Comparing Systems Using Sample Data

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

These slides are available on-line at:

http://www.cse.wustl.edu/~jain/cse567-06/

- Sample Versus Population
- Confidence Interval for The Mean
- Approximate Visual Test
- One Sided Confidence Intervals
- Confidence Intervals for Proportions
- Sample Size for Determining Mean and proportions

Sample

- Old French word \`essample'
  ⇒ \`sample' and \`example'
- One example ≠ theory
- One sample ≠ Definite statement

Sample Versus Population

- Generate several million random numbers with mean μ and standard deviation σ

  Draw a sample of n observations

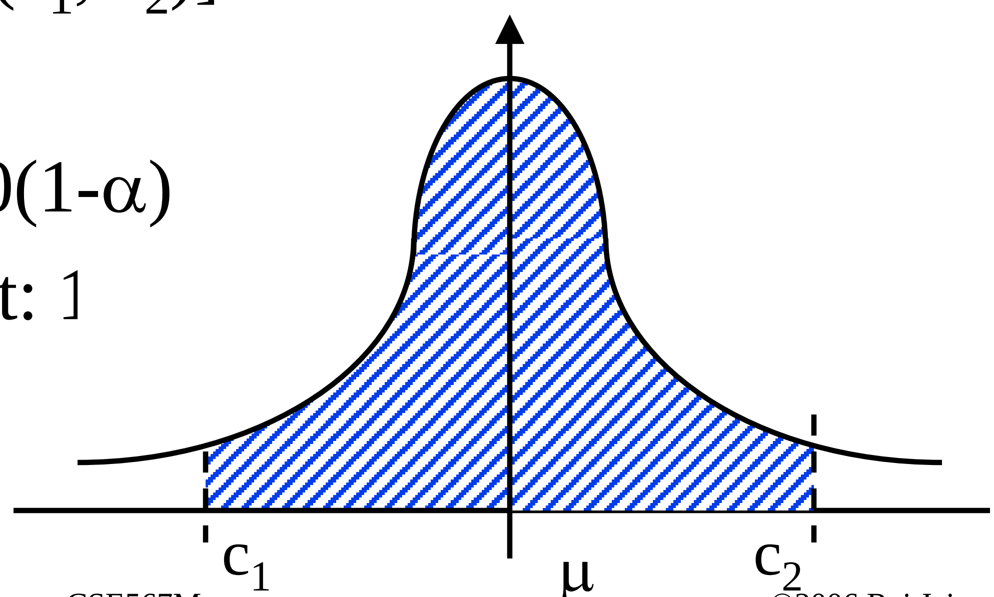
  $\bar{x} \neq \mu$
- Sample mean $\neq$ population mean
- Parameters: population characteristics
  = Unknown = Greek
- Statistics: Sample estimates = Random = English

Confidence Interval for The Mean

- *k* samples ⇒ *k* Sample means
  ⇒ Can't get a single estimate of μ
  ⇒ Use bounds c_{1} and c_{2}:

  $$\text{Probability}\{c_1 \leq \mu \leq c_2\} = 1 - \alpha$$

- Confidence interval: $[(c_1, c_2)]$
- Significance level: α
- Confidence level: $100(1-\alpha)$
- Confidence coefficient: 1



Determining Confidence Interval

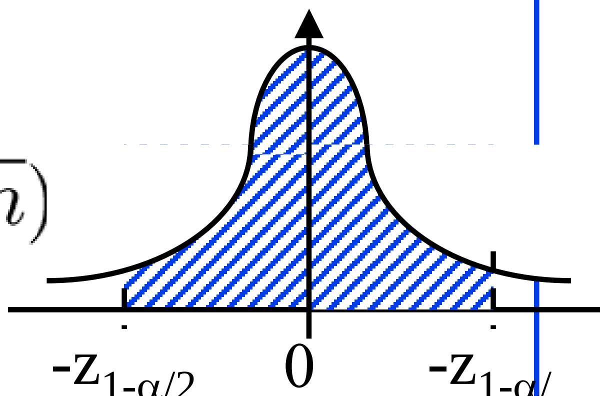
- Use 5-percentile and 95-percentile of the sample means to get 90% Confidence interval $\Rightarrow$ Need many samples.
- Central limit theorem: Sample mean of independent and identically distributed observations:

$$\bar{x} \sim N(\mu, \sigma/\sqrt{n})$$

  Where μ = population mean, σ = population standard deviation
- Standard Error: Standard deviation of the sample mean = $\sigma/\sqrt{n}$
- 100(1-a)% confidence interval for μ:

$$(\bar{x} - z_{1-\alpha/2}s/\sqrt{n}, \bar{x} + z_{1-\alpha/2}s/\sqrt{n})$$

  $z_{1-\alpha/2}$ = $(1-\alpha/2)$-quantile of N(0,1)



Example 13.1

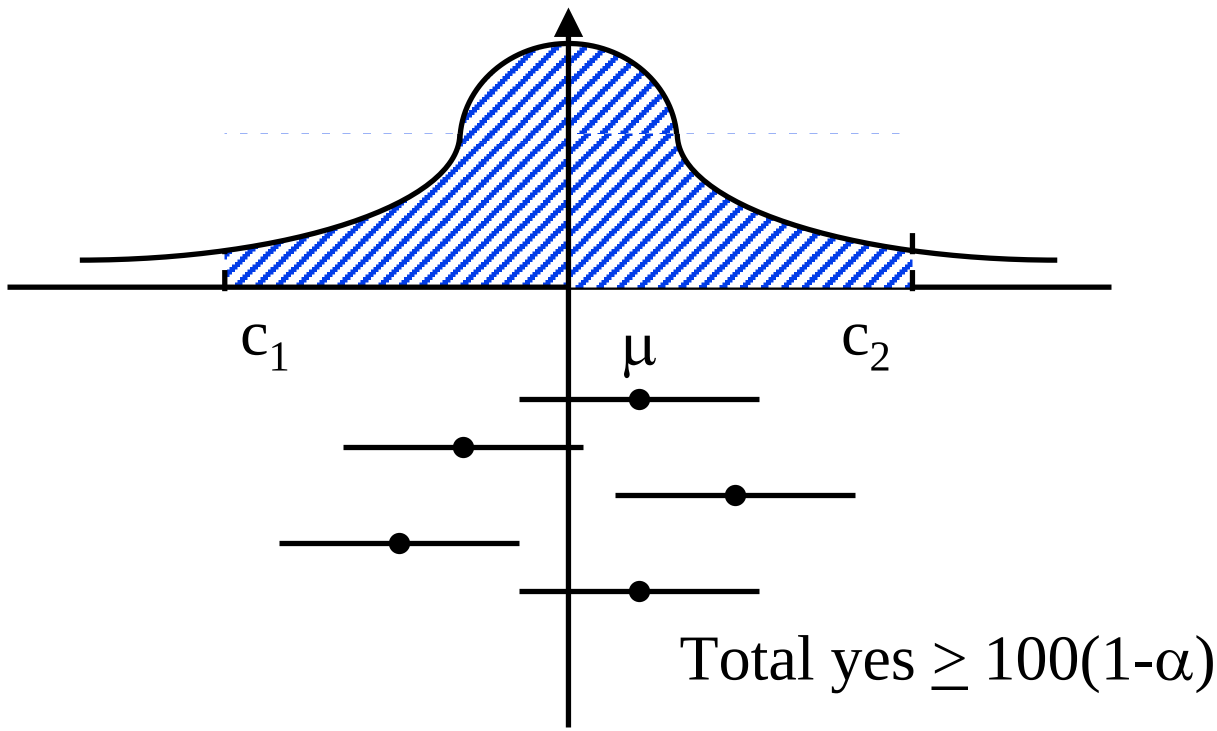
- $\bar{x}$ = 3.90, s = 0.95 and *n* = 32
- A 90% confidence interval for the mean = $3.90 \mp (1.645)(0.95)/\sqrt{32} = (3.62,\ 4.17)$
- We can state with 90% confidence that the population mean is between 3.62 and 4.17 The chance of error in this statement is 10%.

$$\text{A 95\% confidence interval for the mean} = 3.90 \mp (1.960)(0.95)/\sqrt{32} = (3.57,\ 4.23)$$

$$\text{A 99\% confidence interval for the mean} = 3.90 \mp (2.576)(0.95)/\sqrt{32} = (3.46,\ 4.33)$$

Confidence Interval: Meaning

- If we take 100 samples and construct confidence interval for each sample, the interval would include the population mean in 90 cases.



Confidence Interval for Small Samples

- $100(1-\alpha)$ % confidence interval for for $n < 30$:

$$(\bar{x} - t_{[1-\alpha/2;n-1]} s/\sqrt{n}, \bar{x} + t_{[1-\alpha/2;n-1]} s/\sqrt{n})$$

- $t_{[1-\alpha/2;\, n-1]}$ = $(1-\alpha/2)$-quantile of a t-variate with n-1 degrees of freedom

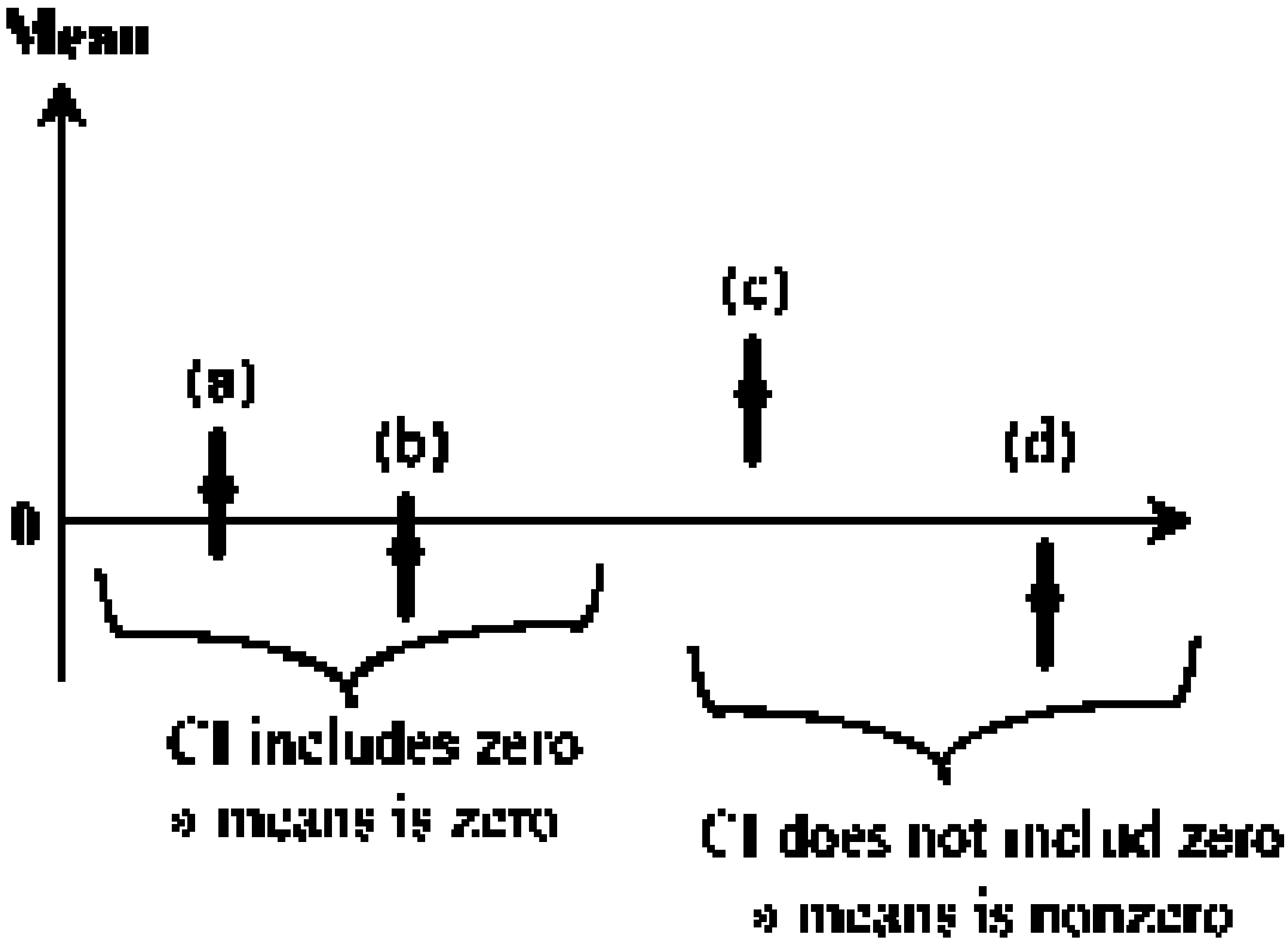
$$\begin{aligned}
&x \sim N(\mu, \sigma^2) \\
&\Rightarrow (\bar{x} - \mu)/(\sigma/\sqrt{n}) \sim N(0,1) \\
&(n-1)s^2/\sigma^2 \sim \chi^2(n-1) \\
&(\bar{x} - \mu)/\sqrt{s^2/n} \sim t(n-1)
\end{aligned}$$

Example 13.2

- Sample: -0.04, -0.19, 0.14, -0.09, -0.14, 0.19, 0.04, and 0.09.
- Mean = 0, Sample standard deviation = 0.138.
- For 90% interval: $t_{[0.95;7]} = 1.895$
- Confidence interval for the mean

$$0 \mp 1.895 \times 0.138 = 0 \mp 0.262 = (-0.262,\ 0.262)$$

Testing For A Zero Mean



Example 13.3

- Difference in processor times: {1.5, 2.6, -1.8, 1.3, -0.5, 1.7, 2.4}.
- Question: Can we say with 99% confidence that one is superior to the other?

  Sample size = n = 7

  Mean = 7.20/7 = 1.03

  Sample variance = (22.84 - 7.20*7.20/7)/6 = 2.57

  Sample standard deviation} = $\sqrt{2.57}$ = 1.60

$$\text{Confidence interval} = 1.03 \mp t * 1.60/\sqrt{7} = 1.03 \mp 0.6t$$

$$100(1-\alpha) = 99,\ \alpha = 0.01,\ 1-\alpha/2 = 0.995$$

$t_{[0.995;\,6]} = 3.707$

- 99% confidence interval = (-1.21, 3.27)

Example 13.3 (Cont)

- Opposite signs $\Rightarrow$ we cannot say with 99% confidence that the mean difference is significantly different from zero.
- Answer: They are same.
- Answer: The difference is zero.

Example 13.4

- Difference in processor times: {1.5, 2.6, -1.8, 1.3, -0.5, 1.7, 2.4}.
- Question: Is the difference 1?
- 99% Confidence interval = (-1.21, 3.27)
- Yes: The difference is 1

Paired vs. Unpaired Comparisons

- **Paired**: one-to-one correspondence between the ith test of system A and the ith test on system B
- Example: Performance on ith workload
- Use confidence interval of the difference
- **Unpaired**: No correspondence
- Example: *n* people on System A, *n* on System B
  $\Rightarrow$Need more sophisticated method

Example 13.5

- Performance: {(5.4, 19.1), (16.6, 3.5), (0.6, 3.4), (1.4, 2.5), (0.6, 3.6), (7.3, 1.7)}. Is one system better?
- Differences: {-13.7, 13.1, -2.8, -1.1, -3.0, 5.6}.

$$\text{Sample mean} = -0.32$$
$$\text{Sample variance} = 81.62$$
$$\text{Sample standard deviation} = 9.03$$
$$\text{Confidence interval for the mean} = -0.32 \mp t\sqrt{(81.62/6)}$$
$$= -0.32 \mp t(3.69)$$
$$t_{[0.95,5]} = 2.015$$
$$90\% \text{ confidence interval} = -0.32 \mp (2.015)(3.69)$$
$$= (-7.75,\ 7.11)$$

- Answer: No. They are not different.

Unpaired Observations

- Compute the sample means:

$$\bar{x}_a = \frac{1}{n_a}\sum_{i=1}^{n_a} x_{ia}$$

$$\bar{x}_b = \frac{1}{n_b}\sum_{i=1}^{n_b} x_{ib}$$

- Compute the sample standard deviations:

$$s_a = \left\{ \frac{\left(\sum_{i=1}^{n_a} x_{ia}^2\right) - n_a \bar{x}_a^2}{n_a - 1} \right\}^{\frac{1}{2}}$$

$$s_b = \left\{ \frac{\left(\sum_{i=1}^{n_b} x_{ib}^2\right) - n_b \bar{x}_b^2}{n_b - 1} \right\}^{\frac{1}{2}}$$

Unpaired Observations (Cont)

- Compute the mean difference: $(\bar{x}_a - \bar{x}_b)$
- Compute the standard deviation of the mean difference:

$$s = \sqrt{\left(\frac{s_a^2}{n_a} + \frac{s_b^2}{n_b}\right)}$$

- Compute the effective number of degrees of freedom:

$$\nu = \frac{\left(\frac{s_a^2}{n_a} + \frac{s_b^2}{n_b}\right)^2}{\frac{1}{n_a+1}\left(\frac{s_a^2}{n_a}\right)^2 + \frac{1}{n_b+1}\left(\frac{s_b^2}{n_b}\right)^2} - 2$$

- Compute the confidence interval for the mean difference:

$$(\bar{x}_a - \bar{x}_b) \mp t_{[1-\alpha/2;\nu]} s$$

Example 13.6

- Times on System A: {5.36, 16.57, 0.62, 1.41, 0.64, 7.26}

  Times on system B: {19.12, 3.52, 3.38, 2.50, 3.60, 1.74}
- Question: Are the two systems significantly different?
- For system A:

$$\text{Mean } \bar{x}_a = 5.31$$
$$\text{Variance } s_a^2 = 37.92$$
$$n_a = 6$$

- For System B:

$$\text{Mean } \bar{x}_b = 5.64$$
$$\text{Variance } s_b^2 = 44.11$$
$$n_b = 6$$

Example 13.6 (Cont)

Mean difference $\bar{x}_a - \bar{x}_b = -0.33$

Standard deviation of the mean difference $= 3.698$

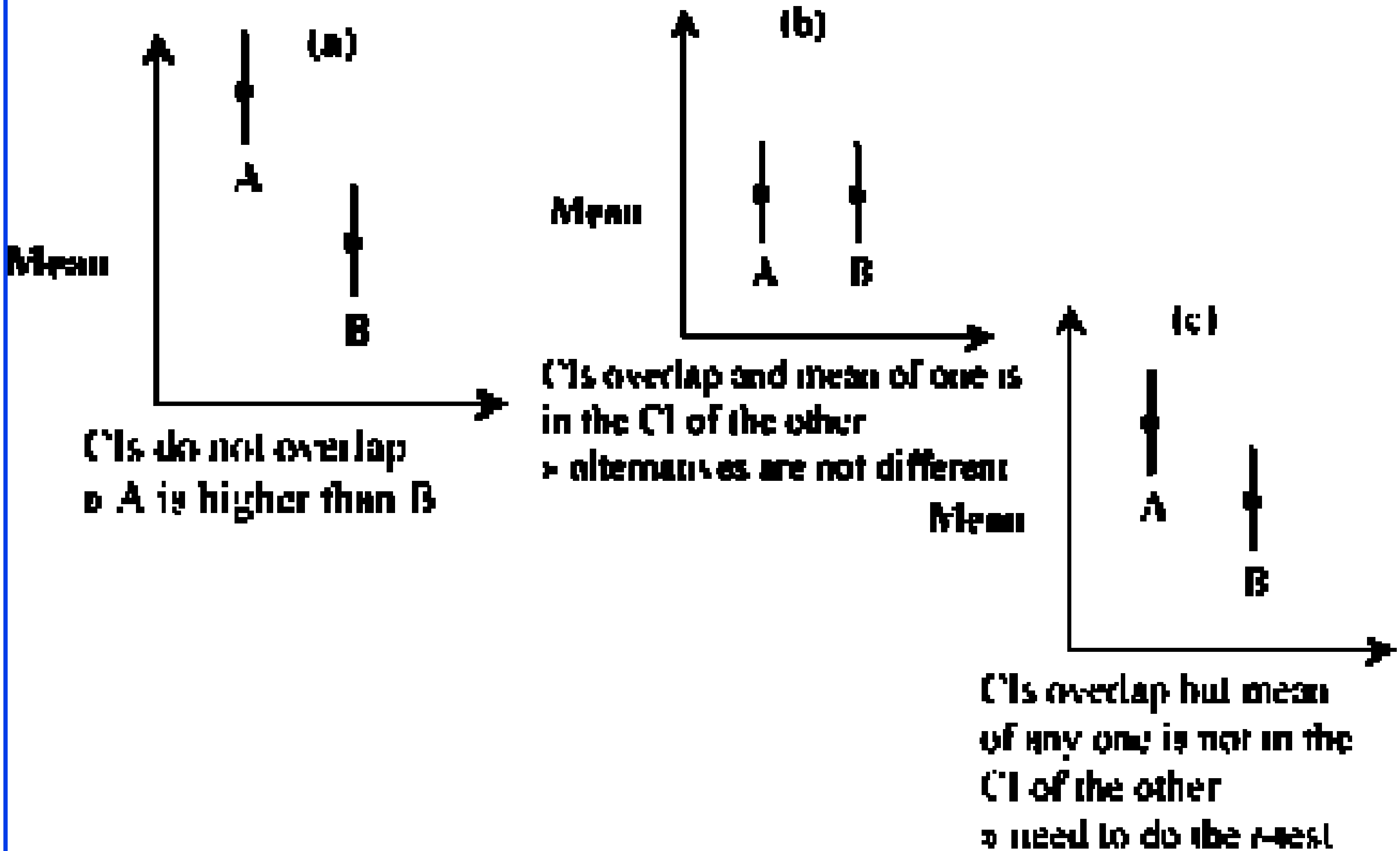
Effective number of degrees of freedom $f = 11.921$

The 0.95-quantile of a t-variate with 12 degrees of freedom $= 1.71$

The 90% confidence interval for the difference $= (-6.92, 6.26)$

- The confidence interval includes zero
  $\Rightarrow$ the two systems are not different.

Approximate Visual Test



Example 13.7

- Times on System A: {5.36, 16.57, 0.62, 1.41, 0.64, 7.26}
  Times on system B: {19.12, 3.52, 3.38, 2.50, 3.60, 1.74}
  $t_{[0.95, 5]} = 2.015$
- The 90% confidence interval for the mean of A = 5.31 ∓ (2.015) $\sqrt{(37.92/6)}$
  = (0.24, 10.38)
- The 90% confidence interval for the mean of B = 5.64 ∓ (2.015) $\sqrt{(44.11/6)}$
  = (0.18, 11.10)
- Confidence intervals overlap and the mean of one falls in the confidence interval for the other.
  ⇒ Two systems are not different at this level of confidence.

What Confidence Level To Use?

- Need not always be 90% or 95% or 99%
- Base on the loss that you would sustain if the parameter is outside the range and the gain you would have if the parameter is inside the range.
- Low loss ⇒ Low confidence level is fine

  E.g., lottery of 5 Million with probability 10^{-7}
- 90% confidence) buy nine million tickets
- 0.01% confidence level is fine.
- 50% confidence level may or may not be too low
- 99% confidence level may or may not be too high

Hypothesis Testing vs. Confidence Intervals

- Confidence interval provides more information
- Hypothesis test = yes-no decision
- Confidence interval also provides possible range
- Narrow confidence interval $\Rightarrow$ high degree of precision
- Wide confidence interval $\Rightarrow$ Low precision
- Example: (-100,100) $\Rightarrow$ No difference

  (-1,1) $\Rightarrow$ No difference
- Confidence intervals tell us not only what to say but also how loudly to say it
- CI is easier to explain to decision makers
- CI is more useful.

  E.g., parameter range (100, 200)

  vs. Probability of (parameter = 110) = 3%

One Sided Confidence Intervals

- Two side intervals: 90\% Confidence
  ⇒ P(Difference > upper limit) = 5%
  ⇒ P(Difference < Lower limit) = 5%
- One sided Question: Is the mean greater than 0?
  ⇒ One side confidence interval
- One sided lower confidence interval for μ:
  $$(\bar{x} - t_{[1-\alpha;n-1]}\frac{s}{\sqrt{n}}, \bar{x})$$
  Note t at 1-α (not 1-α/2)
- One sided upper confidence interval for μ:
  $$\left(\bar{x}, \bar{x} + t_{[1-\alpha;n-1]}\frac{s}{\sqrt{n}}\right)$$
- For large samples: Use z instead of t

Example 13.8

- Time between crashes

System	Number	Mean	Stdv
A	972	124.10	198.20
B	153	141.47	226.11

- Assume unpaired observations
- Mean difference:

$$\bar{x}_A - \bar{x}_B = 124.10 - 141.47 = -17.37$$

- Standard deviation of the difference:

$$s = \sqrt{\left(\frac{s_a^2}{n_a} + \frac{s_b^2}{n_b}\right)} = \sqrt{\frac{(198.20)^2}{972} + \frac{(226.11)^2}{153}} = 19.35$$

- Effective number of degrees of freedom:

Example 13.8 (Cont)

$$\begin{aligned}\nu &= \frac{\left(\frac{s_a^2}{n_a}+\frac{s_b^2}{n_b}\right)^2}{\frac{1}{n_a+1}\left(\frac{s_a^2}{n_a}\right)^2+\frac{1}{n_b+1}\left(\frac{s_b^2}{n_b}\right)^2}-2\\ &= \frac{\left(\frac{(198.20)^2}{972}+\frac{(226.11)^2}{153}\right)^2}{\frac{1}{972+1}\left(\frac{(198.20)^2}{972}\right)^2+\frac{1}{153+1}\left(\frac{(226.11)^2}{153}\right)^2}-2\\ &= 191.05\end{aligned}$$

- $\nu > 30 \Rightarrow$ Use z rather than t
- One sided test $\Rightarrow$ Use $z_{0.90}$=1.28 for 90% confidence
- 90% Confidence interval:

  (-17.37, -17.37+1.28 * 19.35)=(-17.37, 7.402)
- CI includes zero $\Rightarrow$ System A is not more susceptible to crashes than system B.

Confidence Intervals for Proportions

- Proportion = probabilities of various categories
  E.g., P(error)=0.01, P(No error)=0.99
- n_1 of n observations are of type 1 ⇒

$$\text{Sample proportion} = p = \frac{n_1}{n}$$

$$\text{Confidence interval for the proportion} = p \mp z_{1-\alpha/2}\sqrt{\frac{p(1-p)}{n}}$$

- Assumes Normal approximation of Binomial distribution
  ⇒ Valid only if $np \geq 10$.
- Need to use binomial tables if $np < 10$
  Can't use t-values

CI for Proportions (Cont)

- 100(1-α)% one sided confidence interval for the proportion: ‡

$$\left(p, p + z_{1-\alpha}\sqrt{\frac{p(1-p)}{n}}\right) \text{ or } \left(p - z_{1-\alpha}\sqrt{\frac{p(1-p)}{n}}, p\right)$$

‡Provided $np \geq 10$.

Example 13.9

- 10 out of 1000 pages printed on a laser printer are illegible.

$$\text{Sample proportion} = p = \frac{10}{1000} = 0.01$$

- np$\geq$ 10

$$\begin{aligned}\text{Confidence interval} &= p \mp z\sqrt{\frac{p(1-p)}{n}} \\ &= 0.01 \mp z\sqrt{\frac{0.01(0.99)}{1000}} = 0.01 \mp 0.003z\end{aligned}$$

- 90% confidence interval = 0.01 ∓ (1.645)(0.003)
  = (0.005, 0.015)
- 95% confidence interval = 0.01 ∓ (1.960)(0.003)
  = (0.004, 0.016)

Example 13.9 (Cont)

- At 90% confidence:
  0.5% to 1.5% of the pages are illegible
  Chances of error = 10%
- At 95% Confidence:
  0.4% to 1.6% of the pages are illegible
  Chances of error = 5%

Example 13.10

- 40 Repetitions on two systems: System A superior in 26 repetitions
- Question: With 99% confidence, is system A superior?

$$p = 26/40 = 0.65$$

- Standard deviation = $\sqrt{p*(1-p)/n} = 0.075$
- 99% confidence interval = $0.65 \mp (2.576)(0.075)$

$$= (0.46, 0.84)$$

- CI includes 0.5
  $\Rightarrow$ we cannot say with 99% confidence that system A is superior.
- 90% confidence interval = $0.65 \mp (1.645)(0.075) = (0.53, 0.77)$
- CI does not include 0.5
  $\Rightarrow$ Can say with 90% confidence that system A is superior.

Sample Size for Determining Mean

- Larger sample ⇒ Narrower confidence interval \R Higher confidence
- Question: How many observations n to get an accuracy of ± r% and a confidence level of 100(1-α)%?

$$\bar{x} \mp z\frac{s}{\sqrt{n}}$$

- r% Accuracy ⇒

$$\text{CI} = (\bar{x}(1 - r/100), \bar{x}(1 + r/100))$$

$$:\bar{x} \mp z\frac{s}{\sqrt{n}} = \bar{x}\left(1 \mp \frac{r}{100}\right)$$

$$z\frac{s}{\sqrt{n}} = \bar{x}\frac{r}{100}$$

$$n = \left(\frac{100zs}{r\bar{x}}\right)^2$$

Example 13.11

- Sample mean of the response time = 20 seconds

  Sample standard deviation = 5

  Question: How many repetitions are needed to get the response time accurate within 1 second at 95% confidence?
- Required accuracy = 1 in 20 = 5%

  Here, $\bar{x}$ = 20, s= 5, z= 1.960, and r=5,

$$n = \left(\frac{(100)(1.960)(5)}{(5)(20)}\right)^2 = (9.8)^2 = 96.04$$

A total of 97 observations are needed.

Sample Size for Determining Proportions

$$\text{Confidence interval for the proportion} = p \mp z\sqrt{\left(\frac{p(1-p)}{n}\right)}$$

To get a half-width (accuracy of) r:

$$p \mp r = p \mp z\sqrt{\left(\frac{p(1-p)}{n}\right)}$$

$$r = z\sqrt{\left(\frac{p(1-p)}{n}\right)}$$

$$n = z^2\frac{p(1-p)}{r^2}$$

Example 13.12

- Preliminary measurement : illegible print rate of 1 in 10,000.
- Question: How many pages must be observed to get an accuracy of 1 per million at 95% confidence?
- Answer:

$$p = 1/10000 = 1E-4, r = 1E-6, z = 1.960$$

$$n = (1.960)^2 \left(\frac{10^{-4}(1-10^{-4})}{(10^{-6})^2} \right) = 384160000$$

A total of 384.16 million pages must be observed.

Example 13.13

- Algorithm A loses 0.5% of packets and algorithm B loses 0.6%.
- Question: How many packets do we need to observe to state with 95% confidence that algorithm A is better than the algorithm B?
- Answer:

$$\text{CI for algorithm A} = 0.005 \mp 1.960 \left(\frac{0.005(1-0.005)}{n} \right)^{1/2}$$

$$\text{CI for algorithm B} = 0.006 \mp 1.960 \left(\frac{0.006(1-0.006)}{n} \right)^{1/2}$$

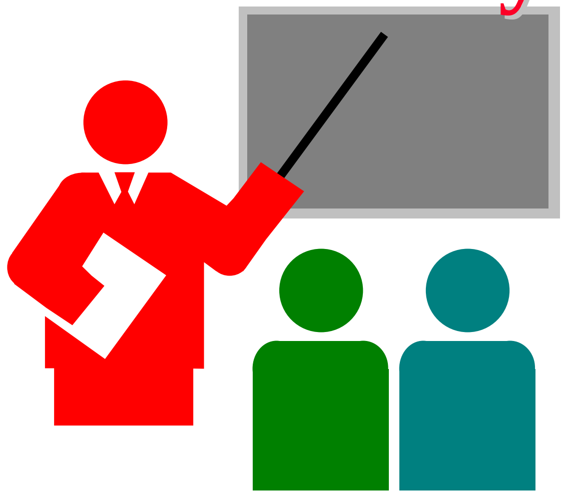
Example 13.13 (Cont)

- For non-overlapping intervals:

$$0.005 \mp 1.960 \left(\frac{0.005(1-0.005)}{n} \right)^{1/2}$$
$$\leq 0.006 \mp 1.960 \left(\frac{0.006(1-0.006)}{n} \right)^{1/2}$$

- n = 84340 $\Rightarrow$ We need to observe 85,000 packets.

Summary



- All statistics based on a sample are random and should be specified with a confidence interval
- If the confidence interval includes zero, the hypothesis that the population mean is zero cannot be rejected
- Paired observations Test the difference for zero mean
- Unpaired observations More sophisticated test
- Confidence intervals apply to proportions too.

Exercise 13.1

- Given two samples $\{x_1, x_2, \ldots, x_n\}$ and $\{y_1, y_2, \ldots, y_n\}$ from normal population $N(\mu,1)$, what is the distribution of:
  - Sample means: $\bar{x}$, $\bar{y}$
  - Difference of the means: $\bar{x}-\bar{y}$
  - Sum of the means: $\bar{x}+\bar{y}$
  - Mean of the means: $(\bar{x}+\bar{y})/2$
  - Normalized sample variances: s_x^2, s_y^2
  - Sum of sample variances: $s_x^2 + s_y^2$
  - Ratio of sample variances: s_x^2/s_y^2
  - Ratio $(\bar{x}-\mu)/s_x/\sqrt{n}$

Exercise 13.2

- Answer the following for the data of Exercise 12.1:
  - What is the 10-percentile and 90-percentile from the sample?
  - What is the mean number of disk I/Os per program?
  - What is the 90% confidence interval for the mean?
  - What fraction of programs make less than or equal to 25 I/Os and what is the 95% confidence interval for the fraction?
  - What is the one sided 90% confidence interval for the mean?

Exercise 13.3

- For the code size data of Table 11.2, find the confidence intervals for the average code sizes on various processors. Choose any two processors and answer the following:
  - At what level of significance, can you say that one is better than the other?
  - How many workloads would you need to decide the superiority at 90% confidence?

Homework

- Read chapter 13
- Submit solution to Exercise 13.2