Day 1B
Asymptotic Theory

© A. Colin Cameron
Univ. of Calif.- Davis

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1. Introduction

OLS for the linear model is the building block for nonlinear regression.

1. Introduction
2. Sequences of random variables
3. Convergence in probability
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2. Sequences of random variables

- Recall a sequence of real numbers
  - e.g. $a_N = 2 + \frac{3}{N}$
- What happens as $N \rightarrow \infty$?
  - mathematical convergence (or divergence)
- A sequence of nonstochastic real numbers $\{a_N\}$ *converges* to a if for any $\varepsilon > 0$, there exists $N^* = N^*(\varepsilon)$ such that for all $N > N^*$,

$$|a_N - a| < \varepsilon.$$

  - e.g. $a_N = 2 + 3/N \rightarrow 2$ since $|a_N - a| = |2 + 3/N - 2| = |3/N| < \varepsilon$ for all $N > N^* = 3/\varepsilon$.

- We instead consider a sequence of random variables b_N.
  - e.g. $b_N = \frac{1}{N}\sum_{i=1}^N x_i^2$
  - e.g. $b_N = \frac{1}{N}\sum_{i=1}^N x_i u_i$
  - e.g. $b_N = \widehat{\beta} = \left(\frac{1}{N}\sum_{i=1}^N x_i^2\right)^{-1} \frac{1}{N}\sum_{i=1}^N x_i u_i$
- What happens as $N \longrightarrow \infty$?
  - $|b_N - b|$ may exceed ε due to randomness, so $b_N \nrightarrow b$ exactly
  - instead use convergence in probability and in distribution.

3. Convergence in probability and consistency

- Informal definition: The sequence $\{b_N\}$ *converges in probability* to b if for any $\varepsilon > 0$
$$\lim_{N\to\infty} \Pr[|b_N - b| < \varepsilon] = 1.$$
- Formal definition: A sequence of random variables $\{b_N\}$ *converges in probability* to b if for any $\varepsilon > 0$ and $\delta > 0$, there exists $N^* = N^*(\varepsilon, \delta)$ such that for all $N > N^*$,
$$\Pr[|b_N - b| < \varepsilon] > 1 - \delta.$$
- Intuition: Convergence in mean square (i.e. $\lim_{N\to\infty} \mathrm{E}[(b_N - b)^2] = 0$) implies convergence in probability.
  - But convergence in probability can happen even if $\mathrm{E}[(b_N - b)^2]$ does not exist.

Consistency

- We write $\text{plim } b_N = b$ or $b_N \xrightarrow{p} b$.
- The limit b may be a constant or a random variable.
  - Often $\widehat{\boldsymbol{\beta}} \xrightarrow{p} \boldsymbol{\beta}$, a constant.
  - Then we say $\widehat{\boldsymbol{\beta}}$ is *consistent* for $\boldsymbol{\beta}$.

4. Law of large numbers

- Easy way to get probability limit when b_N is an average

$$b_N = \bar{X}_N = \frac{1}{N} \sum\nolimits_{i=1}^{N} X_i.$$

  - X_i here is general notation for a random variable. e.g. $X_i = x_i u_i$.

- *Weak Law of Large Numbers (WLLN)*:
  Specifies conditions on the individual terms X_i in $\bar{X}_N$ under which

$$(\bar{X}_N - \mathrm{E}[\bar{X}_N]) \xrightarrow{p} 0.$$

- *Khinchine's Theorem (WLLN)*:
  Let $\{X_i\}$ be i.i.d. (independent and identically distributed).
  If and only if $\mathrm{E}[X_i] = \mu$ exists, then $(\bar{X}_N - \mu) \xrightarrow{p} 0$.

- Other LLN's are Kolmogorov and, for i.n.i.d. data, Markov.
- If a LLN can be applied then

$$\begin{aligned} \text{plim}\,\bar{X}_N &= \lim \mathrm{E}[\bar{X}_N] && \text{in general} \\ &= \lim N^{-1} \textstyle\sum_{i=1}^{N} \mathrm{E}[X_i] && \text{if } X_i \text{ independent over } i \\ &= \mu && \text{if } X_i \text{ i.i.d.} \end{aligned}$$

5. Convergence in distribution

- b_N has (unknown) cumulative distribution function (cdf) F_N.
  Like any other function, F_N may have a limit function.
- *Convergence in Distribution*:
  A sequence of random variables $\{b_N\}$ *converges in distribution* to a random variable b if

$$\lim_{N\rightarrow\infty} F_N = F, \text{ where } F \text{ is the c.d.f. of } b$$

  at every continuity point of F, where convergence is in the usual mathematical sense.
- We write $b_N \xrightarrow{d} b$, and call F the *limit distribution* of $\{b_N\}$.
- Basically F_N is very complicated and F is simple like $\mathcal{N}[0, 1]$.

6. Central limit theorems

- Easy way to get limit distribution when b_N is an average $\bar{X}_N$.
- $\bar{X}_N$ has a degenerate limit distribution with all mass at one point since $\bar{X}_N \xrightarrow{p} \lim \mathrm{E}[\bar{X}_N]$ by a LLN.
- So rescale $\bar{X}_N$ to standardized variate

$$b_N = Z_N = \frac{\bar{X}_N - \mathrm{E}[\bar{X}_N]}{\sqrt{\mathrm{V}[\bar{X}_N]}} \sim [0,\ 1].$$

- *Central Limit Theorem (CLT)*:
  A CLT specifies the conditions on the individual terms X_i in $\bar{X}_N$ under which

$$Z_N \xrightarrow{d} \mathcal{N}[0,1].$$

- *Lindeberg-Levy CLT:*
  Let $\{X_i\}$ be i.i.d. with $\mathrm{E}[X_i] = \mu$ and $\mathrm{V}[X_i] = \sigma^2$.
  Then $Z_N = \sqrt{N}(\bar{X}_N - \mu)/\sigma \xrightarrow{d} \mathcal{N}[0,1]$.

- Note that

$$\begin{aligned} Z_N &= (\bar{X}_N - \mathrm{E}[\bar{X}_N])/\sqrt{\mathrm{V}[\bar{X}_N]} && \text{in general} \\ &= \textstyle\sum_{i=1}^N (X_i - \mathrm{E}[X_i])/\sqrt{\sum_{i=1}^N \mathrm{V}[X_i]} && \text{if } X_i \text{ independent over } i \\ &= \sqrt{N}(\bar{X}_N - \mu)/\sigma && \text{if } X_i \text{ i.i.d.} \end{aligned}$$

- The last expression can be rewritten as

$$\frac{\bar{X}_N - \mu}{\sigma/\sqrt{N}} \xrightarrow{d} \mathcal{N}[0, 1].$$

- It follows that $\sqrt{N}(\bar{X}_N - \mu) \xrightarrow{d} \mathcal{N}[0, \sigma^2]$.
- More generally we often find $\sqrt{N}(\widehat{\beta} - \beta) \xrightarrow{d} \mathcal{N}[0, V]$.
  - Scale consistent $\widehat{\beta}$ up by $\sqrt{N}$ to get a limit distribution.

Multivariate central limit theorem

- Consider vector $\overline{\mathbf{X}}_N$ with mean $\boldsymbol{\mu}_N$ and variance $\mathbf{V}_N$

$$\overline{\mathbf{X}}_N \sim [\boldsymbol{\mu}_N,\ \mathbf{V}_N].$$

- Rescale $\overline{\mathbf{X}}_N$ to standardized variate

$$\mathbf{Z}_N = \mathbf{V}_N^{-1/2}(\mathbf{b}_N - \boldsymbol{\mu}_N) \sim [\mathbf{0},\ \mathbf{I}].$$

- *Central Limit Theorem (CLT)*:
  A CLT specifies the conditions on the individual terms $\mathbf{X}_i$ in $\overline{\mathbf{X}}_N$ under which

$$\mathbf{Z}_N \xrightarrow{d} \mathcal{N}[\mathbf{0},\ \mathbf{I}].$$

7. Some Key Results

- *Probability Continuity and Continuous Mapping Theorems*
  Let $\mathbf{b}_N$ be a vector of random variables, and $g(\cdot)$ be a continuous real-valued function. Then

$$\begin{array}{rlr} \mathbf{b}_N \xrightarrow{p} \mathbf{b}, \text{ a constant} & \Rightarrow g(\mathbf{b}_N) \xrightarrow{p} g(\mathbf{b}) & \text{Probability Continuity} \\ \mathbf{b}_N \xrightarrow{d} \mathbf{b} & \Rightarrow g(\mathbf{b}_N) \xrightarrow{d} g(\mathbf{b}) & \text{Continuous Mapping} \end{array}$$

- *Transformation Theorem:*
  If $a_N \xrightarrow{d} a$ (a random variable) and $b_N \xrightarrow{p} b$ (a constant), then

$$\begin{array}{ll} (i) & a_N + b_N \xrightarrow{d} a + b \\ (ii) & a_N b_N \xrightarrow{d} ab \\ (iii) & a_N / b_N \xrightarrow{d} a/b, \quad \text{provided } \Pr[b=0]=0. \end{array}$$

  - We use especially a matrix version of (ii).

- *Product Limit Normal Rule:*
  For vector $\mathbf{a}_N$ and matrix $\mathbf{H}_N$, if

$$\begin{aligned} \mathbf{a}_N &\xrightarrow{d} \mathcal{N}[\boldsymbol{\mu}, \mathbf{A}] \\ \mathbf{H}_N &\xrightarrow{p} \mathbf{H}, \quad \text{where } \mathbf{H} \text{ is positive definite} \end{aligned}$$

  then

$$\mathbf{H}_N \mathbf{a}_N \xrightarrow{d} \mathcal{N}[\mathbf{H}\boldsymbol{\mu}, \mathbf{HAH}'].$$

- Leading example is OLS:

$$\begin{aligned} \sqrt{N}(\widehat{\boldsymbol{\beta}} - \boldsymbol{\beta}_0) &= (\frac{1}{N}\mathbf{X}'\mathbf{X})^{-1} \times \frac{1}{\sqrt{N}}(\mathbf{X}'\mathbf{u}) \\ &\xrightarrow{d} \mathcal{N}[\mathbf{A}^{-1} \times \mathbf{0}, \mathbf{A}^{-1}\mathbf{B}\mathbf{A}^{-1\prime}]. \end{aligned}$$

8. Simulations for LLN and CLT

Uniform on $(0,1)$ has mean 0 and variance $1/12$.

Sample average of N uniforms has mean 0 and variance $(1/12)/N$.

```
. * Draw from uniform with population mean 0.5
. * Demonstrate LLN by finding average for a very large sample
. * Demonstrate CLT by simulating to obtain many averages
.
. * Small sample: sample mean differs from population mean
. set obs 30
obs was 0, now 30

. set seed 10101

. quietly generate x = runiform()

. mean x

Mean estimation                    Number of obs    =      30

--------------------------------------------------------------
             |       Mean   Std. Err.     [95% Conf. Interval]
-------------+------------------------------------------------
           x |   .5459987   .0511899      .4413036    .6506939
--------------------------------------------------------------
```

For $N = 30$: $\bar{x} = 0.546$ differs appreciably from $\mu = 0.500$.

```
. * Consistency: Large sample: sample mean is very close to population mean
. clear all

. set obs 100000
obs was 0, now 100000

. set seed 10101

. quietly generate x = runiform()

. mean x

Mean estimation                     Number of obs    =   100000

--------------------------------------------------------------
             |       Mean   Std. Err.     [95% Conf. Interval]
-------------+------------------------------------------------
           x |   .4988239   .0009133      .4970339    .5006138
--------------------------------------------------------------
```

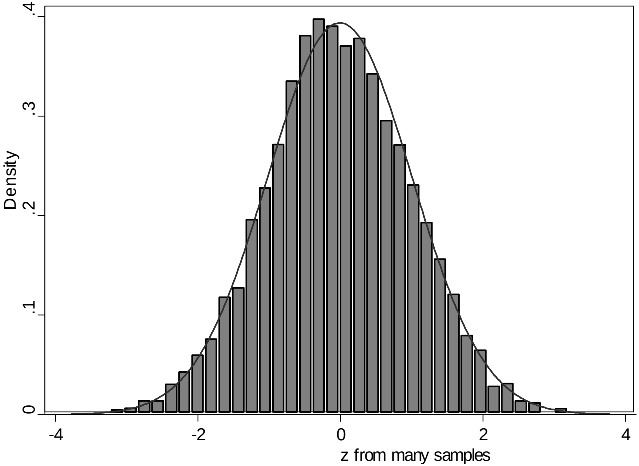
For $N = 100,000$: $\bar{x} = 0.499$ is very close to $\mu = 0.500$.

```
. * Central limit theorem
. * Write program to obtain sample mean for one sample of size numobs (= 30)
. program onesample, rclass
  1.      args numobs
  2.      drop _all
  3.      quietly set obs `numobs'
  4.      generate x = runiform()
  5.      summarize x
  6.      return scalar meanforonesample = r(mean)
  7. end

. * Run this program 10,000 times to get 10,000 sample means
. quietly simulate xbar = r(meanforonesample), seed(10101) reps(10000) nodots: ///
>    onesample 30

. * Summarize the 10,000 sample means and draw histogram
. summarize xbar

    Variable |       Obs        Mean    Std. Dev.       Min        Max
-------------+--------------------------------------------------------
        xbar |     10000    .4995835    .0533809   .3008736   .6990562

. histogram xbar, normal xtitle("xbar from many samples")
(bin=40, start=.30087364, width=.00995456)
```

For $S = 10,000$ simulations each with sample size $N = 30$

$\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_{10000}$ has distribution with mean 0.4996 close to $\mu = 0.500$ and standard deviation 0.0534, close to $\sigma/\sqrt{N} = \sqrt{1/12}/\sqrt{30} = 0.0527$.

$z = (\bar{x} - \mu)/(\sigma/\sqrt{N}) = (\bar{x} - 0.5)/(\sqrt{1/12}/\sqrt{30}) = (\bar{x} - 0.5)/0.0527.$
Histogram and kernel density estimate for $z_1, z_2, \ldots, z_{10000}$.



This is standard normal, as predicted by the CLT.

9. Appendix: Some Further Asymptotic Results

- Alternative modes of convergence of b_N to b
  - *Mean square*: $\lim_{N\to\infty} \mathrm{E}[(b_N - b)^2] = 0$.
  - *Chebychev's inequality:* $\Pr[(Z-\mu)^2 > k] \leq \sigma^2/k$, for any $k > 0$.
  - *Almost sure:* $\Pr\{\omega | \lim b_N(\omega) = b(\omega)\} = 1$.
  - These imply convergence in probability.
- Consequences:
  - $b_N \xrightarrow{p} b$ implies $b_N \xrightarrow{d} b$.
  - The reverse is generally not true, unless b is a constant.
  - For vector r.v.'s define F_N and F to be cdf's of vectors $\mathbf{b}_N$ and $\mathbf{b}$.
- *Strong Law of Large Numbers (LLN):*
  - The convergence is instead almost surely $(\xrightarrow{as})$.

- *Markov SLLN*:
  Let $\{X_i\}$ be i.n.i.d. with $\mathrm{E}[X_i] = \mu_i$.
  If $\sum_{i=1}^{\infty} \left(\mathrm{E}[|X_i - \mu_i|^{1+\delta}] / i^{1+\delta} \right) < \infty$, for some $\delta > 0$, then $(\bar{X}_N - \mathrm{E}[\bar{X}_N]) \xrightarrow{as} 0$.
  - Relaxes i.i.d. assumption at expense of requiring existence of $(1+\delta)^{th}$ absolute moment.
  - Easiest to set $\delta = 1$, so need variance.
- *Liapounov CLT:*
  Let $\{X_i\}$ be independent with $\mathrm{E}[X_i] = \mu_i$ and $\mathrm{V}[X_i] = \sigma_i^2$.
  If $\lim \left(\sum_{i=1}^{N} \mathrm{E}[|X_i - \mu_i|^{2+\delta}] \right) / \left(\sum_{i=1}^{N} \sigma_i^2 \right)^{(2+\delta)/2} = 0$, for some choice of $\delta > 0$, then $Z_N \xrightarrow{d} \mathcal{N}[0,1]$.
  - The Liapounov CLT relaxes i.i.d. assumption but needs existence of $(2+\delta)^{th}$ absolute moment.
- *Cramer-Wold Device:*
  If $\boldsymbol{\lambda}'\mathbf{b}_N \xrightarrow{d} \mathcal{N}[\ ,\ ]$ for all $\boldsymbol{\lambda} \neq \mathbf{0}$ then $\mathbf{b}_N \xrightarrow{d} \mathcal{N}[\ ,\ ]$.
  - So prove a multivariate CLT by proving a scalar CLT for $\boldsymbol{\lambda}'\mathbf{b}_N$.

9. Appendix: Sampling schemes

- Simple Random Sampling (SRS)
  - Randomly draw (y_i, x_i) from the population with equal probabilities.
  - Then x_i i.i.d. So $x_i u_i$ i.i.d. (if errors u_i are i.i.d.), and x_i^2 i.i.d.
  - Can use Khinchine's LLN and Lindeberg-Levy CLT.
- Fixed regressors
  - Experiment where x_i are fixed and we observe the resulting random y_i.
  - Then x_i fixed, u_i i.i.d. implies $x_i u_i$ i.n.i.d. and x_i^2 nonstochastic.
  - Need to use Markov LLN and Liapounov CLT.
- Exogenous Stratified Sampling
  - Oversample some values of x and undersample others.
  - Then x_i i.n.i.d., so $x_i u_i$ i.n.i.d. and x_i^2 i.n.i.d.
  - Need to use Markov LLN and Liapounov CLT.

- These three different sampling schemes ultimately lead to similar asymptotic results.
- Microeconometrics often use survey data obtained by stratified sampling.
- The simplest results assume simple random sampling.
- Big problems arise if the stratified sampling is Instead Endogenous Stratified Sampling
  - Oversample some values of y and undersample others.
  - Estimators can be inconsistent.
  - Leading examples are Tobit and selection models.

9. Appendix: OLS under simple random sampling

- Scalar regressor: $y_i = \beta x_i + u_i$.
- SRS: (x_i, y_i) i.i.d. with x_i i.i.d. with mean μ_x & u_i i.i.d. with mean 0.
  - **1.** As $x_i u_i$ are i.i.d. apply Khinchine's Theorem.
    Then $N^{-1}\sum_i x_i u_i \xrightarrow{p} \mathrm{E}[xu] = \mathrm{E}[x] \times \mathrm{E}[u] = 0$.
  - **2.** As x_i^2 are i.i.d. apply Khinchine's Theorem.
    Then $N^{-1}\sum_i x_i^2 \xrightarrow{p} \mathrm{E}[x^2]$ which we assume exists.
  - **3.** The probability limit is obtained by combining

$$\begin{aligned}
\operatorname{plim} \widehat{\beta} &= \beta + \operatorname{plim}\left(\frac{\frac{1}{N}\sum_{i=1}^N x_i u_i}{\frac{1}{N}\sum_{i=1}^N x_i^2}\right) \\
&= \beta + \frac{\operatorname{plim} \frac{1}{N}\sum_{i=1}^N x_i u_i}{\operatorname{plim} \frac{1}{N}\sum_{i=1}^N x_i^2} \\
&= \beta + \frac{0}{\mathrm{E}[x^2]} = \beta,
\end{aligned}$$

using probability limit continuity $(\operatorname{plim}[a_N / b_N] = a/b \text{ if } b \neq 0)$.

- SRS: assume x_i i.i.d. with mean μ_x and second moment $\mathsf{E}[x^2]$ and assume u_i i.i.d. with mean 0 and variance σ^2.
- Then $x_i u_i$ are i.i.d. with mean $\mathsf{E}[xu] = \mathsf{E}[x] \times \mathsf{E}[u] = 0$, and $\mathsf{V}[xu] = \mathsf{E}[(xu-0)^2] = \mathsf{E}[x^2 u^2] = \mathsf{E}[x^2]\mathsf{E}[u^2] = \sigma^2 \mathsf{E}[x^2]$.
  - **1.** Lindeberg-Levy CLT for $N^{-1}\sum_{i=1}^N x_i u_i$ yields

$$\sqrt{N}\left(\frac{N^{-1}\sum_{i=1}^N x_i u_i - 0}{\sqrt{\sigma^2 \mathsf{E}[x^2]}}\right) = \frac{\frac{1}{\sqrt{N}}\sum_{i=1}^N x_i u_i}{\sqrt{\sigma^2 \mathsf{E}[x^2]}} \xrightarrow{d} \mathcal{N}[0,1].$$

  - **2.** Convert to $\frac{1}{\sqrt{N}}\sum_{i=1}^N x_i u_i$

$$\begin{aligned} \frac{1}{\sqrt{N}}\sum_{i=1}^N x_i u_i &= \sqrt{\sigma^2 \mathsf{E}[x^2]} \times \frac{\frac{1}{\sqrt{N}}\sum_{i=1}^N x_i u_i}{\sqrt{\sigma^2 \mathsf{E}[x^2]}} \\ &\xrightarrow{d} \sqrt{\sigma^2 \mathsf{E}[x^2]} \times \mathcal{N}[0,1] \\ &\xrightarrow{d} \mathcal{N}[0, \sigma^2 \mathsf{E}[x^2]] \end{aligned}$$

using product limit normal rule.

- 3. **3.** The limit distribution is obtained by combining

$$
\begin{aligned}
\sqrt{N}(\widehat{\beta}-\beta) &= \frac{\frac{1}{\sqrt{N}}\sum_{i=1}^{N} x_i u_i}{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \\
&\xrightarrow{d} \frac{\mathcal{N}\left[0, \sigma^2 \mathrm{E}[x^2]\right]}{\mathrm{plim}\, \frac{1}{N}\sum_{i=1}^{N} x_i^2} \\
&\xrightarrow{d} \frac{\mathcal{N}\left[0, \sigma^2 \mathrm{E}[x^2]\right]}{\mathrm{E}[x^2]} \\
&\xrightarrow{d} \mathcal{N}\left[0, \sigma^2 \left(\mathrm{E}[x^2]\right)^{-1}\right]
\end{aligned}
$$

using $\mathrm{plim}\, N^{-1}\sum_{i=1}^{N} x_i^2 = \mathrm{E}[x^2]$ from consistency proof and the product normal limit rule (or $a_N \times b_N \xrightarrow{d} a \times b$ if $a_N \xrightarrow{d} a$ and $b_N \xrightarrow{p} b$).