

Empirical Methods

Topic 2c:

Instrumental Variables Estimation

Instrumental Variables (IV)

Instrumental Variables Overview I

- We turn finally to Instrumental Variables estimation
 - ▶ This is a critically important topic
 - ▶ As it is the first and most important tool in handling the violation of the most important CLRM assumption

$$E(\epsilon_i | x_i) = 0$$

IV Basics

Instrumental Variables I

- Let's formalize how IV "works" using our familiar notation

$$y_i = x_i' \beta + \epsilon_i$$

- But assume $E(\epsilon_i | x_i) \neq 0$, in particular

- Suppose some elements of x_i are *endogenous* while others are *exogenous*, i.e. $x_i' = [x_{1i}' \quad x_{2i}']$ with
 - x_{1i} a $K_1 \times 1$ vector of included endogenous variables
 - x_{2i} a $K_2 \times 1$ vector of included exogenous variables
 - And $K_1 + K_2 = K$
- Note difference in notation here compared to what we had earlier
 - Where \tilde{M} and \tilde{K} were the numbers of included endogenous and exogenous variables

Instrumental Variables II

- To estimate our model when $E(\epsilon_i|x_i) \neq 0$, we need extra information
 - ▶ In particular, we need some variables to “move x_i ” in ways that are uncorrelated with ϵ_i
- These variables are called **Instrumental Variables**
 - ▶ Let z_i be a $L \times 1$ vector of instruments with $z'_i = [z'_{1i} \quad x'_{2i}]$ with
 - ★ z_{1i} a $L_1 \times 1$ vector of excluded (from this equation) exogenous variables
 - ★ (Note in our earlier notation, $L_1 = K^*$)
 - ★ x_{2i} (still) is a $K_2 \times 1$ vector of included exogenous variables
 - ★ And $L_1 + K_2 = L$

Instrumental Variables III

Instrumental Variables have two critical properties:

① (IV1) Instrument Exogeneity

- ▶ $\frac{1}{N} Z' \epsilon = \frac{1}{N} \sum_{i=1}^N z_i \epsilon_i \xrightarrow{P} E(z_i \epsilon_i) = 0$
- ▶ In words: The instruments are uncorrelated with the error
 - ★ Usually ensured by assuming $E(\epsilon_i | z_i) = 0$
 - ★ And evaluated by thinking about $Cov(z_i, \epsilon_i)$

Instrumental Variables IV

- **NOTE:** Instrument Exogeneity also implies the instruments don't *themselves* belong in the structural equation.
- Suppose they did, i.e. suppose:

True model: $y_i = x'_i \beta + z'_i \gamma + \epsilon_i^*$

You estimate: $y_i = x'_i \beta + \epsilon_i$
(using z_i as an instrument)

Instrumental Variables V

$$\begin{array}{lcl} \text{True model: } y_i & = & x_i' \beta + z_i' \gamma + \epsilon_i^* \\ \text{You estimate: } y_i & = & x_i' \beta + \epsilon_i \\ & & (\text{using } z_i \text{ as an instrument}) \end{array}$$

- Just because you don't include z_i in your model doesn't mean it's not actually *in there*
 - ▶ It's clearly true that $\epsilon_i = z_i' \gamma + \epsilon_i^*$
- Thus even if $\text{Cov}(z_i, \epsilon_i^*) = 0$, you have...

$$\begin{aligned} \text{Cov}(z_i, \epsilon_i) &= \text{Cov}(z_i, z_i' \gamma + \epsilon_i^*) \\ &= V(z_i)' \gamma \neq 0 \end{aligned}$$

- ▶ ...and you've violated Instrument Exogeneity

Instrumental Variables VI

Two critical IV properties, cont.:

② (IV2) Instrument Relevance

- ▶ $\frac{1}{N} Z' X = \frac{1}{N} \sum_{i=1}^N z_i x'_i \xrightarrow{P} E(z_i x'_i) \equiv \Sigma_{zx} \neq 0$
- ▶ In words: The instruments are correlated with the RHS variables
 - ★ Evaluated by estimating $Cov(z_i, x_i)$
 - ★ (In a “first-stage” regression)
 - ★ (To be introduced soon)

Instrumental Variables VII

- As well as one final regularity assumption,
Assumption 6': Regular Z's:

$$\blacktriangleright \frac{1}{N} Z'Z = \frac{1}{N} \sum_{i=1}^N z_i z'_i \xrightarrow{P} E(z_i z'_i) \equiv \Sigma_{ZZ}$$

- Where Σ_{ZZ} is a finite $L \times L$ matrix
- (In words: A standard regularity condition analogous to OLS's (A6, Regular X's))

Instrumental Variables Intuition I

- OK, fine for the math. But what is the intuition for IV?
- It's a sequence of logic that goes like this:
 - ① In essence, the OLS estimate $\hat{\beta}_k$ measures the correlation between y_i and x_{ik}
 - ★ (Controlling for the other x's)
 - ② Under the CLRM Assumptions, this measures the *causal* effect of x_{ik} on y_i
 - ★ (Especially (A1, Linearity) and (A2, Mean-zero error))

Instrumental Variables Intuition II

Sequence of logic, cont.:

- ③ Sometimes, however, we have endogeneity and (A2, Mean-zero error) *doesn't hold*
 - ▶ ($E(\epsilon_i|x_i) \neq 0$)
 - ▶ (The bias formula shows that $E(\hat{\beta}_k) \neq \beta_k$)
 - ▶ (Thus OLS *cannot* recover the causal effect of x_{ik} on y_i)

Instrumental Variables Intuition III

Sequence of logic, cont.:

- ④ IV provides a solution: find an instrument that, as it varies...
 - ▶ ...causes x_i to vary...
 - ★ [Assumption (IV2, Instrument relevance)]
 - ▶ ...in a way that *isn't* correlated with ϵ_i ...
 - ★ [Assumption (IV1, Instrument exogeneity)]
 - ▶ ...and let that “clean” variation in x_{ik} measure the causal effect of β_k

That's It!

Fitting our example into this framework

- We can fit our earlier example into this framework
- Our demand curve was written as:

$$q_i = \alpha_0 + \alpha_1 p_i + \alpha_2 inc_i + \epsilon_{i1}$$

- Thus:

- ▶ $y_i = q_i$,
- ▶ $x'_{1i} = p_i$, $x'_{2i} = [1 \ inc_i]$, thus $x'_i = [p_i \ 1 \ inc_i]$
- ▶ $z'_{1i} = w_i$, $x'_{2i} = [1 \ inc_i]$, thus $z'_i = [w_i \ 1 \ inc_i]$

Instrumental Variables Notes I

Note:

- ① Once we move into instrumental variables, we focus on large-sample properties, i.e.
 - ▶ Consistency rather than Unbiasedness
 - ★ Indeed taking the expectation of the IV estimator is a *pain in the neck*
 - ★ Whereas taking its probability limit is easy
 - ▶ Asymptotic Normality rather than Normality
 - ▶ We'll discuss the properties of the IV estimator after defining it

Instrumental Variables Notes II

Note:

- ② z_i is always constructed so that its exogenous components, x_{2i} , “instrument for themselves”

- ▶ So $z'_i = [z'_{1i} \quad x'_{2i}]$
 - ★ (where z_{1i} are the instruments for the RHS endog variables, x_{1i})
- ▶ The real trick is therefore to find the z_{1i} ,
 - ★ In our example, $z'_{1i} = [w_i]$, $x'_{2i} = [1 \quad inc_i]$
 - ★ And thus $z'_i = [w_i \quad 1 \quad inc_i]$

Instrumental Variables Notes III

Note, cont:

- ③ What might qualify as instruments? The two key IV conditions suggest the answer:
 - ① Instrument Exogeneity \Rightarrow variables uncorrelated with the error term
 - ★ (i.e. Exogenous variables)
 - ② Instrument Relevance \Rightarrow variables *in the (some!) model*
 - ★ (*Even if the full model isn't specified*)
 - ★ (Without this, there is no justification for the claim that $\Sigma_{zx} \neq 0$)

Instrumental Variables Notes IV

- All the exogenous variables (across all equations) are candidates.
 - ▶ Thus cost/competition shifters are good candidates in our example:
 - ★ They both plausibly influence our (unspecified) supply equation...
 - ★ (And - hopefully - can be assumed to be exogenous)
 - ★ (And don't belong in the demand curve directly)
 - ▶ What if we haven't written down a full system of simultaneous equations?
 - ★ Where do instruments come from in this case???
 - ★ Answer: * _____

IV & 2SLS: Just- versus Over-identified

- The exact form of the IV estimator depends on the number of
 - ▶ Instruments versus RHS variables (parameters)
- If $L = K$, we say we are **just-identified**.
 - ▶ We can estimate by (simple) IV
 - ★ Note the condition $L = K$ is the same as the condition $L_1 = K_1$
- If $L > K$, we say we are **over-identified**.
 - ▶ We can estimate by Two-Stage Least Squares (2SLS)
- And finally if $L < K$, we say we are* _____
 - ▶ * _____

OLS and IV as moment estimators

Aside: An alternative way to derive the OLS estimator I

- You've been taught OLS minimizes the sum of squared residuals
 - ▶ It can also be rationalized another - completely different - way
- Recall our key assumption that $E(\epsilon_i|x_i) = 0 \Rightarrow \text{Cov}(x_i, \epsilon_i) = 0$
 - ▶ This is a "population moment condition", i.e.
 - ▶ It is a *moment condition* that we assume *holds in the population*
- Moment conditions play an important role in econometrics
 - ▶ One of the most widely used estimation methods is the Generalized Method of Moments (GMM)

Aside: An alternative way to derive the OLS estimator II

- The general idea is to solve a system of equations for parameters that satisfy the moment condition in one's sample
 - ▶ The sample analog to $\text{Cov}(x_i, \epsilon_i) = 0$ is $\frac{1}{N}X'e = 0 \Leftrightarrow X'e = 0$
- Suppose we imposed (A1, Linearity) and (A2, Mean-zero error)

$$\begin{aligned}y &= X\beta + \epsilon && \text{is the PopRegFn} \\&= X\tilde{\beta} + e && \text{is the SampRegFn}\end{aligned}$$

- ▶ ...and decided to choose an estimator, $\tilde{\beta}$ to satisfy the moment condition, $X'e = 0$

Aside: An alternative way to derive the OLS estimator III

$$\begin{aligned} X'e &= 0 \\ X'(y - X\tilde{\beta}) &= 0 \\ X'y &= X'X\tilde{\beta} \\ \tilde{\beta} &= (X'X)^{-1}X'y \end{aligned}$$

- That looks familiar! $\tilde{\beta} = \hat{\beta}$, the OLS estimator of β !

$\hat{\beta}^{OLS}$ solves the sample analog of the population moment condition, $Cov(x_i, \epsilon_i) = 0$

IV as the solution to a moment condition

- This same principle underlies all IV estimators
 - ▶ i.e., both the just- and over-identified cases
- Instead of imposing the OLS population moment condition,
 $\text{Cov}(x_i, \epsilon_i) = 0$,
 - ▶ IV does so with the instrument matrix, z_i , i.e. $\text{Cov}(z_i, \epsilon_i) = 0$
- Why using z_i and not x_i ?
 - ▶ Because of endogeneity, $\text{Cov}(\textcolor{red}{x}_i, \epsilon_i) \neq 0\dots$
 - ▶ ... but with a valid instrument matrix $\text{Cov}(\textcolor{blue}{z}_i, \epsilon_i) = 0$

Just-identified IV

Just-identified IV Estimation I

- In the simplest case, we are just-identified, i.e.
 - ▶ $L = K$, i.e.
 - ★ the number of instruments we have is equal to the number of parameters, OR
 - ▶ $L_1 = K_1$, i.e.
 - ★ the number of instruments for our RHS endogenous variables equals the number of our RHS endogenous variables
 - ▶ (These are the same because the K_2 elements in x_{2i} are present in both X and Z ...
 - ★ ...and therefore don't influence whether or not you're just-identified)

Just-identified IV Estimation II

- In the just-identified case, the IV estimator just sets the sample analog of the (identifying) moment condition to 0

$$Z'\epsilon = 0 \Rightarrow$$

$$Z'(y - X\beta) = 0 \Rightarrow$$

$$\hat{\beta}_{IV} = (Z'X)^{-1}Z'y$$

- Being just-identified is important, as it ensures that $(Z'X)$ is square
 - (Assumption (IV2) plus a final assumption that $\text{rank}(Z) = \text{rank}(X) = K$ ensures $Z'X$ is invertible)

Just-identified IV Properties: Consistency

- As suggested, we focus on the consistency rather than the unbiasedness of the IV estimator
- By the properties of the probability limit operator:

$$\begin{aligned}\hat{\beta}_{IV} &= \beta + (Z'X)^{-1}Z'\epsilon \\ p\lim \hat{\beta}_{IV} &= p\lim \beta + p\lim (Z'X)^{-1}p\lim Z'\epsilon \\ p\lim \hat{\beta}_{IV} &= \beta + p\lim \left(\frac{1}{N}Z'X\right)^{-1}p\lim \frac{1}{N}Z'\epsilon \\ &= \beta + \Sigma_{ZX}^{-1} 0 \quad \text{by (IV1) + (IV2)} \\ &= \beta\end{aligned}$$

- Thus the IV estimator is consistent

Just-identified IV Properties: Asymptotic Normality I

- We turn next to the asymptotic distribution of $\hat{\beta}_{IV}$
- From the last slide, we can write

$$\begin{aligned}\hat{\beta}_{IV} &= \beta + (Z'X)^{-1}Z'\epsilon \\ \Rightarrow \sqrt{N}(\hat{\beta}_{IV} - \beta) &= (\frac{1}{N}Z'X)^{-1}\frac{1}{\sqrt{N}}Z'\epsilon\end{aligned}$$

- ▶ (This should look familiar - it's very similar to the OLS formulas...
 - ★ ...but with Z' in place of X')

Just-identified IV Properties: Asymptotic Normality II

$$\sqrt{N}(\hat{\beta}_{IV} - \beta) = (\frac{1}{N}Z'X)^{-1}\frac{1}{\sqrt{N}}Z'\epsilon$$

- We know from earlier that

$$\frac{1}{N}(Z'X)^{-1} \xrightarrow{P} E(Z'X) = \Sigma_{ZX} \quad \text{and}$$

$$\frac{1}{N}(Z'Z)^{-1} \xrightarrow{P} E(Z'Z) = \Sigma_{ZZ}$$

- What of $\frac{1}{\sqrt{N}}Z'\epsilon$?

Just-identified IV Properties: Asymptotic Normality III

- We could (but won't) show that

$$\frac{1}{\sqrt{N}} Z' \epsilon \xrightarrow{d} N(E(z_i \epsilon_i), V(z_i \epsilon_i))$$

where

- ▶ $E(z_i \epsilon_i) = \underline{\hspace{10em}}$
- ▶ The form of $V(z_i \epsilon_i) = E(\epsilon_i^2 z_i z_i') = E(\epsilon_i^2)E(z_i z_i')$ depends on further assumptions about the variance-covariance matrix of ϵ

Just-identified IV Properties: Asymptotic Normality IV

- If we're willing to make our earlier assumptions (A3, Homoskedasticity) and (A4, No Correlation), then

$$\begin{aligned} V(z_i \epsilon_i) &= E(\epsilon_i)^2 E(z_i z_i') \\ &= \sigma^2 E(z_i z_i') \quad \text{under (A3) and (A4)} \\ &= \sigma^2 \Sigma_{zz} \quad \text{under (our new) (A6')} \end{aligned}$$

- By Slutsky's Theorem, then:

$$\begin{aligned} \sqrt{N}(\hat{\beta}_{IV} - \beta) &\xrightarrow{d} \Sigma_{ZX}^{-1} N(0, \sigma^2 \Sigma_{zz}) \\ &= N(0, \sigma^2 \Sigma_{ZX}^{-1} \Sigma_{zz} \Sigma_{ZX}^{-1}) \end{aligned}$$

Just-identified IV Properties: Asymptotic Normality V

$$\sqrt{N}(\hat{\beta}_{IV} - \beta) \xrightarrow{d} N(0, \sigma^2 \Sigma_{ZX}^{-1} \Sigma_{ZZ} \Sigma_{ZX}^{-1})$$

- We can approximate this in small samples with

$$\sqrt{N}(\hat{\beta}_{IV} - \beta) \stackrel{a}{\sim} N(0, s^2 (\frac{1}{N} Z' X)^{-1} (\frac{1}{N} Z' Z) (\frac{1}{N} Z' X)^{-1})$$

$$\hat{\beta}_{IV} \stackrel{a}{\sim} N(\beta, \frac{s^2}{N} (\frac{1}{N} Z' X)^{-1} (\frac{1}{N} Z' Z) (\frac{1}{N} Z' X)^{-1})$$

$$\hat{\beta}_{IV} \stackrel{a}{\sim} N(\beta, s^2 (Z' X)^{-1} (Z' Z) (Z' X)^{-1})$$

- where $e_i = y_i - x_i' \hat{\beta}_{IV}$ and $s^2 = \frac{1}{N} \sum_{i=1}^N e_i^2$

★ (Note for IV, we always get the "sandwich formula", even if (A3) and (A4) hold)

Just-identified IV Properties: Summary

- Based on these two properties, we can say that the IV estimator is consistent and asymptotically normally distributed:

$$\hat{\beta}_{IV} \stackrel{a}{\sim} N(\beta, s^2(Z'X)^{-1}(Z'Z)(Z'X)^{-1})$$

- If the variance-covariance matrix of the errors is heteroskedastic,* then the asymptotic distribution of $\hat{\beta}_{IV}$ is

$$\sqrt{N}(\hat{\beta}_{IV} - \beta) \xrightarrow{d} N(0, \Sigma_{ZX}^{-1} \lim_{N \rightarrow \infty} E \left[\left(\frac{1}{N} \sum_{i=1}^N \epsilon_i^2 z_i z_i' \right) \right] \Sigma_{ZX}^{-1})$$

and we can approximate it with

$$\hat{\beta}_{IV} \stackrel{a}{\sim} N(\beta, (Z'X)^{-1} (\sum_{i=1}^N e_i^2 z_i z_i') (Z'X)^{-1})$$

Over-identified IV / 2SLS

Two-Stage Least Squares (2SLS)

- If one has more instruments than parameters ($L > K$), then our moment conditions are:

$$Z'\epsilon = Z'(y - X\beta) = 0$$

- This is of dimension $L \times 1$, but we only have K unknowns in β
 - ▶ There generally will not be any way to exactly satisfy *all* the L moments
- Q: So what do we do? Which $\hat{\beta}_{IV}$ should we choose?*

- ▶ _____
- ▶ _____
- ▶ _____

2SLS - Two-Stage Least Squares I

If interpreted *literally*, Two-Stage Least Squares proposes:

- ① Stage 1: Regress the included RHS endogenous variables, x_{1i} , on **all** the instruments, z_i ;

$$\begin{aligned} X_1 &= Z\pi + \nu \quad \Rightarrow \\ \hat{\pi} &\quad \Rightarrow \\ \hat{X}_1 &= Z\hat{\pi} \end{aligned}$$

- ▶ Where we assume for simplicity that we have just a single endogenous variable, i.e. X_1 is $N \times 1$
 - ★ (If we had more, we would run regress each column of X_1 on the full matrix of instruments, Z , getting a $\hat{\pi}$ for each column)
- ▶ This is (These are) called the "**First-Stage Regression(s)**"

2SLS: The First Stage I

- Economists pay close attention to the results of the first stage when evaluating an IV regression
- They pay particular attention to the joint significance of the instruments for X_1, Z_1 , in $Z = [Z_1 \ X_2]$
 - ▶ i.e. in the reduced-form equation,

$$x_{1i} = z'_{1i}\pi_1 + x'_{2i}\pi_2 + \nu_{i1}$$

- ▶ We calculate the F-statistic for the hypothesis, $H_0 : \pi_1 = 0$.
 - ★ This has L_1 numerator degree of freedom and $N - K_2 - 1$ denominator degrees of freedom

2SLS: The First Stage II

- A typical rule of thumb is that the F-test on the instruments *should exceed 10*.
 - ▶ (If you have just one instrument, the F-statistic is the square of the t-statistic...)
 - ▶ ...so this means a t-statistic in excess of $\sqrt{10} = 3.16$
 - ★ [This is from the paper by Staiger and Stock (1997)]
- We'll discuss why once I give the intuition of the IV estimator

2SLS - Two-Stage Least Squares II

- ② Stage 2: "Regress" y on \hat{X}_1 and X_2 , i.e.

$$\begin{aligned}y &= \hat{X}_1\beta_1 + X_2\beta_2 + \epsilon \\&= \hat{X}\beta + \epsilon\end{aligned}\quad \text{where } \hat{X} = [\hat{X}_1 \quad X_2]$$

- ③ That's it!
- ④ Those are the two stages in Two-Stage Least Squares, but ...
- ▶ How does that compare with the intuition we covered earlier?

2SLS Intuition I

No surprise: it's the same intuition:

- We'd like to estimate

$$y = X_1\beta_1 + X_2\beta_2 + \epsilon$$

- ▶ but X_1 is endogenous, i.e. $E(\epsilon|X_1) \neq 0$
- ▶ (And even if $E(\epsilon|X_2) = 0$, we showed that correlation between ϵ and *any* X 's biases *all* coefficients)
- We estimate instead:

$$y = \hat{X}_1\beta_1 + X_2\beta_2 + \epsilon$$

- ▶ where $\hat{X}_1 = Z\hat{\pi}$ from the First-Stage regression
 - ★ Critically: \hat{X}_1 is that part of X_1 that *can be explained by Z*

2SLS Intuition II

$$\begin{aligned}y &= X_1\beta_1 + X_2\beta_2 + \epsilon \\y &= \hat{X}_1\beta_1 + X_2\beta_2 + \epsilon\end{aligned}$$

2SLS Intuition, cont.

- We've essentially replaced the "problematic" (i.e. endogenous) X_1 with its prediction as a function of Z
 - ▶ Since it's a function of Z , *all of which are exogenous*, \hat{X}_1 isn't correlated with ϵ ... even if X_1 is
 - ★ (Because under Assumption (IV1), $E(\epsilon|Z) = 0$)
- Thus no more endogeneity problem!
 - ▶ \Rightarrow consistent estimation of β_1 and β_2 !

IV Intuition Redux I

- So the intuition of 2SLS is:
 - ▶ “Replace the problematic variables with their fitted values (which are a function of exogenous instruments)”
- Another way to say the same thing goes like this:
- Imagine taking one of the elements of the problematic (endogenous) X_1
- And dividing it into two parts:
 - ① A problematic part
 - ★ Which is correlated with ϵ_i
 - ② A non-problematic part
 - ★ Which is uncorrelated with ϵ_i

IV Intuition Redux II

- We'd like to rely only on the *non-problematic* variation in X_1 to identify β
 - ▶ Leaving aside the problematic variation
- This is imperfect of course
 - ▶ As relying on less than the full variation in any variable means we'll get noisier estimates of $\hat{\beta}$
 - ▶ But imprecision is better than bias!

IV Intuition Redux III

- This is exactly what IV does:
 - ▶ It relies on variation in X_1 induced by variation in the instruments, Z
 - ▶ Since these instruments are uncorrelated with ϵ , this is “non-problematic” variation
 - ★ You can imagine...

See Figure in Class

2SLS - Two-Stage Least Squares III

- **Important note:**
 - ▶ You should never literally run the 2 regressions in 2SLS as it gives the wrong standard errors for $\hat{\beta}_{2SLS}$
 - ★ Why? Because we are using a fitted value in the second stage regression (\hat{X}_1)
 - ★ This introduces additional error into $V(\hat{\beta}_{2SLS})$, but Stata and R don't know you are using a fitted value
 - ★ (and therefore don't account for it)
- Of course, you could bootstrap the standard errors, but
 - ▶ I didn't teach you how to bootstrap standard errors. [:)]
 - ▶ There is an easier solution

2SLS - Two-Stage Least Squares IV

- Instead: Simply use \hat{X}_1 as part of a just-identified IV specification,
 - ▶ i.e. instrument for $X = [X_1 \ X_2]$ with $Z_{2SLS} = [\hat{X}_1 \ X_2]$
 - ★ This is $N \times K$ no matter how many instruments were in Z_1
- ⇒ Thus, from our earlier equation: $\hat{\beta}_{2SLS} = \hat{\beta}_{IV}$ using $Z_{2SLS} = [\hat{X}_1 \ X_2]$ as the instrument matrix

$$\hat{\beta}_{2SLS} = (Z'_{2SLS} X)^{-1} Z'_{2SLS} y$$

- We're all set to show the properties of the 2SLS estimator...
 - ▶ Except to do so we need a convenient way to represent \hat{X}_1

2SLS using P_Z I

- Recall our projection matrix from earlier, $P_X = X(X'X)^{-1}X'$
 - ▶ Which gives the fitted value of a regression of <anything> on X
- Earlier, we said the first-stage regression is the regression of x_{1i} on z_i :

$$\begin{aligned} X_1 &= Z\pi + \nu & \Rightarrow \\ \hat{\pi} &= (Z'Z)^{-1}Z'X_1 & \Rightarrow \\ \hat{X}_1 &= Z\hat{\pi} \\ &= Z(Z'Z)^{-1}Z'X_1 \\ \Rightarrow \hat{X}_1 &= P_Z X_1 \end{aligned}$$

2SLS using P_Z II

- Recall that a general instrument vector is written as $Z = [Z_1 \quad X_2]$
 - ▶ So it includes the instrument(s) for X_1 (Z_1) as well as the exogenous variables, X_2
- We can use this fact and the properties of the projection matrix to write Z_{2SLS} in a convenient form:
 - ▶ (1) $P_Z X_2 = ???$
 - ▶ (2) Last slide we showed that $P_Z X_1 = \hat{X}_1$
 - ▶ (1) + (2) $\Rightarrow Z_{2SLS} \equiv [\hat{X}_1 \quad X_2] = P_Z [X_1 \quad X_2] = P_Z X$
- Thus:

$$Z_{2SLS} = P_Z X \quad \text{and} \quad Z'_{2SLS} = X' P_Z$$

2SLS using P_Z III

$$Z_{2SLS} = P_Z X \quad \text{and} \quad Z'_{2SLS} = X' P_Z$$

- These allow us to write the formula for the 2SLS estimator in terms of its fundamental elements

$$\begin{aligned}\hat{\beta}_{2SLS} &= (Z'_{2SLS} X)^{-1} Z'_{2SLS} y \\ &= (X' P_Z X)^{-1} X' P_Z y\end{aligned}$$

$$\hat{\beta}_{2SLS} = (X' Z (Z' Z)^{-1} Z' X)^{-1} X' Z (Z' Z)^{-1} Z' y$$

- (This representation is much easier to work with to show consistency and asymptotic normality)

2SLS Properties: Summary I

- One can derive the properties of the 2SLS estimator in much the same way as we did for the just-identified IV estimator
 - ▶ So I'll just summarize the formulas for you here:
 - ★ The 2SLS estimator is consistent:

$$\hat{\beta}_{2SLS} \xrightarrow{P} \beta$$

- ★ Under (A3) and (A4) - homoscedasticity and no serial correlation - the 2SLS estimator is asymptotically normal with approximate distribution:

$$\hat{\beta}_{2SLS} \stackrel{a}{\sim} N(\beta, \sigma^2(X' P_Z X)^{-1})$$

$$\stackrel{a}{\sim} N(\beta, \sigma^2(X' Z(Z' Z)^{-1} Z' X)^{-1})$$

2SLS Properties: Summary II

$$\begin{aligned}\hat{\beta}_{2SLS} &= (X'P_Z X)^{-1} X' P_Z y \\ \hat{\beta}_{2SLS} &\stackrel{a}{\sim} N(\beta, \sigma^2 (X'P_Z X)^{-1})\end{aligned}$$

- Compare the formulas above to the OLS formulas:
 - ▶ $\hat{\beta} = (X'X)^{-1} X'y$ and $\hat{\beta} \stackrel{a}{\sim} N(\beta, \sigma^2 (X'X)^{-1})$
- Endogeneity requires us to instrument for “problematic” X_1 with Z_1 , with two effects:
 - ① We can only rely on that variation in X induced by Z (in blue)
 - ★ (i.e. $X'P_Z X$ instead of $X'X$)
 - ② And this induces *higher variance* in $V(\hat{\beta}_{2SLS})$ relative to $V(\hat{\beta})$ (in red)
 - ★ Due to relying only on that part of the variation in X induced by Z , $X'P_Z X$

Instrumental Variables Comments I

- As mentioned earlier, in the over-identified case, we have more moments than parameters to estimate
 - ▶ So we may not be able to find a single β that solves all of them
- The 2SLS estimator is the most efficient one
 - ▶ (Under our assumptions, particularly (A3) and (A4))
- More generally, one must weight the L moments to solve for the K parameters in β
 - ▶ The next - optional - slides show the form of the IV estimator for an arbitrary weighting matrix, W
 - ▶ (Where the 2SLS weighting matrix is $W = (Z'Z)^{-1}$)

Instrumental Variables Comments II*

- Formally, let M be an $(L \times L)$ matrix of weights to give to each of our moments
- Let Q be the quadratic form (the matrix analog to a sum of squares & cross products) in the sample moments:

$$Q = \underbrace{(y - X\beta)' Z}_{(1 \times L)} \underbrace{W}_{(L \times L)} \underbrace{Z'(y - X\beta)}_{(L \times I)}$$

Note:

- ▶ Q is a scalar
- ▶ The optimal weighting matrix in general is proportional to the inverse of the variance of the moment conditions.
 - ★ Under (A3) and (A4), $V(Z'\epsilon) = E(Z'\epsilon\epsilon'Z) = (Z'(\sigma^2 I_N)Z) = \sigma^2(Z'Z)$
 - ★ Thus the 2SLS estimator uses the weighting matrix $W = (Z'Z)^{-1}$

Instrumental Variables Comments III*

- For an arbitrary W , taking derivatives w.r.t β and solving yields

$$\hat{\beta} = (X' Z W Z' X)^{-1} X' Z W Z' y$$

- You can also show:

$$\begin{aligned}\hat{\beta} &\stackrel{a}{\sim} N(\beta, AV_{\beta}) \\ AV_{\beta} &\approx (X' Z W Z' X)^{-1} X' Z W \Omega W Z' X (X' Z W Z' X)^{-1} \\ \Omega &= V(Z'\epsilon) = E(Z'\epsilon\epsilon'Z)\end{aligned}$$

Show yourself you get the 2SLS formula if $\Omega = \sigma^2 Z' Z$ and $W = (Z' Z)^{-1}$

- (What a complicated mess!)
- (But useful if you take further econometrics...)

Instrumental Variables Comments IV

- While these formulas are superficially complicated, efficient weighting mechanisms pop up frequently in econometrics:
 - ▶ Weighting moments for efficient estimation (GMM)
 - ★ What we've done here
 - ▶ Weighting observations for heteroscedasticity correction (GLS)
 - ▶ Weighting equations for cross-equation correlations (SUR)

IV: Practical Considerations

IV: Practical considerations

- We close our discussion of IV with some practical considerations:
 - ➊ Avoiding the need for instruments
 - ➋ Finding instruments
 - ➌ IV standard errors
 - ➍ Weak Instruments
 - ➎ Testing
 - ★ Endogeneity
 - ★ Overidentification

Avoiding the need for instruments |

- We've talked to this point as if the presence of a "problematic" RHS variable is a given
 - ▶ Induced by there being correlation between at least one x_i and ϵ_i
 - ▶ And focused on finding an instrument(s) z_i to shift x_i in a way that's uncorrelated with ϵ_i
- But I have to emphasize that there is another - indeed easier - solution if the endogeneity is due to a correlated unobservable (if it's possible):
 - ▶ *Take the problematic variation out of the error term*

Avoiding the need for instruments II

- In particular, suppose there is some *potentially measurable* economic variable that
 - ▶ Isn't currently in the econometric model
 - ★ And is thus in ϵ_i
 - ▶ Is correlated with one of our x 's
 - ★ Causing endogeneity
- If we can just include that variable in the econometric model, all is good:
 - ▶ We'll be picking up its effect (taking it *out* of ϵ_i)
 - ▶ (Hopefully) leaving whatever is left in ϵ_i uncorrelated with x_i
 - ★ Permitting consistent estimation with OLS

Avoiding the need for instruments III

- Some support for this line of argument in the academic literature
 - ▶ e.g. Rossi (2014, *Marketing Science*), "Even the Rich Can Make Themselves Poor: A Critical Examination of IV Methods in Marketing Applications"
- Thus always keep this strategy in the back of your mind!
 - ▶ If it's possible, it is very likely to be a better strategy than IV as retains all the variable in x ; to estimate β
 - ▶ (Example: Ruralness in Marilyn's Bachelor's thesis)

Finding instruments I

- One of the greatest challenges with IV estimation is *finding instruments*
- We need something that's both exogenous w.r.t the error in the equation of interest *and* correlated with an endogenous variable of interest
- This can be very, very challenging

Finding instruments II

- For example, imagine modeling a family's decisions:
 - ▶ Whether and how much to work, whether and for how long to go to school, whether and how many children to have, where to live, etc.
 - ▶ Each plausibly impacts each other (structural equations), requiring instruments for each in the appropriate equation
 - ▶ Good luck!!!
- In practice, researchers usually focus on a subset of the decisions
 - ▶ And/or try to jointly model them all as a function of (hopefully!) exogenous "initial conditions"
 - ▶ (Where born, parent's characteristics, "innate" attributes, etc.)
- We'll go through many examples of this in class and on your problem set(s)

Finding instruments III

- Indeed, let's return to Marilyn's bachelor's thesis seeking to measure the impact of cross-border workers on anti-immigrant vote shares among a panel of 200 Swiss cities over 10 years:

$$v_{it} = \beta_1 + \beta_2 CBW_{it} + \tilde{x}'_i \tilde{\beta} + \epsilon_{it}$$

- Recall what caused our concerns about endogeneity:
 - (I think: correlated unobservables. Possibly also endogeneity, but probably not)
- What would be the qualitative features of a good instrument?
 - (Hint: Relevance:) Something correlated with the number of cross-border workers...
 - (Hint: Exogeneity:) ... that is uncorrelated with unobserved determinants of anti-immigrant vote shares (ϵ_{it})
- Any ideas???

IV Standard Errors I

- It's very common for standard errors on IV estimates to be larger - and perhaps much larger - than their OLS counterparts
- We've hinted at why this is a few slides ago

IV Standard Errors II

- IV “works” by having an instrument, z_{1i} , “move around” the included RHS endogenous variable, x_{1i}
 - ▶ Recall $\hat{\beta}_{2SLS} = (X'P_Z X)^{-1} X' P_Z y$
- This is necessarily imperfect, as z_{1i} isn’t perfectly correlated with x_{1i}
 - ▶ (And if it was, then it *wouldn’t* satisfy (IV1), Instrument Exogeneity)
- As a result, there is less instrument-induced-variation in x_{1i} than x_{1i} could provide by itself (if it weren’t endogenous)
 - ▶ And less x -variation means higher standard errors

Weak Instruments I

- Many applied researchers often worry about *Weak Instruments*
- What does this mean?
 - ▶ Weak instruments have no precise definition
 - ▶ A useful working definition is instruments for which the F-test on the joint significance of the instruments in the first-stage regression is “small”
 - ▶ (Recall we wanted an F-test of about 10 when we had a single RHS endogenous variable)

Weak Instruments II

- Weak instruments are problematic because they can exacerbate *finite-sample bias*
 - ▶ i.e. IV may be consistent in large samples, but is in general still biased
 - ★ (The bias is generally towards the OLS estimate)
 - ▶ And this bias increases the weaker is the correlation between instruments and included endogenous variables

Weak Instruments III

- With a single endogenous regressor, Staiger and Stock (1997, *Econometrica*) estimate the size of the bias as $1/F$
 - ▶ Where F is the value of the first-stage F-statistic introduced earlier
- With multiple endogenous regressors, Stock, Wright, and Yogo (2002) calculate the minimum eigenvalue of a matrix-analogue to the first-stage F-statistic
 - ▶ And provide critical values for this eigenvalue for different bias tolerances

Weak Instruments III

- Well, this is all quite depressing
 - ▶ What should you do???
- No great options, but here's what we have:
 - ① Try to include covariates that soak up the source of endogeneity
 - ② If the problem is due to too many instruments, some of which are weak, then just drop the weak ones and keep the strong ones
 - ★ (Can test with individual t-values in the first-stage regression(s))
 - ③ If problem is small-sample bias, can use estimators other than 2SLS
 - ★ e.g., LIML, Split-sample IV, Jackknife IV
 - ★ But all have downsides (harder to implement, less efficiency, etc.)
 - ④ Consider alternative research designs
 - ★ Particularly (field) experiments

Testing

- There are two types of tests that often arise in the context of IV estimation
 - ➊ Testing endogeneity
 - ➋ Testing overidentifying restrictions

Endogeneity Test I

- Since we've spent so much time worrying about endogeneity...
 - ▶ Finding them, higher standard errors, weak instruments, etc.
- It would be nice if we could test for it!
- Indeed, there is a test as long as you have at least one potential instrument
 - ▶ (So we're not completely out of the woods)
 - ▶ (And note: we are testing for endogeneity...)
 - ▶ ... *conditional* on the validity of our instrument)
- How?

Endogeneity Test II

- Consider both structural and reduced-form equations with scalar x_{1i} :

$$y_i = x_{1i}\beta_1 + x'_{2i}\beta_2 + \epsilon_{i1} \quad (1)$$

$$x_{1i} = z'_{1i}\pi_1 + x'_{2i}\pi_2 + \nu_{i1} \quad (2)$$

- We'd like to test whether x_{1i} is correlated with ϵ_{i1} in (1)
 - Perhaps we can use equation (2) to do so!
 - Since ϵ_{i1} is (by assumption) uncorrelated with both z_{1i} and x_{2i} ...
 - ...then the only way x_{1i} could be correlated with ϵ_{i1} is if ν_{i1} is
 - ★ Why is this true?

Endogeneity Test III

- We don't observe ν_{i1} , but we can estimate it as the residual in the equation (2), $\hat{\nu}_{i1}$
- We can test whether this correlated with ϵ_{1i} by simply putting it into Equation (1).
 - ▶ If the parameter on it is significant, then we have endogeneity
- Formally estimate the following by OLS:

$$y_i = x'_{1i}\beta_1 + x'_{2i}\beta_2 + \delta\hat{\nu}_{i1} + \epsilon_{i1}$$

and test $H_0 : \delta = 0$

- This is called (Hausman) endogeneity test
 - ▶ Note you might be surprised by the familiarity of the estimated coefficients (other than $\hat{\delta}$ in this regression)

Overidentifying Test I

- In general, we would *love* to test the validity of an instrument
 - ▶ In other words, is it really the case that $Z'\epsilon = 0???$
- In principle, we have an estimate of ϵ_i , e_i , so can't we use this as a proxy?
 - ▶ Unfortunately not
 - ▶ We showed earlier that the $Z'\epsilon$ is *exactly* zero when we are just-identified
 - ★ (Thus no test is possible)

Overidentifying Test II

- But... we can test whether $Z'\epsilon = 0$ when we are *over-identified*
 - ▶ As $Z'\epsilon = 0$ in the population, but $Z'\epsilon$ won't (exactly) equal zero in any sample
 - ▶ So the question is whether the deviation of $Z'\epsilon$ from zero is statistically large
- To note: this way we can test the validity of *some* of the instruments
 - ▶ But may not know which one(s) are causing trouble if we reject!
 - ▶ (So a bit frustrating...)

Overidentifying Test III

- The formal test has three steps:
 - ① Estimate (1) by 2SLS $\Rightarrow e_{i1}$
 - ② Regress e_{i1} on z_{1i} and x_{2i} (i.e. all the exogenous variables)
 - ★ And calculate the R^2
 - ③ Then, under H_0 : *Instrument validity*, $NR^2 \stackrel{a}{\sim} \chi^2_{L_1 - K_1}$
 - ★ where the degrees of freedom equal the number of “extra” (i.e. overidentifying) instruments you have
- Last note: the overidentifying test is often also called the “J-Test” (from Sargan (1958))

Examples Redux

Examples Redux

- Recall that we said there are three common sources of endogeneity:
 - ① Correlated unobservables
 - ② Measurement error (in X)
 - ③ Reverse causality / Simultaneous equations
- I also showed three examples whose results suggested bias of the type we had anticipated
 - ▶ Can we “solve” these issues using IV estimation?

Correlated Unobservables Example Redux I

- For the first, correlated unobservables/wage-ability example, we use data on married women's wages
 - ▶ And found (perhaps implausibly) high estimates of the returns to education (of 10.9%)
- Authors have proposed using as an instrument for a woman's education the *education of her parents*
- Do you think these are likely to satisfy the conditions for a good instrument?*
 - ▶ Relevance: _____
 - ▶ Exogeneity: _____

Correlated Unobservables Example Redux II

- Remember what we said was the likely sign of the bias?
 - ▶ _____
- Let's see what happens when we instrument with father's education

See Stata Example in Class

- Do these results seem (more) reasonable to you?*

- ▶ _____
- ▶ _____

Measurement Error Example Redux I

- For this second, measurement-error example, we used data from average health insurance coverage across the 50 US states (and the District of Columbia) in 2007
 - And (perhaps) found evidence of attenuation bias (0.23% pretty small)
- The author of the study from which I grabbed the data suggested using average high-school completion rate as an IV for their permanent income
- Do you think these are likely to satisfy the conditions for a good instrument?
 - Relevance: _____
 - Exogeneity: _____

Measurement Error Example Redux II

- Let's see what happens when we instrument with whether someone got an advanced degree

See Stata Example in Class

- Do these results seem (more) reasonable to you?*

- ▶ _____
- ▶ _____

- Which do you believe (most)?*

- ▶ _____

Simultaneous Equations Example Redux I

- For our final, simultaneous equations example, we use annual data on the purchase of truffles
- This is a classic Supply and Demand environment
 - ▶ So it's natural to use a supply shifter as an instrument for a demand equation
 - ▶ In this data we have the rental price of...

Simultaneous Equations Example Redux II

- Do you think this is likely to satisfy the conditions for a good instrument?*
 - ▶ Relevance: _____
 - ▶ Exogeneity: _____
- Remember what we said was the likely sign of the bias?
 - ▶ _____

Simultaneous Equations Example Redux III

- Let's see what happens when we instrument with the rental price of truffle pigs

See Stata Example in Class

- Do these results seem (more) reasonable to you?*



IV Conclusions I

- Understanding the potential sources of bias in regression...
 - ▶ ...and how to resolve it using Instrumental Variables...
 - ▶ ...*cannot* be overestimated as a key skill in your “Econometrician’s toolkit”
- In my view it’s what separates “Careful Econometricians” from “Regression Runners”
 - ▶ Please be one of the **former** and not one of the **latter**!

IV Conclusions II

- In the remainder of the course, we will cover the second-most common method to address endogeneity bias
 - ▶ Panel Data Methods

Coming Up Next!

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