alE

Intro to Econometrics: Recitation 8

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November 12, 2019

Roadmap for today

- Chapter 6 quick review:
  - Asymptotic order notation
  - The basic toolkit: CMT, delta method and limit theorems
- BH Chapter 7:
  - Asymptotic properties in the LP/LR model

Asymptotic order notation

Deterministic sequences

- Consider the claim:

  "The sequence $a_n = n^2$ diverges to infinity an order of magnitude faster than $b_n = n$"

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- Note: we're assuming for simplicity that $b_n > 0$

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Deterministic sequences: examples

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  1. $x_n \in O(x_n)$ but the same doesn't hold for $o(x_n)$
  2. If $x_n \in O(An^2 + Bn + C)$, then $x_n \in O(n^2)$; moreover, $x_n \in o(n^3)$
     - ⋆ Similar fact for higher degree polynomials goes through

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  3. $x_n \in O(y_n)$ iff $x_n/y_n \in o(1)$; same for O
  4. If $x_n \to x$, then $x_n \in O(1)$

Asymptotic order notation

Deterministic sequences: results

Lemma

For any positive sequences x_n, y_n, z_n and w_n,

1. If $x_n \in o(z_n)$ and $y_n \in o(w_n)$, then
$$x_n y_n \in o(z_n w_n)$$
$$x_n + y_n \in o(z_n + w_n)$$
and the same holds for O
2. If $x_n \in o(z_n)$ and $y_n \in O(w_n)$, then
$$x_n y_n \in o(z_n w_n)$$
$$x_n + y_n \in O(z_n + w_n)$$

Asymptotic order notation

Deterministic sequences: results

- Proof:
  - First part of (1) follows from limit arithmetic
  - First part of (2) is a consequence of the fact that $a_n \to 0$ and b_n bounded implies $a_n b_n \to 0$
  - Second part of (1) and (2): use

$$\frac{x_n + y_n}{z_n + w_n} = \frac{x_n}{z_n}\frac{z_n}{z_n + w_n} + \frac{y_n}{w_n}\frac{w_n}{z_n + w_n}$$

    the ratio $z_n/(z_n + w_n) \in [0, 1]$ is bounded

Asymptotic order notation

Sequences of random variables

- Analogs: let X_n be a sequence of random variables and a_n a positive deterministic sequence
  - $X_n \in O_p(a_n)$ iff $\dfrac{X_n}{a_n}$ is *stochastically* bounded
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- Definition of stochastically bounded.

  For every $\delta > 0$ there exists M_δ such that

$$\Pr\{|X_n| \leq M_\delta\} > 1 - \delta$$

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- Result: lemma goes through with o and O replaced with o_p and O_p

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- Proof. Let Y be st $X_n \xrightarrow{d} Y$. Denote F_Y and F_n the CDF of Y and X_n, respectively. Fix $\delta > 0$.
  - Let M_δ be such that

$$F_Y(M_\delta) - F_Y(-M_\delta) = \Pr\{Y \in (-M_\delta, M_\delta]\} > 1 - \frac{\delta}{2}$$

  - In addition, we can choose M_δ st F_Y continuous at M_δ and $-M_\delta$ (why?)

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- That implies
$$\Pr\{|X_n| \leq M_\delta\} \geq F_n(M_\delta) - F_n(-M_\delta) > 1 - \delta$$

The asymptotics toolkit

- You need to know the following by heart:
  1. General results
     - ⋆ Continuous mapping theorem
     - ⋆ Slutzky's theorem
     - ⋆ Delta method
  2. Results about averages
     - ⋆ Law of large numbers
     - ⋆ Central Limit Theorem

Continuous mapping theorem

- Let $F : U \to V$ have a set of discontinuities U_0
- If $X_n \xrightarrow{d} X$ or $X_n \xrightarrow{p} X$, then $F(X_n) \to F(X)$ as long as

$$\Pr\{X \in U_0\} = 0$$

Slutzky's theorem

- If $X_n \xrightarrow{d} X$ and $Y_n \xrightarrow{p} c$ where c is non-random, then
  1. $X_n + Y_n \xrightarrow{d} X + c$
  2. $X_n Y_n \xrightarrow{d} cX$
  3. $X_n / Y_n \xrightarrow{d} X/c$ as long as $c \neq 0$
- These results follow from CMT, plus the fact that

$$(X_n, Y_n) \xrightarrow{d} (X, c)$$

provided that c is non-random.

Delta method

- If μ is non-random,

$$\sqrt{n}(X_n - \mu) \xrightarrow{d} Z$$

and g is differentiable at μ, then

$$\sqrt{n}(g(X_n) - g(\mu)) \xrightarrow{d} g'(\mu)Z$$

- Remarks.
  1. No assumption about normality is needed for Z.
  2. The theorem goes through in the multivariate case
     - Example: $F(\gamma_1, \gamma_2) = \gamma_1\gamma_2$

Results about averages

- Let $\{X_i\}$ be sampled iid from some distribution. Denote

$$\bar{X}_n = \frac{1}{n}\sum_{i=1}^{n} X_i$$

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- Central limit theorem. If $\{X_i\}$ are sampled iid from distribution with finite mean μ and variance σ^2,

$$\sqrt{n}\left(\bar{X}_n - \mu\right) \xrightarrow{d} Z \sim N(0, \sigma^2)$$

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$$\bar{X}_n - \mu = \frac{1}{\sqrt{n}} \left[\sqrt{n}(\bar{X}_n - \mu) \right] = O_p(n^{-1/2}) O_p(1) = O_p(n^{-1/2})$$

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- Hence (with finite second moments) the convergence of $\bar{X}_n$ to μ is no slower than $n^{-1/2}$ goes to 0.

OLS asymptotics: the linear projection model

- Consider the following assumptions:

(1) (y_i, x_i) sampled iid

(2) $(y_i^2) < \infty$

(2') $(y_i^4) < \infty$

(3) $(\|x_i\|^2) < \infty$

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(4) $[x_i x_i']$ positive definite

- Notation:

$$[x_i x_i'] =: Q_{xx}$$

$$[x_i y_i] =: Q_{xy}$$

OLS asymptotics: the linear projection model

- Results:
  1. Under (1), (2), (3) and (4), OLS is consistent for the population projection coefficient:
  $$\hat{\beta} = \left(\sum_{i=1}^{n} x_i x_i' \right)^{-1} \sum_{i=1}^{n} x_i y_i \xrightarrow{p} \beta := Q_{xx}^{-1} Q_{xy}$$
  2. Under (1), (2'), (3') and (4), OLS is asymptotically normal:
  $$\sqrt{n} \left[\left(\sum_{i=1}^{n} x_i x_i' \right)^{-1} \sum_{i=1}^{n} x_i y_i - \beta \right] \xrightarrow{d} N\left(0, Q_{xx}^{-1} \Omega Q_{xx}^{-1}\right)$$
     - ★ β is again the population projection coefficient
     - ★ $\Omega = [u_i^2 x_i x_i']$
     - ★ $u_i := y_i - x_i' \beta$
- Notation:
$$V_\beta = Q_{xx}^{-1} \Omega Q_{xx}^{-1}$$

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  (5) $(y_i|x_i) = x_i'\beta$

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(4)&\quad [x_i x_i'] \text{ positive definite}\\
(5)&\quad (y_i|x_i) = x_i'\beta\\
(6)&\quad \mathbf{V}[y_i|x_i] \equiv \sigma^2
\end{aligned}
$$

- Assumptions (1), (2), (3), (4) and (5) are called the linear regression model
- Again (2') and (3') are required for asymptotic normality
- If (6) is assumed, we have the homoskedastic linear regression model

OLS asymptotics: the linear regression model

- Finite sample variance of OLS:

$$\hat{\beta} = (X'X)^{-1}X'Y \implies \mathbf{V}(\hat{\beta}|X) = (X'X)^{-1}X'\mathbf{V}(Y|X)X(X'X)^{-1}$$

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- It is true however that

$$nV_{\hat{\beta}} \xrightarrow{p} V_{\beta}$$

(why?)

OLS asymptotics: estimating the limiting variance

- We know that the limiting variance of OLS in the LPM is

$$V_\beta = Q_{xx}^{-1} \Omega Q_{xx}^{-1}$$

- A valid estimator for $\Omega = [u_i^2 x_i x_i']$ is

$$\hat{\Omega} = \frac{1}{n} \sum_{i=1}^{n} \hat{u}_i^2 x_i x_i'$$

- One estimator for V_β is

$$\hat{V}_\beta^{\text{HC0}} = \hat{Q}_{xx}^{-1} \hat{\Omega} \hat{Q}_{xx}^{-1}$$

Prediction: regression intervals

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- Note that for fixed x,

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so that

$$\left(x'\hat{V}_\beta x\right)^{-1/2}\sqrt{n}[\hat{m}(x) - m(x)] \xrightarrow{d} N(0,1)$$

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- That motivates the approximation

$$\hat{m}(x) \approx N\left(m(x), \frac{1}{n}x'\hat{V}_\beta x\right)$$

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- Forecast error is

$$\tilde{e}_{n+1} = y_{n+1} - x'\hat{\beta} = x'\beta + e_i - x'\hat{\beta} = e_{n+1} + x'(\beta - \hat{\beta})$$

  - The true regression has an error e_{n+1}
  - In addition to that, there is an estimation noise coming from $\hat{\beta}$ being different than β

Prediction: forecast errors

- Finite sample variance of e_{n+1}:

$$[\hat{e}_{n+1}^2 | x_{n+1}] = \sigma^2(x_{n+1}) + x_{n+1}' V_{\hat{\beta}} x_{n+1}$$

- Can we build a confidence interval for the forecast?