

STAT 830

Convergence in Distribution

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Purposes of These Notes

- Define convergence in distribution
- State central limit theorem
- Discuss Edgeworth expansions
- Discuss extensions of the central limit theorem
- Discuss Slutsky's theorem and the δ method.

- Undergraduate version of central limit theorem:

Theorem

If X_1, \dots, X_n are iid from a population with mean μ and standard deviation σ then $n^{1/2}(\bar{X} - \mu)/\sigma$ has approximately a normal distribution.

- Also Binomial(n, p) random variable has approximately a $N(np, np(1 - p))$ distribution.
- Precise meaning of statements like “ X and Y have approximately the same distribution”?

Towards precision

- Desired meaning: X and Y have nearly the same cdf.
- But care needed.
- **Q1:** If n is a large number is the $N(0, 1/n)$ distribution close to the distribution of $X \equiv 0$?
- **Q2:** Is $N(0, 1/n)$ close to the $N(1/n, 1/n)$ distribution?
- **Q3:** Is $N(0, 1/n)$ close to $N(1/\sqrt{n}, 1/n)$ distribution?
- **Q4:** If $X_n \equiv 2^{-n}$ is the distribution of X_n close to that of $X \equiv 0$?

Some numerical examples?

- Answers depend on how close close needs to be so it's a matter of definition.
- In practice the usual sort of approximation we want to make is to say that some random variable X , say, has nearly some continuous distribution, like $N(0, 1)$.
- So: want to know probabilities like $P(X > x)$ are nearly $P(N(0, 1) > x)$.
- Real difficulty: case of discrete random variables or infinite dimensions: not done in this course.
- Mathematicians' meaning of close: Either they can provide an upper bound on the distance between the two things or they are talking about taking a limit.
- In this course we take limits.

- **Definition:** A sequence of random variables X_n converges in distribution to a random variable X if

$$E(g(X_n)) \rightarrow E(g(X))$$

for every bounded continuous function g .

Theorem

The following are equivalent:

- ① X_n converges in distribution to X .
- ② $P(X_n \leq x) \rightarrow P(X \leq x)$ for each x such that $P(X = x) = 0$.
- ③ The limit of the characteristic functions of X_n is the characteristic function of X : for every real t

$$E(e^{itX_n}) \rightarrow E(e^{itX}).$$

These are all implied by $M_{X_n}(t) \rightarrow M_X(t) < \infty$ for all $|t| \leq \epsilon$ for some positive ϵ .

Answering the questions

- $X_n \sim N(0, 1/n)$ and $X = 0$. Then

$$P(X_n \leq x) \rightarrow \begin{cases} 1 & x > 0 \\ 0 & x < 0 \\ 1/2 & x = 0 \end{cases}$$

- Now the limit is the cdf of $X = 0$ except for $x = 0$ and the cdf of X is not continuous at $x = 0$ so yes, X_n converges to X in distribution.
- I asked if $X_n \sim N(1/n, 1/n)$ had a distribution close to that of $Y_n \sim N(0, 1/n)$.
- The definition I gave really requires me to answer by finding a limit X and proving that both X_n and Y_n converge to X in distribution.
- Take $X = 0$. Then

$$E(e^{tX_n}) = e^{t/n+t^2/(2n)} \rightarrow 1 = E(e^{tX})$$

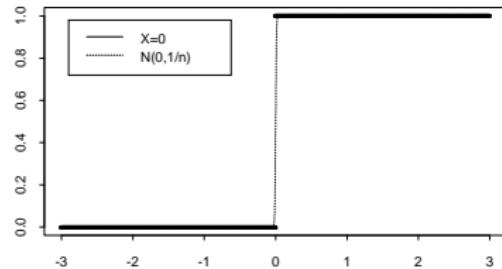
and

$$E(e^{tY_n}) = e^{t^2/(2n)} \rightarrow 1$$

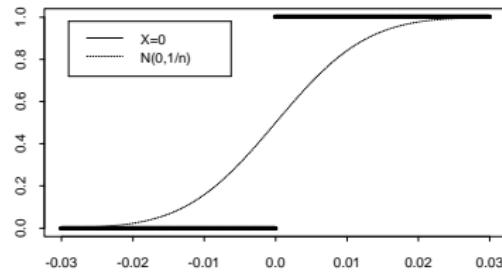
so that both X_n and Y_n have the same limit in distribution.

First graph

$N(0,1/n)$ vs $X=0$; $n=10000$

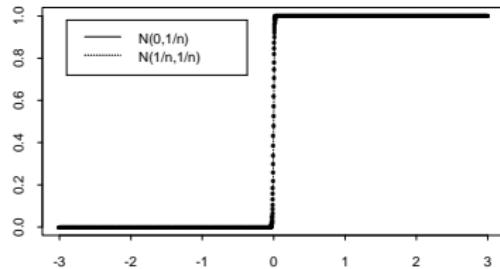


$N(0,1/n)$ vs $X=0$; $n=10000$

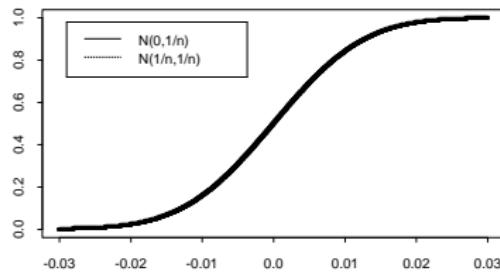


Second graph

$N(1/n, 1/n)$ vs $N(0, 1/n)$; $n=10000$



$N(1/n, 1/n)$ vs $N(0, 1/n)$; $n=10000$

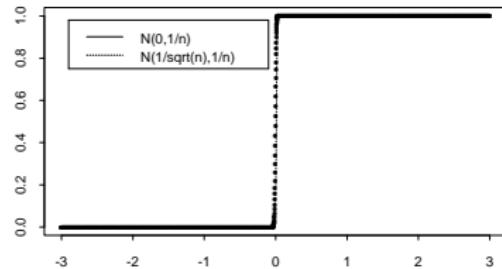


Scaling matters

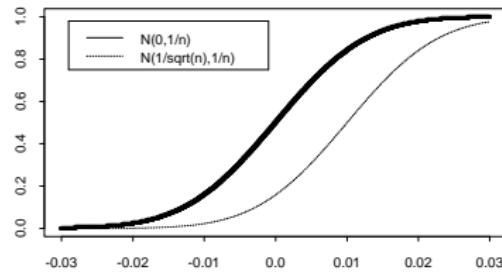
- Multiply both X_n and Y_n by $n^{1/2}$ and let $X \sim N(0, 1)$. Then $\sqrt{n}X_n \sim N(n^{-1/2}, 1)$ and $\sqrt{n}Y_n \sim N(0, 1)$.
- Use characteristic functions to prove that both $\sqrt{n}X_n$ and $\sqrt{n}Y_n$ converge to $N(0, 1)$ in distribution.
- If you now let $X_n \sim N(n^{-1/2}, 1/n)$ and $Y_n \sim N(0, 1/n)$ then again both X_n and Y_n converge to 0 in distribution.
- If you multiply X_n and Y_n in the previous point by $n^{1/2}$ then $n^{1/2}X_n \sim N(1, 1)$ and $n^{1/2}Y_n \sim N(0, 1)$ so that $n^{1/2}X_n$ and $n^{1/2}Y_n$ are **not** close together in distribution.
- You can check that $2^{-n} \rightarrow 0$ in distribution.

Third graph

$N(1/\sqrt{n}, 1/n)$ vs $N(0, 1/n)$; $n=10000$



$N(1/\sqrt{n}, 1/n)$ vs $N(0, 1/n)$; $n=10000$



Summary

- To derive approximate distributions:
- Show sequence of rvs X_n converges to some X .
- The limit distribution (i.e. dstbn of X) should be non-trivial, like say $N(0, 1)$.
- Don't say: X_n is approximately $N(1/n, 1/n)$.
- Do say: $n^{1/2}(X_n - 1/n)$ converges to $N(0, 1)$ in distribution.

Theorem

If X_1, X_2, \dots are iid with mean 0 and variance 1 then $n^{1/2}\bar{X}$ converges in distribution to $N(0, 1)$. That is,

$$P(n^{1/2}\bar{X} \leq x) \rightarrow \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-y^2/2} dy.$$

Proof of CLT

- As before

$$E(e^{itn^{1/2}\bar{X}}) \rightarrow e^{-t^2/2}.$$

This is the characteristic function of $N(0, 1)$ so we are done by our theorem.

- This is the worst sort of mathematics – much beloved of statisticians
 - reduce proof of one theorem to proof of much harder theorem.
- Then let someone else prove that.

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Edgeworth expansions

- In fact if $\gamma = E(X^3)$ then

$$\phi(t) \approx 1 - t^2/2 - i\gamma t^3/6 + \dots$$

keeping one more term.

- Then

$$\log(\phi(t)) = \log(1 + u)$$

where

$$u = -t^2/2 - i\gamma t^3/6 + \dots$$

- Use $\log(1 + u) = u - u^2/2 + \dots$ to get

$$\log(\phi(t)) \approx [-t^2/2 - i\gamma t^3/6 + \dots] - [\dots]^2/2 + \dots$$

which rearranged is

$$\log(\phi(t)) \approx -t^2/2 - i\gamma t^3/6 + \dots$$

Edgeworth Expansions

- Now apply this calculation to

$$\log(\phi_T(t)) \approx -t^2/2 - iE(T^3)t^3/6 + \dots.$$

- Remember $E(T^3) = \gamma/\sqrt{n}$ and exponentiate to get

$$\phi_T(t) \approx e^{-t^2/2} \exp\{-i\gamma t^3/(6\sqrt{n}) + \dots\}.$$

- You can do a Taylor expansion of the second exponential around 0 because of the square root of n and get

$$\phi_T(t) \approx e^{-t^2/2} \left(1 - i\gamma t^3/(6\sqrt{n})\right)$$

neglecting higher order terms.

- This approximation to the characteristic function of T can be inverted to get an **Edgeworth** approximation to the density (or distribution) of T which looks like

$$f_T(x) \approx \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \left[1 - \gamma(x^3 - 3x)/(6\sqrt{n}) + \dots\right].$$

Remarks

- The error using the central limit theorem to approximate a density or a probability is proportional to $n^{-1/2}$.
- This is improved to n^{-1} for symmetric densities for which $\gamma = 0$.
- These expansions are **asymptotic**.
- This means that the series indicated by \dots usually does **not** converge.
- When $n = 25$ it may help to take the second term but get worse if you include the third or fourth or more.
- You can integrate the expansion above for the density to get an approximation for the cdf.

Multivariate convergence in distribution

- **Definition:** $X_n \in R^p$ converges in distribution to $X \in R^p$ if

$$E(g(X_n)) \rightarrow E(g(X))$$

for each bounded continuous real valued function g on R^p .

- This is equivalent to either of

- ▶ **Cramér Wold Device:** $a^t X_n$ converges in distribution to $a^t X$ for each $a \in R^p$. or
- ▶ **Convergence of characteristic functions:**

$$E(e^{ia^t X_n}) \rightarrow E(e^{ia^t X})$$

for each $a \in R^p$.

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Extensions of the CLT

- ① Y_1, Y_2, \dots iid in R^p , mean μ , variance covariance Σ then $n^{1/2}(\bar{Y} - \mu)$ converges in distribution to $MVN(0, \Sigma)$.
- ② Lyapunov CLT: for each n X_{n1}, \dots, X_{nn} independent rvs with

$$E(X_{ni}) = 0 \quad \text{Var}\left(\sum_i X_{ni}\right) = 1 \quad \sum_i E(|X_{ni}|^3) \rightarrow 0$$

then $\sum_i X_{ni}$ converges to $N(0, 1)$.

- ③ Lindeberg CLT: 1st two cond of Lyapunov and

$$\sum_i E(X_{ni}^2 \mathbf{1}(|X_{ni}| > \epsilon)) \rightarrow 0$$

each $\epsilon > 0$. Then $\sum_i X_{ni}$ converges in distribution to $N(0, 1)$.
(Lyapunov's condition implies Lindeberg's.)

- ④ Non-independent rvs: m -dependent CLT, martingale CLT, CLT for mixing processes.
- ⑤ Not sums: Slutsky's theorem, δ method.

Theorem

If X_n converges in distribution to X and Y_n converges in distribution (or in probability) to c , a constant, then $X_n + Y_n$ converges in distribution to $X + c$. More generally, if $f(x, y)$ is continuous then $f(X_n, Y_n) \Rightarrow f(X, c)$.

- Warning: the hypothesis that the limit of Y_n be constant is essential.

Theorem

Suppose:

- Sequence Y_n of rvs converges to some y , a constant.
- $X_n = a_n(Y_n - y)$ then X_n converges in distribution to some random variable X .
- f is differentiable ftn on range of Y_n .

Then $a_n(f(Y_n) - f(y))$ converges in distribution to $f'(y)X$.

If $X_n \in R^p$ and $f : R^p \mapsto R^q$ then f' is $q \times p$ matrix of first derivatives of components of f .

Example

- Suppose X_1, \dots, X_n are a sample from a population with mean μ , variance σ^2 , and third and fourth central moments μ_3 and μ_4 .
- Then

$$n^{1/2}(s^2 - \sigma^2) \Rightarrow N(0, \mu_4 - \sigma^4)$$

where \Rightarrow is notation for convergence in distribution.

- For simplicity I define $s^2 = \bar{X^2} - \bar{X}^2$.

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How to apply δ method

- ① Write statistic as a function of averages:

- ▶ Define

$$W_i = \begin{bmatrix} X_i^2 \\ X_i \end{bmatrix}.$$

- ▶ See that

$$\bar{W}_n = \begin{bmatrix} \bar{X}^2 \\ \bar{X} \end{bmatrix}$$

- ▶ Define

$$f(x_1, x_2) = x_1 - x_2^2$$

- ▶ See that $s^2 = f(\bar{W}_n)$.

- ② Compute mean of your averages:

$$\mu_W \equiv E(\bar{W}_n) = \begin{bmatrix} E(X_i^2) \\ E(X_i) \end{bmatrix} = \begin{bmatrix} \mu^2 + \sigma^2 \\ \mu \end{bmatrix}.$$

- ③ In δ method theorem take $Y_n = \bar{W}_n$ and $y = E(Y_n)$.

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Delta Method Continues

- ⑦ Take $a_n = n^{1/2}$.
- ⑧ Use central limit theorem:

$$n^{1/2}(Y_n - y) \Rightarrow MVN(0, \Sigma)$$

where $\Sigma = \text{Var}(W_i)$.

- ⑨ To compute Σ take expected value of

$$(W - \mu_W)(W - \mu_W)^t$$

There are 4 entries in this matrix. Top left entry is

$$(X^2 - \mu^2 - \sigma^2)^2$$

This has expectation:

$$E\{(X^2 - \mu^2 - \sigma^2)^2\} = E(X^4) - (\mu^2 + \sigma^2)^2.$$

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Delta Method Continues

- Using binomial expansion:

$$\begin{aligned} E(X^4) &= E\{(X - \mu + \mu)^4\} \\ &= \mu_4 + 4\mu\mu_3 + 6\mu^2\sigma^2 + 4\mu^3E(X - \mu) + \mu^4. \end{aligned}$$

- So $\Sigma_{11} = \mu_4 - \sigma^4 + 4\mu\mu_3 + 4\mu^2\sigma^2$.
- Top right entry is expectation of

$$(X^2 - \mu^2 - \sigma^2)(X - \mu)$$

which is

$$E(X^3) - \mu E(X^2)$$

- Similar to 4th moment get

$$\mu_3 + 2\mu\sigma^2$$

- Lower right entry is σ^2 .
- So

$$\Sigma = \begin{bmatrix} \mu_4 - \sigma^4 + 4\mu\mu_3 + 4\mu^2\sigma^2 & \mu_3 + 2\mu\sigma^2 \\ \mu_3 + 2\mu\sigma^2 & \sigma^2 \end{bmatrix}$$

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Delta Method Continues

- 7 Compute derivative (gradient) of f : has components $(1, -2x_2)$.
Evaluate at $y = (\mu^2 + \sigma^2, \mu)$ to get

$$a^t = (1, -2\mu).$$

- This leads to

$$n^{1/2}(s^2 - \sigma^2) \approx n^{1/2}[1, -2\mu] \begin{bmatrix} \bar{X}^2 - (\mu^2 + \sigma^2) \\ \bar{X} - \mu \end{bmatrix}$$

which converges in distribution to

$$(1, -2\mu)MVN(0, \Sigma).$$

- This rv is $N(0, a^t \Sigma a) = N(0, \mu_4 - \sigma^4)$.

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Alternative approach

- Suppose c is constant. Define $X_i^* = X_i - c$.
- Sample variance of X_i^* is same as sample variance of X_i .
- All central moments of X_i^* same as for X_i so no loss in $\mu = 0$.
- In this case:

$$a^t = (1, 0) \quad \Sigma = \begin{bmatrix} \mu_4 - \sigma^4 & \mu_3 \\ \mu_3 & \sigma^2 \end{bmatrix}.$$

- Notice that

$$a^t \Sigma = [\mu_4 - \sigma^4, \mu_3] \quad a^t \Sigma a = \mu_4 - \sigma^4.$$

Special Case: $N(\mu, \sigma^2)$

- Then $\mu_3 = 0$ and $\mu_4 = 3\sigma^4$.
- Our calculation has

$$n^{1/2}(s^2 - \sigma^2) \Rightarrow N(0, 2\sigma^4)$$

- You can divide through by σ^2 and get

$$n^{1/2}(s^2/\sigma^2 - 1) \Rightarrow N(0, 2)$$

- In fact ns^2/σ^2 has χ^2_{n-1} distribution so usual CLT shows

$$(n-1)^{-1/2}[ns^2/\sigma^2 - (n-1)] \Rightarrow N(0, 2)$$

(using mean of χ^2_1 is 1 and variance is 2).

- Factor out n to get

$$\sqrt{\frac{n}{n-1}}n^{1/2}(s^2/\sigma^2 - 1) + (n-1)^{-1/2} \Rightarrow N(0, 2)$$

which is δ method calculation except for some constants.

- Difference is unimportant: Slutsky's theorem.

Example – median

- Many, many statistics which are not explicitly functions of averages can be studied using averages.
- Later we will analyze MLEs and estimating equations this way.
- Here is an example which is less obvious.
- Suppose X_1, \dots, X_n are iid cdf F , density f , median m .
- We study \hat{m} , the sample median.
- If $n = 2k - 1$ is odd then \hat{m} is the k th largest.
- If $n = 2k$ then there are many potential choices for \hat{m} between the k th and $k + 1$ th largest.
- I do the case of k th largest.
- The event $\hat{m} \leq x$ is the same as the event that the number of $X_i \leq x$ is at least k .
- That is

$$P(\hat{m} \leq x) = P\left(\sum_i 1(X_i \leq x) \geq k\right)$$

The median

- So

$$\begin{aligned} P(\hat{m} \leq x) &= P\left(\sum_i 1(X_i \leq x) \geq k\right) \\ &= P\left(\sqrt{n}(\hat{F}_n(x) - F(x)) \geq \sqrt{n}(k/n - F(x))\right). \end{aligned}$$

- From Central Limit theorem this is approximately

$$1 - \Phi\left(\frac{\sqrt{n}(k/n - F(x))}{\sqrt{F(x)(1 - F(x))}}\right).$$

- Notice $k/n \rightarrow 1/2$.

Median

- If we put $x = m + y/\sqrt{n}$ (where m is true median) we find

$$F(x) \rightarrow F(m) = 1/2.$$

- Also $\sqrt{n}(F(x) - 1/2) \rightarrow f(m)$ where f is density of F (if f exists).
- So

$$P(\sqrt{n}(\hat{m} - m) \leq y) \rightarrow 1 - \Phi(-2f(m)y)$$

- That is,

$$\sqrt{n}(\hat{m} - 1/2) \rightarrow N(0, 1/(4f^2(m))).$$