e.g.,

$$\text{Earnings}_i = \pi_0 + \pi_1 \text{Draft}_i + w_i$$

we can estimate our desired effect:

$$(\text{Effect of } \text{veteran status} \text{ on } \text{earnings}) = \frac{\pi_1}{\gamma_1}$$

Instrumental variables

Estimation: Bring it all together

So with instrumental variables, we estimate β_1 using

$$\hat{\beta}_1^{\text{IV}} = \frac{\hat{\pi}_1}{\hat{\gamma}_1}$$

where $\hat{\pi}_1$ and $\hat{\gamma}_1$ come from the two equations we just discussed.

Q: Can we trust $\hat{\beta}_1^{\text{IV}}$?

A: Yes... **if we have a valid instrument.**

$$\text{plim}\left(\hat{\beta}_1^{\text{IV}}\right) = \beta_1 + \frac{\text{Cov}(\text{Instrument}, u)}{\text{Cov}(\text{Instrument}, \text{Endog. variable})}$$

which equals β_1 as long as our instrument is **exogenous** (numerator) and **relevant** (denominator).

Figure 1

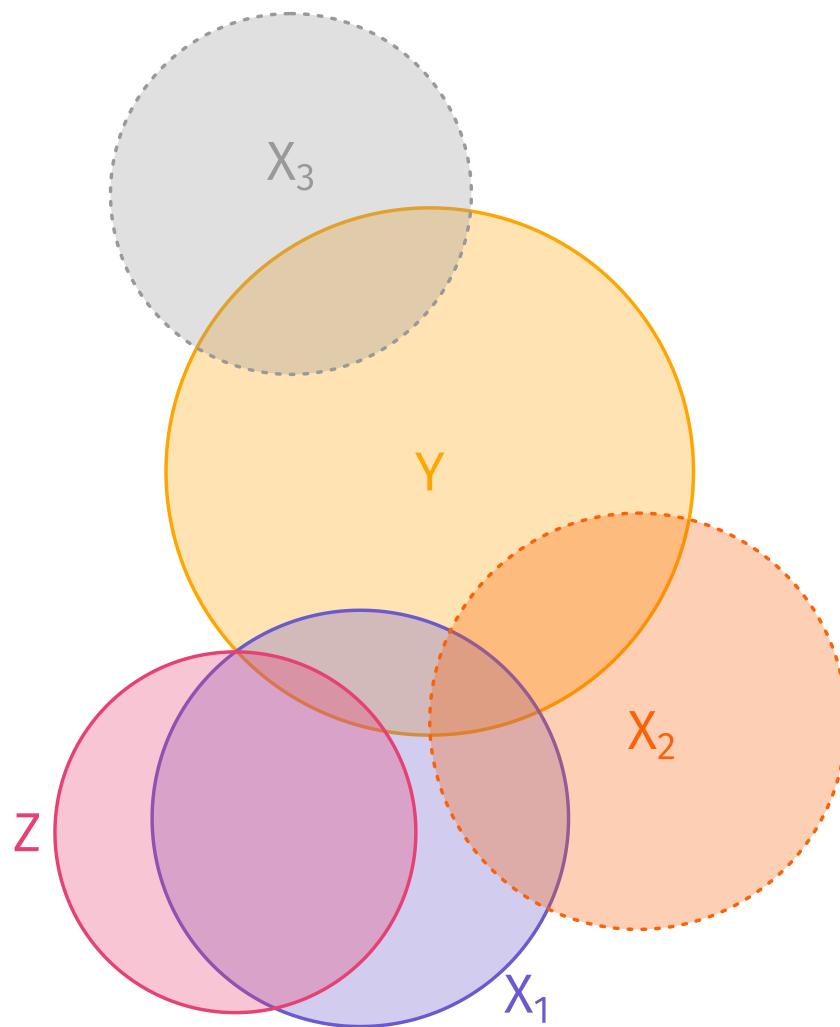


Figure 2

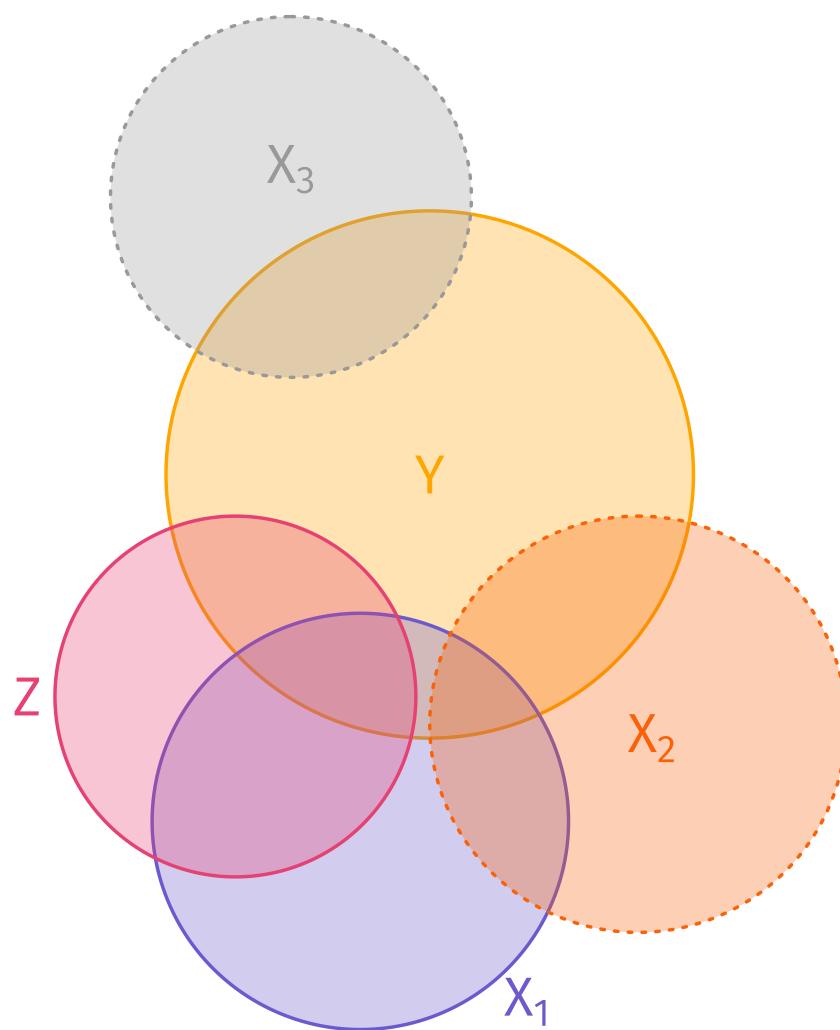


Figure 3

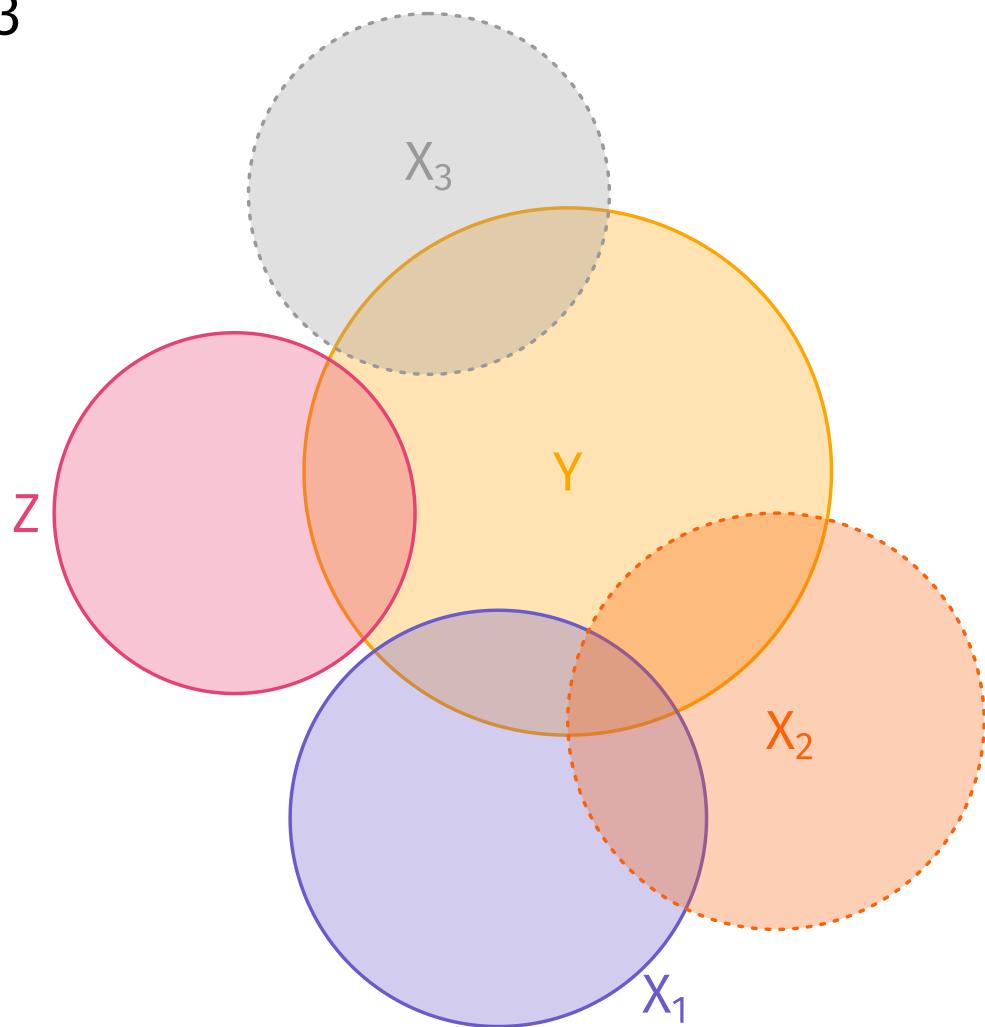
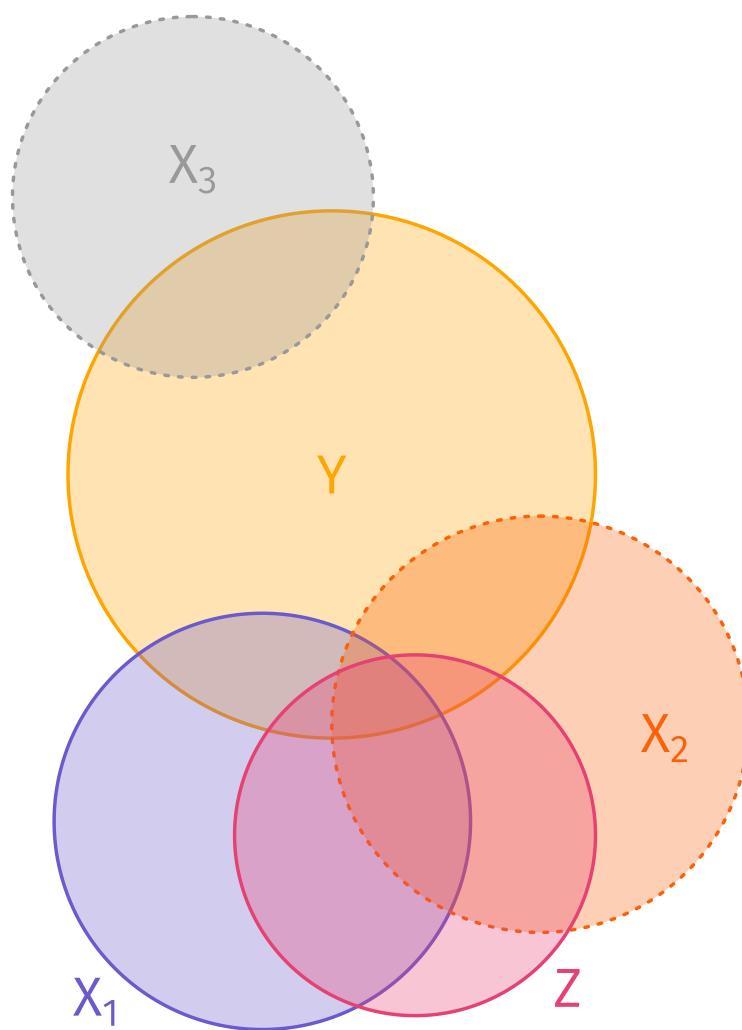


Figure 4



Venn diagram explanation

In these figures (Venn diagrams)

- Each circle illustrates a variable.
- Overlap gives the share of correlation between two variables.
- Dotted borders denote *omitted* variables.

Take-aways

- Figure 1: **Valid instrument** (relevant; exogenous)
- Figure 2: **Invalid instrument** (relevant; not exogenous)
- Figure 3: **Invalid instrument** (not relevant; not exogenous)
- Figure 4: **Invalid instrument** (relevant; not exogenous)

Let's work an example in R.

Instrumental variables

Example in R

Back to our age-old battle to estimate the returns to education.

```
#> # A tibble: 722 x 4
#>   wage education education_dad education_mom
#>   <int>     <int>        <int>        <int>
#> 1  769       12          8          8
#> 2  808       18          14         14
#> 3  825       14          14         14
#> 4  650       12          12         12
#> 5  562       11          11          6
#> 6  600       10          8          8
#> 7 1154       15          5          14
#> 8 1000       12          11         12
#> 9  930       18          14         13
#> 10 900        15          12         12
#> # ... with 712 more rows
```

Instrumental variables

Example in R

OLS for the returns to education will likely (definitely) be biased...

$$\text{Wage}_i = \beta_0 + \beta_1 \text{Education}_i + u_i$$

(Likely biased) OLS results:

Term	Est.	S.E.	t stat.	p-Value
Intercept	176.504	89.152	1.98	0.0481
Education	58.594	6.439	9.10	<0.0001

but what if mother's education provides a valid instrument?

Instrumental variables

Example in R

We can check/test the *relevance* of **mother's education** for **education**.

This regression is known as the **first stage**:

The effect of the **instrument** on our endogenous explanatory variable.

$$\text{Education}_i = \gamma_0 + \gamma_1 (\text{Mother's Education})_i + v_i$$

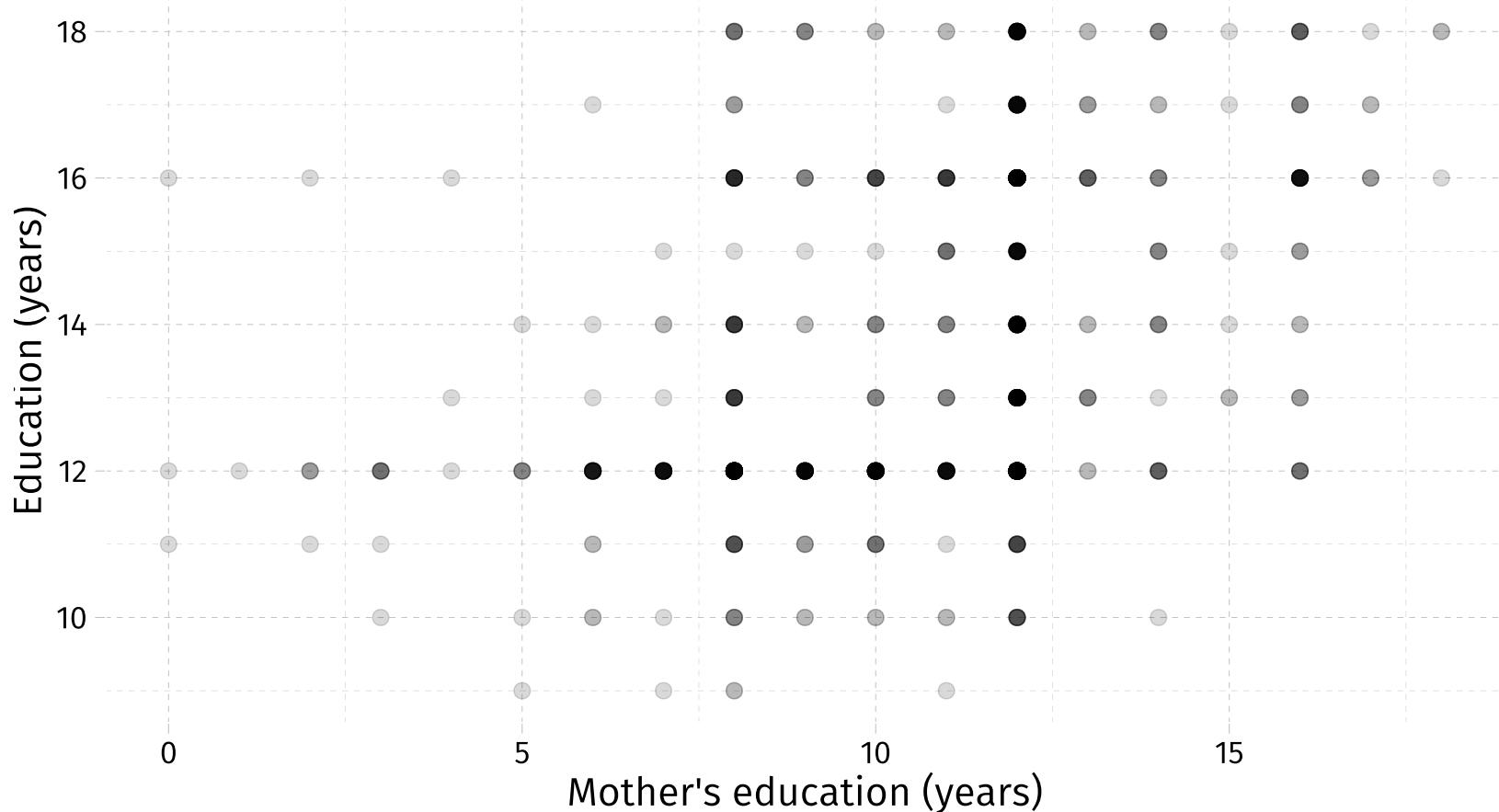
First-stage results:

Term	Est.	S.E.	t stat.	p-Value
Intercept	10.487	0.306	34.32	<0.0001
Mother's Education	0.294	0.027	10.75	<0.0001

The *p*-value suggests a very strong relationship (very *relevant*).

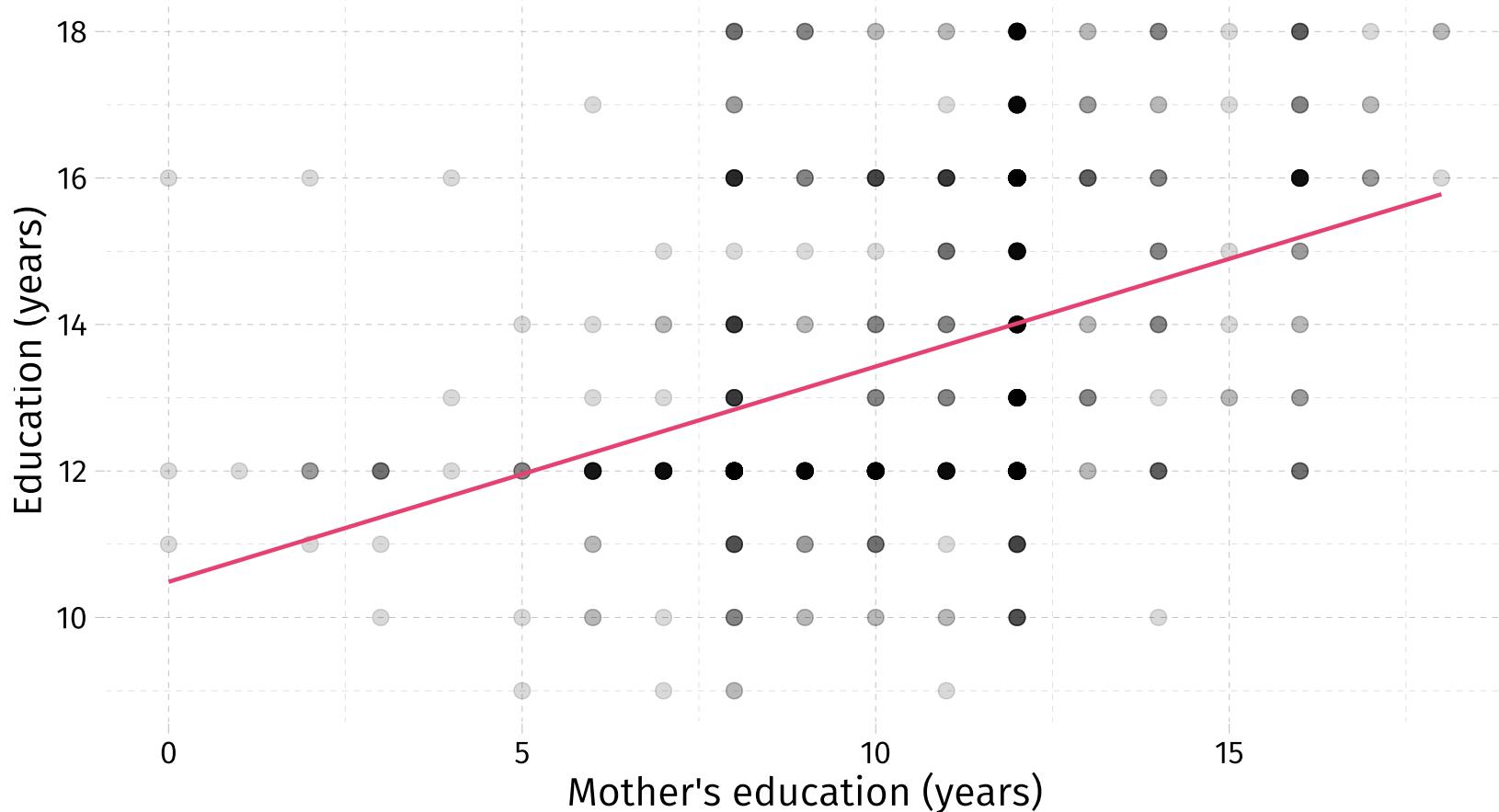
Instrumental variables

Visualizing the first stage



Instrumental variables

Visualizing the first stage



Instrumental variables

Exogeneity

Q: What does **exogeneity** mean in this case?

A: We need two things

1. Mother's education (our instrument) must only affect earnings through education (our endogenous explanatory variable).
2. Mother's education must be uncorrelated with other factors that affect wages (our outcome variable).

We want to be able to compare two people (A and B) whose mothers have different levels of education and say that the only differences between the two people (A and B) are due to their mothers' educational levels.

Q: Does *mother's education* seem likely to satisfy exogeneity?

Instrumental variables

Example in R

Now, let's estimate the **reduced form**:

The effect of the **instrument** on our **outcome variable**.

$$\text{Wage}_i = \pi_0 + \pi_1(\text{Mother's Education})_i + w_i$$

Reduced-form results:

Term	Est.	S.E.	t stat.	p-Value
Intercept	633.34	58.58	10.81	<0.0001
Mother's Education	31.81	5.24	6.07	<0.0001

Q₁: How do we interpret this estimated coefficient ($\hat{\pi}_1$)?

Q₂: If our instrument is *valid*, can we interpret these estimates as **causal**?

Instrumental variables

Example in R

So what is our IV-based estimate for the returns to education?

$$\text{Wage}_i = \beta_0 + \beta_1 \text{Education}_i + u_i$$

We know that the IV estimate for β_1 is

$$\hat{\beta}_1^{\text{IV}} = \frac{\hat{\pi}_1}{\hat{\gamma}_1}$$

1. In the **reduced-form equation**, we estimated $\hat{\pi}_1 \approx 31.81$.
2. In the **first-stage equation**, we estimated $\hat{\gamma}_1 \approx 0.294$.

$$\implies \hat{\beta}_1^{\text{IV}} = \frac{\hat{\pi}_1}{\hat{\gamma}_1} = \frac{31.81}{0.294} \approx 108.2$$

Instrumental variables

Example in R

Alternative: Use the function `iv_robust()` from the `estimatr` package.

This new function `iv_robust` works very similar to our good friend `lm`:

```
iv_robust(y ~ x | z, data = dataset)
```

- `formula` Specify the regression followed by `|` and your instrument (`z`).
- `data` You still need a dataset.

Note: As you might guess by its name, `iv_robust` calculates heteroskedasticity-robust standard errors by default.

Instrumental variables

Example in R

In practice...

```
# Estimate our IV regression  
iv_est <- iv_robust(wage ~ education | education_mom, data = wage_df)
```

Term	Est.	S.E.	t stat.	p-Value
Intercept	-501.474	226.476	-2.21	0.0271
Education	108.214	16.810	6.44	<0.0001

Instrumental variables

More

So now we know how to "do" instrumental variables *when we have one endogenous variable and one exogenous variable.*

1. Estimate the reduced form (regress **outcome var.** on **instrument**).
2. Estimate the first stage (regress **expl. var.** on **instrument**).
3. Calculate the IV estimate using the estimates from (1) and (2).

Our magical **instrument** isolates the exogenous variation in our **endogenous variable**.

Q: What if we want more? (E.g., more instruments or endog. variables)

A: Too bad.

Instrumental variables

More

So now we know how to "do" instrumental variables *when we have one endogenous variable and one exogenous variable.*

1. Estimate the reduced form (regress **outcome var.** on **instrument**).
2. Estimate the first stage (regress **expl. var.** on **instrument**).
3. Calculate the IV estimate using the estimates from (1) and (2).

Our magical **instrument** isolates the exogenous variation in our **endogenous variable**.

Q: What if we want more? (E.g., more instruments or endog. variables)

A: ~~Too bad.~~ Extend IV to **two-stage least squares (2SLS)**.

Two-stage least squares

Two-stage least squares

Intro

The intuition and insights of IV carry over into two-stage least squares.

Plus: The *first stage* that we've been discussing is actually the *first* of the two stages in two-stage least squares.

Endogenous model

$$\text{Outcome}_i = \beta_0 + \beta_1 (\text{Endog. var.})_i + u_i$$

First stage

$$(\text{Endog. var.})_i = \pi_0 + \pi_1 \text{Instrument}_i + v_i$$

Second stage

$$\text{Outcome}_i = \delta_0 + \delta_1 \widehat{(\text{Endog. var.})}_i + \varepsilon_i$$

Reduced form

$$\text{Outcome}_i = \pi_0 + \pi_1 \text{Instrument}_i + w_i$$

where $\widehat{(\text{Endog. var.})}_i$ denotes the predicted values (*fitted values*) from the first-stage regression.

Two-stage least squares

Intro

Two-stage least squares is very flexible—we include other controls, additional endogenous variables, and have multiple instruments.

But don't get too distracted by this fancy flexibility.

We still need **valid** instruments.

Two-stage least squares

In R

Back to our *returns to education* example.

$$\text{Wage}_i = \beta_0 + \beta_1 \text{Education}_i + u_i$$

Imagine that mother's and father's education are both valid instruments.

Then our **first-stage regression** is

$$\text{Education}_i = \gamma_0 + \gamma_1 (\text{Mother's education})_i + \gamma_2 (\text{Father's education})_i + v_i$$

which we can estimate via OLS.

Q: Why?

Two-stage least squares

In R

$$\text{Education}_i = \gamma_0 + \gamma_1(\text{Mother's education})_i + \gamma_2(\text{Father's education})_i + v_i$$

```
stage1 ← lm(education ~ education_mom + education_dad, wage_df)
```

First-stage results:

Term	Est.	S.E.	t stat.	p-Value
Intercept	9.845	0.305	32.31	<0.0001
Mother's Education	0.149	0.032	4.62	<0.0001
Father's Education	0.216	0.028	7.84	<0.0001

Our instruments each appear to be *relevant*.

Formally, we should jointly test them (e.g., F test).

Two-stage least squares

In R

Using our estimated first stage, we grab the *fitted endogenous variable*

$$\widehat{\text{Education}}_i = \widehat{\gamma}_0 + \widehat{\gamma}_1 (\text{Mother's education})_i + \widehat{\gamma}_2 (\text{Father's education})_i$$

```
# Add fitted values from first stage  
wage_df$education_hat ← stage1$fitted.values
```

Now we use OLS (again) to estimate the **second-stage regression**

$$\text{Wage}_i = \delta_0 + \delta_1 \widehat{\text{Education}}_i + \varepsilon_i$$

Two-stage least squares

In R

$$\text{Wage}_i = \delta_0 + \delta_1 \widehat{\text{Education}}_i + \varepsilon_i$$

```
stage2 ← lm(wage ~ education_hat, wage_df)
```

Second-stage results:

Term	Est.	S.E.	t stat.	p-Value
Intercept	-454.683	198.149	-2.29	0.022
Fitted Education	104.789	14.462	7.25	<0.0001

Ordinary least squares

Term	Est.	S.E.	t stat.	p-Value
Intercept	176.504	89.152	1.98	0.0481
Education	58.594	6.439	9.10	<0.0001

Instrumental variables

Term	Est.	S.E.	t stat.	p-Value
Intercept	-501.474	226.476	-2.21	0.0271
Education	108.214	16.810	6.44	<0.0001

Two-stage least squares w/ two instruments

Term	Est.	S.E.	t stat.	p-Value
Intercept	-454.683	198.149	-2.29	0.022
Education	104.789	14.462	7.25	<0.0001

Two-stage least squares

In R

As you probably guessed, R will do both of the stages for you.

```
iv_robust(y ~ x1 + x2 + ... | z1 + z2 + ..., data)
```

In our case, we have

- one explanatory variable (x) (*education*)
- two instruments (z) (*parents' educations*)

```
iv_robust(wage ~ education | education_mom + education_dad, data = wage_df)
```

Term	Est.	S.E.	t stat.	p-Value
Intercept	-454.683	199.946	-2.27	0.0233
Education, fitted	104.789	14.852	7.06	<0.0001

Two-stage least squares

There's more!

Because 2SLS **isolates exogenous variation in an endogenous variable**, we apply it in other settings that are biased from *endogenous* relationships.

Common applications

- **General causal inference** for observational data (as we've seen).
- **Experiments:** Randomize a treatment that affects an endog. variable.
- **Measurement error:** Regress noisy x_1 on noisy x_2 to capture signal.
- **Simultaneous relationships** (e.g., p and q from supply and demand).

However, in any 2SLS/IV setting, you need to mind the requirements for **valid instruments**—exogeneity and relevance.

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