MATH 450: Mathematical statistics

December 8th, 2020

Lecture 25: Review

Notes

- The exam will be on

  12/15/2020, Tuesday, 10:30am -12:30pm

  (note that this is **different** than our usual meeting time)

  The final exam will follow the same format as the midterm.
- There will a practice exam next lecture (Thursday)
- Please fill out the course evaluation before this Friday

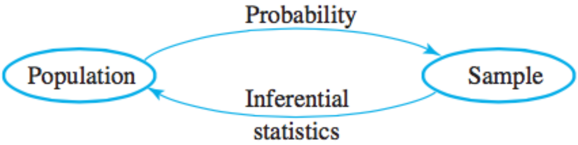
Overview

Week 1	Probability reviews
Week 2	Chapter 6: Statistics and Sampling Distributions
Week 4	Chapter 7: Point Estimation
Week 7	Chapter 8: Confidence Intervals
Week 10	Chapter 9, 10: Test of Hypothesis

Chapter 6: Statistics and Sampling Distributions

Chapter 6

Random sample



Definition

The random variables $X_1, X_2, ..., X_n$ are said to form a (simple) random sample of size n if

1. the X_i's are independent random variables
2. every X_i has the same probability distribution

1. If the distribution and the statistic T is simple, try to construct the pmf of the statistic
2. If the probability density function $f_X(x)$ of X's is known, the
   - try to represent/compute the cumulative distribution (cdf) of T
     $$\mathbb{P}[T \leq t]$$
   - take the derivative of the function (with respect to t)

Section 6.3: Linear combination of normal random variables

Theorem

Let $X_1, X_2, \ldots, X_n$be independent normal random variables (with possibly different means and/or variances). Then

$$T = a_1X_1 + a_2X_2 + \ldots + a_nX_n$$

also follows the normal distribution.

Section 6.3: Computations with normal random variables

If X has a normal distribution with mean μ and standard deviation σ, then

$$Z = \frac{X - \mu}{\sigma}$$

has a standard normal distribution. Thus

$$\begin{aligned} P(a \le X \le b) &= P\left(\frac{a-\mu}{\sigma} \le Z \le \frac{b-\mu}{\sigma}\right) \\ &= \Phi\left(\frac{b-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right) \end{aligned}$$

$$P(X \le a) = \Phi\left(\frac{a-\mu}{\sigma}\right) \quad P(X \ge b) = 1 - \Phi\left(\frac{b-\mu}{\sigma}\right)$$

Theorem

Let $X_1, X_2, \ldots, X_n$ be independent random variables (with possibly different means and/or variances). Define

$$T = a_1X_1 + a_2X_2 + \ldots + a_nX_n$$

then the mean and the standard deviation of T can be computed by

- $E(T) = a_1E(X_1) + a_2E(X_2) + \ldots + a_nE(X_n)$
- $\sigma_T^2 = a_1^2\sigma_{X_1}^2 + a_2^2\sigma_{X_2}^2 + \ldots + a_n^2\sigma_{X_n}^2$

Theorem

Let $X_1, X_2, \ldots, X_n$ be a random sample from a distribution with mean μ and variance σ^2. Then, in the limit when $n \to \infty$, the standardized version of $\bar{X}$ have the standard normal distribution

$$\lim_{n\to\infty} \mathbb{P}\left(\frac{\bar{X}-\mu}{\sigma/\sqrt{n}} \leq z\right) = \mathbb{P}[Z \leq z] = \Phi(z)$$

Rule of Thumb:

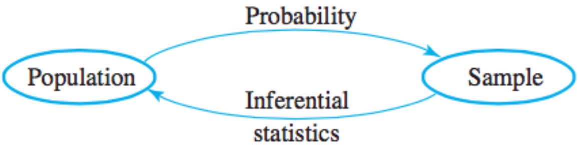
If $n > 30$, the Central Limit Theorem can be used for computation.

Chapter 7: Point Estimation

7.1 Point estimate
- unbiased estimator
- mean squared error

7.2 Methods of point estimation
- method of moments
- method of maximum likelihood.

Point estimate



Definition

A point estimate $\hat{\theta}$ of a parameter θ is a single number that can be regarded as a sensible value for θ.

$$\begin{array}{ccccc} \text{population parameter} & \Longrightarrow & \textit{sample} & \Longrightarrow & \textit{estimate} \\ \theta & \Longrightarrow & X_1, X_2, \ldots, X_n & \Longrightarrow & \hat{\theta} \end{array}$$

Definition

The mean squared error of an estimator $\hat{\theta}$ is

$$E[(\hat{\theta} - \theta)^2]$$

Theorem

$$MSE(\hat{\theta}) = E[(\hat{\theta} - \theta)^2] = V(\hat{\theta}) + \left(E(\hat{\theta}) - \theta\right)^2$$

Bias-variance decomposition

$$\text{Mean squared error} = \text{variance of estimator} + (bias)^2$$

Unbiased estimators

Definition

A point estimator $\hat{\theta}$ is said to be an unbiased estimator of θ if

$$E(\hat{\theta}) = \theta$$

for every possible value of θ.

Unbiased estimator

$\Leftrightarrow$ Bias $= 0$

$\Leftrightarrow$ Mean squared error $=$ variance of estimator

Method of moments: ideas

- Let $X_1, \ldots, X_n$ be a random sample from a distribution with pmf or pdf
$$f(x; \theta_1, \theta_2, \ldots, \theta_m)$$
- Assume that for $k = 1, \ldots, m$
$$\frac{X_1^k + X_2^k + \ldots + X_n^k}{n} = E(X^k)$$
- Solve the system of equations for $\theta_1, \theta_2, \ldots, \theta_m$

Maximum likelihood estimator

- Let $X_1, X_2, ..., X_n$ have joint pmf or pdf

$$f_{joint}(x_1, x_2, \ldots, x_n; \theta)$$

  where θ is unknown.

- When $x_1, \ldots, x_n$ are the observed sample values and this expression is regarded as a function of θ, it is called the likelihood function.
- The maximum likelihood estimates θ_{ML} are the value for θ that maximize the likelihood function:

$$f_{joint}(x_1, x_2, \ldots, x_n; \theta_{ML}) \geq f_{joint}(x_1, x_2, \ldots, x_n; \theta) \qquad \forall \theta$$

How to find the MLE?

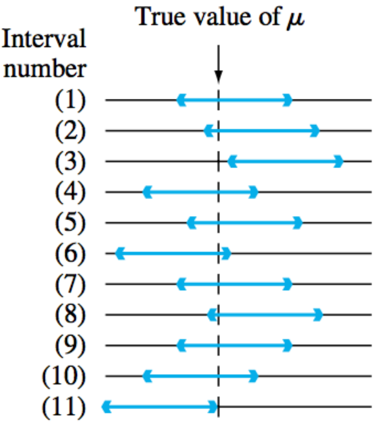
- Step 1: Write down the likelihood function.
- Step 2: Can you find the maximum of this function?
- Step 3: Try taking the logarithm of this function.
- Step 4: Find the maximum of this new function.

To find the maximum of a function of θ:

- compute the derivative of the function with respect to θ
- set this expression of the derivative to 0
- solve the equation

Chapters 8 and 10: Confidence intervals

Interpreting confidence interval



95% confidence interval: If we repeat the experiment many times, the interval contains μ about 95% of the time

Confidence intervals

- By target
  - Chapter 8: Confidence intervals for population means
  - Chapter 8: Prediction intervals for an additional sample
  - Chapter 10: Confidence intervals for difference between two population means
    - independent samples
    - paired samples
- By types
  - (Standard) two-sided confidence intervals
  - One-sided confidence intervals (confidence bounds)
- By distributions of the statistics
  - z-statistic
  - t-statistic

- Section 8.1
  - Normal distribution, σ is known
- Section 8.2
  - ~~Normal distribution~~, ~~σ is known~~
  - $n > 40$
- Section 8.3
  - Normal distribution, ~~σ is known~~
  - n is small

$\rightarrow$ t-distribution

Assumptions:

- Normal distribution
- σ is known

A $100(1-\alpha)\%$ **confidence interval** for the mean μ of a normal population when the value of σ is known is given by

$$\left(\bar{x} - z_{\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}, \bar{x} + z_{\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}\right) \tag{8.5}$$

or, equivalently, by $\bar{x} \pm z_{\alpha/2} \cdot \sigma/\sqrt{n}$.

If after observing $X_1, X_2, \ldots, X_n$ $(n > 40)$, we compute the observed sample mean $\bar{x}$ and sample standard deviation s. Then

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

is a 95% confidence interval of μ

Let $\overline{x}$ and s be the sample mean and sample standard deviation computed from the results of a random sample from a normal population with mean μ. Then a **100(1 − α)% confidence interval for μ**, the **one-sample t CI**, is

$$\left(\overline{x} - t_{\alpha/2,n-1} \cdot \frac{s}{\sqrt{n}}, \overline{x} + t_{\alpha/2,n-1} \cdot \frac{s}{\sqrt{n}}\right) \tag{8.15}$$

or, more compactly, $\overline{x} \pm t_{\alpha/2,n-1} \cdot s/\sqrt{n}$.

An **upper confidence bound for μ** is

$$\overline{x} + t_{\alpha,n-1} \cdot \frac{s}{\sqrt{n}}$$

and replacing + by − in this latter expression gives a **lower confidence bound for μ**; both have confidence level $100(1 - \alpha)\%$.

Prediction intervals

- We have available a random sample $X_1, X_2, \ldots, X_n$ from a normal population distribution
- We wish to predict the value of X_{n+1}, a single future observation.

A **prediction interval (PI)** for a single observation to be selected from a normal population distribution is

$$\bar{x} \pm t_{\alpha/2,n-1} \cdot s\sqrt{1 + \frac{1}{n}} \tag{8.16}$$

The *prediction level* is $100(1 - \alpha)\%$.

- Independent samples
  1. $X_1, X_2, \ldots, X_m$ is a random sample from a population with mean μ_1 and variance σ_1^2.
  2. $Y_1, Y_2, \ldots, Y_n$ is a random sample from a population with mean μ_2 and variance σ_2^2.
  3. The X and Y samples are independent of each other.
- Paired samples
  1. There is only one set of n individuals or experimental objects
  2. Two observations are made on each individual or object

Difference between population means: independent samples

The **two-sample t confidence interval for $\mu_1 - \mu_2$** with confidence level $100(1-\alpha)\%$ is then

$$\bar{x} - \bar{y} \pm t_{\alpha/2,\nu}\sqrt{\frac{s_1^2}{m} + \frac{s_2^2}{n}}$$

A one-sided confidence bound can be calculated as described earlier.

Difference between population means: paired samples

- The paired t CI for μ_D is

$$\bar{d} \pm t_{\alpha/2,n-1} \frac{s_D}{\sqrt{n}}$$

- A one-sided confidence bound results from retaining the relevant sign and replacing $t_{\alpha/2,n-1}$ by $t_{\alpha,n-1}$.

Principles for deriving CIs

If $X_1, X_2, \ldots, X_n$ is a random sample from a distribution $f(x, \theta)$, then

- Find a random variable $Y = h(X_1, X_2, \ldots, X_n; \theta)$ such that he probability distribution of Y does not depend on θ or on any other unknown parameters.
- Find constants a, b such that

$$P\left[a < h(X_1, X_2, \ldots, X_n; \theta) < b\right] = 1 - \alpha$$

- Manipulate these inequality to isolate θ

$$P\left[\ell(X_1, X_2, \ldots, X_n) < \theta < u(X_1, X_2, \ldots, X_n)\right] = 1 - \alpha$$

Examples

- For μ and X_{n+1}

$$\frac{\bar{X} - \mu}{S/\sqrt{n}} \sim t_{n-1}, \quad \frac{\bar{X} - X_{n+1}}{S\sqrt{1 + 1/n}} \sim t_{n-1}$$

- Difference between two means [independent samples]

$$\frac{(\bar{X} - \bar{Y}) - (\mu_1 - \mu_2)}{\sqrt{\frac{S_1^2}{m} + \frac{S_2^2}{n}}} \sim t_\nu$$

- Difference between two means [paired samples]

$$T = \frac{\bar{D} - \mu_D}{S_D/\sqrt{n}} \sim t_{n-1}$$

Chapters 9 and 10: Tests of hypotheses

Test of hypotheses

- By target
  - Chapter 9: population mean
  - Chapter 10: difference between two population means
    - independent samples
    - paired samples
- By the alternative hypothesis
  - $>$
  - $<$
  - $\neq$
- By the type of test
  - z-test
  - t-test
- By method of testing
  - Rejection region
  - p-value

Hypothesis testing

In any hypothesis-testing problem, there are two contradictory hypotheses under consideration

- The null hypothesis, denoted by H_0, is the claim that is initially assumed to be true
- The alternative hypothesis, denoted by H_a, is the assertion that is contradictory to H_0.

Implicit rules

- H_0 will always be stated as an equality claim.
- If θ denotes the parameter of interest, the null hypothesis will have the form
$$H_0 : \theta = \theta_0$$
- θ_0 is a specified number called the *null value*
- The alternative hypothesis will be either:
  - $H_a : \theta > \theta_0$
  - $H_a : \theta < \theta_0$
  - $H_a : \theta \neq \theta_0$

Test procedures

A test procedure is specified by the following:

- A test statistic T: a function of the sample data on which the decision (reject H_0 or do not reject H_0) is to be based
- A rejection region $\mathcal{R}$: the set of all test statistic values for which H_0 will be rejected
- A type I error consists of rejecting the null hypothesis H_0 when it is true
- A type II error involves not rejecting H_0 when H_0 is false.

Hypothesis testing for one parameter: rejection region method

1. Identify the parameter of interest
2. Determine the null value and state the null hypothesis
3. State the appropriate alternative hypothesis
4. Give the formula for the test statistic
5. State the rejection region for the selected significance level α
6. Compute statistic value from data
7. Decide whether H_0 should be rejected and state this conclusion in the problem context

Null hypothesis: $\mu = \mu_0$

Test statistic:

$$Z = \frac{\bar{X} - \mu_0}{\sigma/\sqrt{n}}$$

Alternative Hypothesis	**Rejection Region for Level α Test**
H_a: $\mu > \mu_0$	$z \geq z_\alpha$ (upper-tailed test)
H_a: $\mu < \mu_0$	$z \leq -z_\alpha$ (lower-tailed test)
H_a: $\mu \neq \mu_0$	either $z \geq z_{\alpha/2}$ or $z \leq -z_{\alpha/2}$ (two-tailed test)

Null hypothesis: $\mu = \mu_0$
Test statistic:

$$Z = \frac{\bar{X} - \mu_0}{S/\sqrt{n}}$$

Alternative Hypothesis	Rejection Region for Level α Test
H_a: $\mu > \mu_0$	$z \geq z_\alpha$ (upper-tailed test)
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H_a: $\mu \neq \mu_0$	either $z \geq z_{\alpha/2}$ or $z \leq -z_{\alpha/2}$ (two-tailed test)

[Does not need the normal assumption]

t-test

Null hypothesis: H_0: $\mu = \mu_0$

Test statistic value: $t = \dfrac{\bar{x} - \mu_0}{s/\sqrt{n}}$

Alternative Hypothesis	**Rejection Region for a Level α Test**
H_a: $\mu > \mu_0$	$t \geq t_{\alpha,n-1}$ (upper-tailed)
H_a: $\mu < \mu_0$	$t \leq -t_{\alpha,n-1}$ (lower-tailed)
H_a: $\mu \neq \mu_0$	either $t \geq t_{\alpha/2,n-1}$ or $t \leq -t_{\alpha/2,n-1}$ (two-tailed)

[Require normal assumption]

DEFINITION The ***P*-value** (or *observed significance level*) is the smallest level of significance at which H_0 would be rejected when a specified test procedure is used on a given data set. Once the P-value has been determined, the conclusion at any particular level α results from comparing the P-value to α:

1. P-value $\leq \alpha \Rightarrow$ reject H_0 at level α.
2. P-value $> \alpha \Rightarrow$ do not reject H_0 at level α.

P-values for z-tests

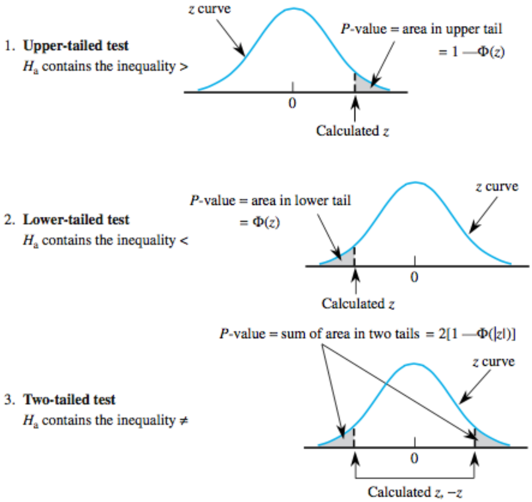

Figure 9.7 Determination of the P-value for a z test

P-values for t-tests

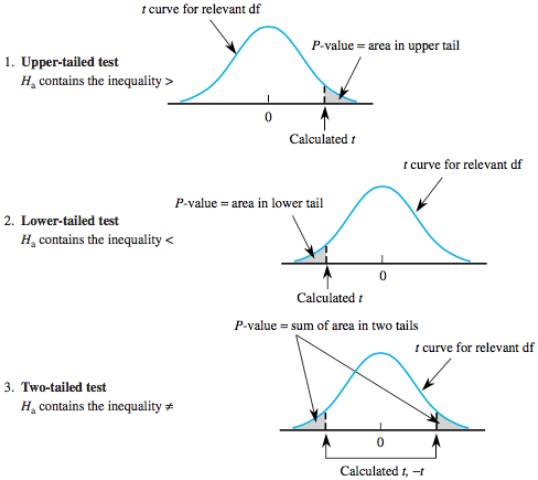

Figure 9.8 P-values for t tests

Testing by rejection region method

- Parameter of interest: μ = true average activation temperature
- Hypotheses

$$H_0 : \mu = 130$$
$$H_a : \mu \neq 130$$

- Test statistic:

$$z = \frac{\bar{x} - 130}{1.5/\sqrt{n}}$$

- Rejection region: either $z \leq -z_{0.005}$ or $z \geq z_{0.005} = 2.58$
- Substituting $\bar{x} = 131.08$, $n = 25 \rightarrow z = 2.16$.
- Note that $-2.58 < 2.16 < 2.58$. We fail to reject H_0 at significance level 0.01.
- The data does not give strong support to the claim that the true average differs from the design value.

1. Parameter of interest: μ = true average wafer thickness
2. Null hypothesis: H_0: $\mu = 245$
3. Alternative hypothesis: H_a: $\mu \neq 245$
4. Formula for test statistic value: $z = \dfrac{\bar{x} - 245}{s/\sqrt{n}}$
5. Calculation of test statistic value: $z = \dfrac{246.18 - 245}{3.60/\sqrt{50}} = 2.32$
6. Determination of P-value: Because the test is two-tailed,

$$P\text{-value} = 2[1 - \Phi(2.32)] = .0204$$

7. Conclusion: Using a significance level of .01, H_0 would not be rejected since $.0204 > .01$. At this significance level, there is insufficient evidence to conclude that true average thickness differs from the target value.

Interpreting P-values

A P-value:

- is not the probability that H_0 is true
- is not the probability of rejecting H_0
- is the probability, calculated assuming that H_0 is true, of obtaining a test statistic value at least as contradictory to the null hypothesis as the value that actually resulted

Testing the difference between two population means

- Setting: independent normal random samples $X_1, X_2, \dots, X_m$ and $Y_1, Y_2, \dots, Y_n$ with known values of σ_1 and σ_2. Constant Δ_0.
- Null hypothesis:

$$H_0 : \mu_1 - \mu_2 = \Delta_0$$

- Alternative hypothesis:
  (a) $H_a : \mu_1 - \mu_2 > \Delta_0$
  (b) $H_a : \mu_1 - \mu_2 < \Delta_0$
  (c) $H_a : \mu_1 - \mu_2 \neq \Delta_0$
- When $\Delta = 0$, the test (c) becomes

$$H_0 : \mu_1 = \mu_2$$
$$H_a : \mu_1 \neq \mu_2$$

Difference between 2 means (independent samples)

Proposition

The **two-sample t test** for testing H_0: $\mu_1 - \mu_2 = \Delta_0$ is as follows:

$$\text{Test statistic value: } t = \frac{\bar{x} - \bar{y} - \Delta_0}{\sqrt{\dfrac{s_1^2}{m} + \dfrac{s_2^2}{n}}}$$

Alternative Hypothesis	**Rejection Region for Approximate Level α Test**
H_a: $\mu_1 - \mu_2 > \Delta_0$	$t \geq t_{\alpha,\nu}$ (upper-tailed test)
H_a: $\mu_1 - \mu_2 < \Delta_0$	$t \leq -t_{\alpha,\nu}$ (lower-tailed test)
H_a: $\mu_1 - \mu_2 \neq \Delta_0$	either $t \geq t_{\alpha/2,\nu}$ or $t \leq -t_{\alpha/2,\nu}$ (two-tailed test)

A P-value can be computed as described in Section 9.4 for the one-sample t test.

The paired t-test

Idea: to test hypotheses about $\mu_1 - \mu_2$ when data is paired:

1. form the differences $D_1, D_2, \ldots, D_n$
2. carry out a one-sample t-test (based on $n - 1$ df) on the differences.

THE PAIRED t TEST

Null hypothesis: H_0: $\mu_D = \Delta_0$ (where $D = X - Y$ is the difference between the first and second observations within a pair, and $\mu_D = \mu_1 - \mu_2$)

Test statistic value: $t = \dfrac{\overline{d} - \Delta_0}{s_D/\sqrt{n}}$ (where $\overline{d}$ and s_D are the sample mean and standard deviation, respectively, of the d_i's)

Alternative Hypothesis	**Rejection Region for Level α Test**
H_a: $\mu_D > \Delta_0$	$t \geq t_{\alpha,n-1}$
H_a: $\mu_D < \Delta_0$	$t \leq -t_{\alpha,n-1}$
H_a: $\mu_D \neq \Delta_0$	either $t \geq t_{\alpha/2,n-1}$ or $t \leq -t_{\alpha/2,n-1}$

A P-value can be calculated as was done for earlier t tests.

Practice problems

Problem 1

A company that makes cola drinks states that the mean caffeine content per one 12-ounce bottle of cola is 40 milligrams. You work as a quality control manager and are asked to test this claim. During your tests, you find that a random sample of 30 bottles of cola (12-ounce) has a mean caffeine content of 39.2 milligrams. From a previous study, you know that the standard deviation of the population is $\sigma = 7.5$ milligrams. We assume that the caffeine content is normally distributed.

(a) (20 points) At α= 1% level of significant, can you reject the company's claim? What is the P-value associated with the test?

Problem 2

(20 points) In an experiment designed to study the effects of illumination level on task performance, subjects were required to insert a netipped probe into the eyeholes of ten needles in rapid succession both for a low light level with a black background and a higher level with a white background. Each data value is the time (sec) required to complete the task.

Subject	1	2	3	4	5
Black	25.85	28.84	32.05	25.74	20.89
White	18.23	20.84	22.96	19.68	19.50

Subject	6	7	8	9
Black	41.05	25.01	24.96	27.47
White	24.98	16.61	16.07	24.59

Does the data indicate that the higher level of illumination yields a decrease of more than 5 sec in true average task completion time with significance level $\alpha = 0.01$?

Problem 3

Let $0 < \theta < \infty$ and $X_1, X_2, \ldots, X_n$ sample from a distribution with density function

$$f(x;\theta) = \frac{1}{\theta}, \quad 0 \leq x \leq \theta.$$

(a) (20 points) Construct an estimator of θ by the method of moments.

Problem 4

3. (20 points) Extensive monitoring of a computer time-sharing system has suggested that response time to a particular editing command is normally distributed with standard deviation 30 ms.

   A new operating system has been installed, and we wish to estimate the true average response time μ for the new environment. Assuming that response times are still normally distributed with $\sigma = 30$, what sample size is necessary to ensure that the resulting 90% CI has a width of (at most) 10?

Problem 5

As the population ages, there is increasing concern about accident-related injuries to the elderly. An article reported on an experiment in which the maximum lean angle (the furthest a subject is able to lean and still recover in one step) was determined for both a sample of younger females (21–29 years) and a sample of older females (67–81years). The following observations are consistent with summary data given in the article:

- Younger females: 29, 34, 33, 27, 28, 32, 31, 34, 32, 27
- Older females: 18, 15, 23, 13, 12.

The data are assumed to be normally distributed.

(a) (20 points) Calculate a 90% confidence interval for the difference between the true average maximum lean angles of younger females and of older females.