

Purpose and Nature of Sampling

- **Nature:** only incomplete view of a true picture available in real life
- **Purpose:** to describe a clearly defined population on the basis of sample information
- **Statistics:** Various functions of the data may be used to calculate measures, each of which is a reflection of some special feature of the population. These sample measure are called **statistics**

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Measure of Central Tendency (Location)

- **Sample Mean:** of a set of numbers (**lower case in expressions**) x_1, x_2, \dots, x_n is given by

$$\bar{x} = \frac{x_1 + \dots + x_n}{n} = \frac{\sum_{i=1}^n x_i}{n}$$

- **Note:**
 - sample mean is a “statistic” and is not a true mean but an estimate of mean

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Measure of Dispersion

- **Sample Variance** of the set x_1, x_2, \dots, x_n of **numerical observations**, denoted by s^2 is given by

$$s^2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}$$

Degree of freedom= $n-1$
Why not n ?

- Sample variance is a statistic used to estimate variance
- The **sample standard deviation**, denoted by s , is the positive square root of the sample variance

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Degree of Freedom (DoF)

- DoF: the number of **independent** pieces of information
- DoF=the number of values **free to vary** in calculation of a statistic
- Suppose there are n observations $x_i, i=1, \dots, n$. To calculate the sample mean, there are n independent pieces of information available for calculation of the statistic:

$$\bar{x} = \frac{x_1 + \dots + x_n}{n} = \frac{\sum_{i=1}^n x_i}{n}$$

DoF= n

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DoF of $x_i - \bar{x}$

- x_i -average is called *residual* or *centered-measure* and $\Sigma(x_i\text{-average})=0$
- Let $n=3$; $x_1=1, x_2=2, x_3=3$; average $=(1+2+3)/3=2$
- That is, if we know x_1 -average $(=-1)$ and x_2 -average $(=0)$, then x_3 -average must be known $(=1)$
 → If you know two of x_i -average, you know the third. The **number of values free to vary** is 2!
- How many independent pieces of information do we have about $(x_i\text{-average})$? **Answer: 2**
- For x_i -average, $i=1, \dots, n$, there are only $n-1$ pieces of independent information that are free to vary because the average has taken one piece of information and the n th value is subject to zero sum.

Taking average of $(x_i\text{-average})^2$

- Again, let $n=3$ and $x_1=1, x_2=2, x_3=3$
- x_1 -average $=-1$; x_2 -average $=0$, and x_3 -average $=1$
- What is the good estimate of $E(x\text{-mean})^2$?
 $\Sigma(x_i\text{-average})^2/3$ or $\Sigma(x_i\text{-average})^2/2$?
- $\Sigma(x_i\text{-average})^2/3=2/3$ or $\Sigma(x_i\text{-average})^2/2=1$
 more plausible?
 $\Sigma(x_i\text{-average})^2/2!$

More on the DoF of $(x_i - \text{average})^2$

- Average is used to estimate the mean
 - What if “median” is used to estimate of mean?
 - Again, let $n=3$ and $x_1=1, x_2=2, x_3=3$: median= x_2
 - DoF of $(x_i - \text{median})^2$?
 - Since x_2 has been used to estimate the mean, only $x_1 - \text{median} = -1$ and $x_3 - \text{median} = 1$ are left to estimate the distance from the center!
- The estimate of $E(x - \text{mean})^2$? $\Sigma(x_i - \text{median})^2/2$

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Sample Covariance

- **There must be correlations among measurements. For example, the higher blood pressure level often comes with the higher cholesterol level.**
- **The co-variation of two measurements is measured by sample covariance: (the trend that one is larger then the other is larger or one is smaller then the other is smaller)**

$$\text{Cov}(x, y) = s_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}_i)}{n-1}$$

- $X \uparrow, Y \uparrow \Rightarrow \text{Cov} > 0$: positively correlated
- $X \uparrow, Y \downarrow \Rightarrow \text{Cov} < 0$: negatively correlated

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Sample Correlation Coefficient

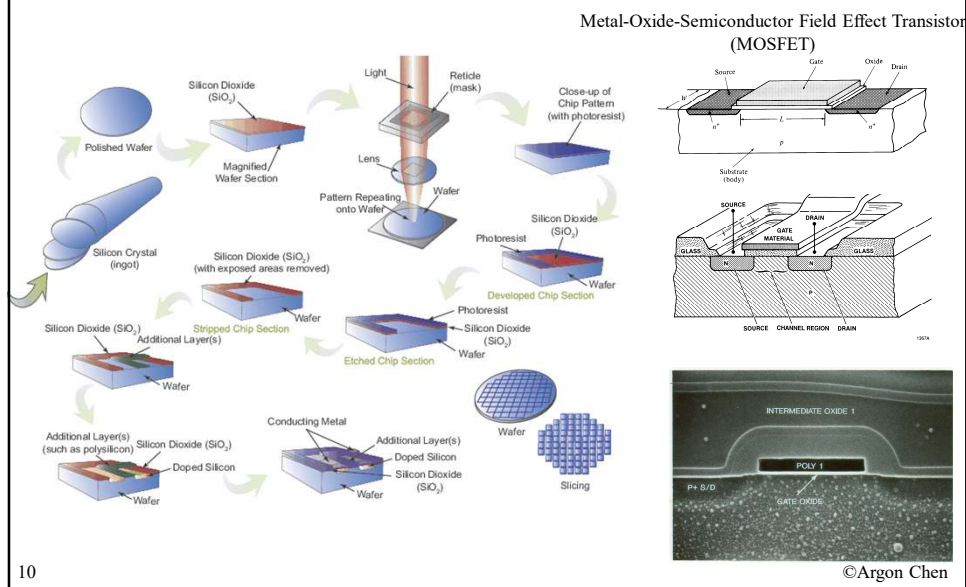
- Correlation coefficient is defined as ρ ($-1 \leq \rho_{xy} \leq 1$):

$$\rho_{xy} = \frac{s_{xy}}{s_x s_y} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}$$

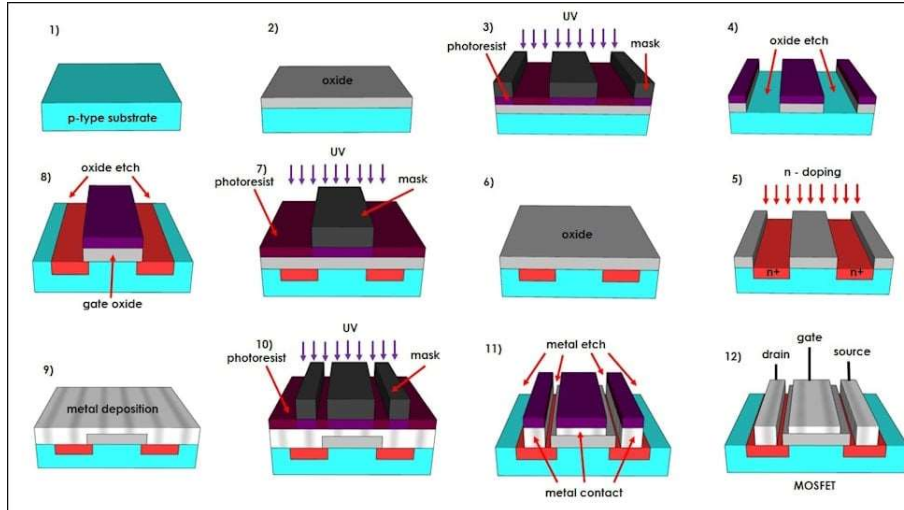
- $-1 \leq \rho_{xy} < 0$: negatively correlated; $0 < \rho_{xy} \leq 1$: positively correlated
- $\rho_{xy} = 0$: no correlation; $\rho_{xy} = \pm 1$: perfect correlation
- Let $x' = (x - \bar{x})/s_x$ and $y' = (y - \bar{y})/s_y$
 $\rightarrow \text{Cov}(x', y') = \rho_{xy}$

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Semiconductor Manufacturing



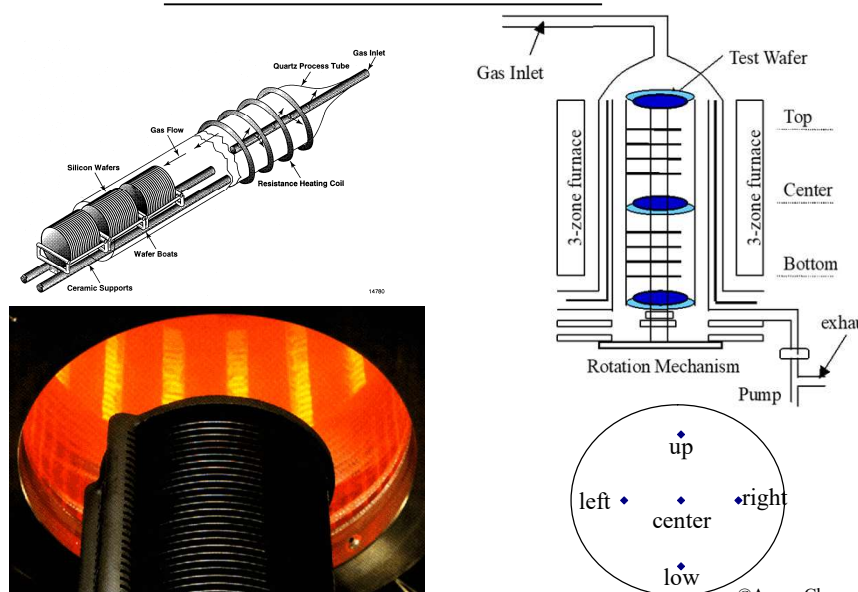
MOSFET Fabrication



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Oxidation Furnace



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Thickness of SiO₂ Layer

- Example: 85 readings of SiO₂ average thickness (with target thickness=350Å) are collected

| Recipe | Thickness target | Thickness (Top Zone) | | | | | Thickness (Center Zone) | | | | | Thickness (Bottom Zone) | | | | | Average |
|---------|------------------|----------------------|--------|-------|------|-------|-------------------------|--------|-------|------|-------|-------------------------|--------|-------|------|-------|---------|
| | | Upper | Center | Lower | Left | Right | Upper | Center | Lower | Left | Right | Upper | Center | Lower | Left | Right | |
| F38C-13 | 350 | 349 | 349 | 352 | 347 | 353 | 352 | 352 | 353 | 351 | 354 | 355 | 351 | 350 | 352 | 350 | 352.33 |
| F38C-13 | 350 | 347 | 349 | 352 | 349 | 353 | 354 | 353 | 354 | 352 | 354 | 353 | 351 | 350 | 352 | 354 | 352.40 |
| F38C-13 | 350 | 350 | 352 | 349 | 354 | 353 | 355 | 356 | 355 | 354 | 356 | 353 | 357 | 362 | 355 | 361 | 354.80 |
| F38C-13 | 350 | 346 | 348 | 351 | 346 | 351 | 352 | 352 | 352 | 349 | 353 | 351 | 351 | 357 | 352 | 357 | 351.20 |
| F38C-13 | 350 | 347 | 349 | 350 | 349 | 351 | 351 | 352 | 351 | 350 | 353 | 350 | 353 | 356 | 353 | 357 | 351.47 |
| F38C-13 | 350 | 345 | 348 | 350 | 346 | 350 | 350 | 352 | 350 | 348 | 352 | 351 | 351 | 353 | 351 | 356 | 350.20 |
| F38C-13 | 350 | 349 | 350 | 353 | 349 | 353 | 354 | 354 | 354 | 351 | 355 | 351 | 352 | 360 | 353 | 362 | 353.33 |
| F38C-13 | 350 | 348 | 349 | 351 | 347 | 351 | 352 | 352 | 352 | 350 | 353 | 352 | 350 | 357 | 350 | 357 | 351.40 |
| F38C-13 | 350 | 349 | 351 | 353 | 348 | 353 | 354 | 354 | 353 | 352 | 354 | 353 | 353 | 359 | 352 | 358 | 353.07 |
| F38C-13 | 350 | 351 | 353 | 355 | 354 | 358 | 352 | 353 | 353 | 351 | 354 | 353 | 353 | 355 | 351 | 360 | 353.73 |
| F38C-13 | 350 | 351 | 352 | 354 | 353 | 357 | 353 | 352 | 353 | 351 | 353 | 353 | 353 | 354 | 351 | 358 | 353.27 |
| F38C-13 | 350 | 347 | 347 | 349 | 346 | 349 | 351 | 352 | 352 | 351 | 353 | 349 | 350 | 359 | 352 | 356 | 350.87 |
| F38C-13 | 350 | 347 | 349 | 351 | 347 | 350 | 352 | 352 | 351 | 348 | 351 | 350 | 351 | 361 | 350 | 359 | 351.50 |
| F38C-13 | 350 | 348 | 349 | 349 | 348 | 351 | 352 | 353 | 352 | 351 | 354 | 351 | 351 | 360 | 351 | 360 | 352.07 |
| F38C-13 | 350 | 347 | 349 | 351 | 346 | 351 | 352 | 352 | 350 | 353 | 352 | 349 | 351 | 360 | 351 | 358 | 351.47 |
| F38C-13 | 350 | 347 | 349 | 350 | 346 | 350 | 351 | 351 | 350 | 352 | 351 | 349 | 350 | 359 | 351 | 357 | 350.87 |
| F38C-13 | 350 | 348 | 342 | 353 | 290 | 251 | 252 | 352 | 352 | 354 | 354 | 359 | 366 | 374 | 369 | 374 | 357.33 |
| F38C-13 | 350 | 350 | 355 | 357 | 354 | 356 | 338 | 359 | 338 | 342 | 340 | 356 | 351 | 361 | 357 | 361 | 356.73 |
| F38C-13 | 350 | 352 | 350 | 355 | 350 | 356 | 340 | 344 | 345 | 347 | 345 | 355 | 354 | 360 | 356 | 362 | 352.43 |
| F38C-13 | 350 | 348 | 346 | 349 | 345 | 353 | 344 | 343 | 343 | 343 | 345 | 353 | 352 | 363 | 353 | 362 | 349.47 |
| F38C-13 | 350 | 351 | 347 | 352 | 348 | 357 | 345 | 345 | 344 | 346 | 345 | 354 | 353 | 364 | 354 | 364 | 351.27 |
| F38C-13 | 350 | 351 | 349 | 353 | 349 | 356 | 340 | 346 | 345 | 346 | 347 | 354 | 354 | 360 | 356 | 360 | 351.47 |
| F38C-13 | 350 | 350 | 349 | 353 | 350 | 358 | 348 | 350 | 346 | 346 | 350 | 358 | 356 | 366 | 357 | 366 | 353.53 |
| F38C-13 | 350 | 350 | 349 | 352 | 350 | 358 | 348 | 350 | 346 | 347 | 350 | 358 | 355 | 365 | 357 | 366 | 353.40 |
| F38C-13 | 350 | 352 | 351 | 355 | 350 | 358 | 348 | 348 | 346 | 346 | 349 | 356 | 353 | 365 | 356 | 364 | 353.13 |
| F38C-13 | 350 | 350 | 350 | 350 | 349 | 353 | 344 | 344 | 345 | 343 | 346 | 353 | 346 | 358 | 355 | 358 | 344.27 |
| F38C-13 | 350 | 347 | 348 | 351 | 347 | 350 | 337 | 337 | 338 | 336 | 339 | 351 | 349 | 361 | 351 | 361 | 346.87 |
| F38C-13 | 350 | 349 | 350 | 353 | 349 | 355 | 344 | 344 | 345 | 344 | 346 | 350 | 349 | 348 | 349 | 350 | 348.33 |
| F38C-13 | 350 | 349 | 349 | 351 | 349 | 355 | 345 | 345 | 346 | 345 | 348 | 352 | 352 | 364 | 354 | 361 | 351.00 |
| F38C-13 | 350 | 349 | 350 | 354 | 350 | 354 | 344 | 345 | 345 | 345 | 346 | 351 | 357 | 363 | 353 | 361 | 351.13 |
| F38C-13 | 350 | 348 | 350 | 353 | 348 | 354 | 345 | 345 | 345 | 344 | 347 | 352 | 352 | 364 | 354 | 362 | 350.87 |
| F38C-13 | 350 | 352 | 350 | 352 | 348 | 355 | 349 | 349 | 348 | 348 | 350 | 349 | 351 | 363 | 352 | 362 | 351.87 |
| F38C-13 | 350 | 351 | 349 | 351 | 347 | 354 | 349 | 350 | 348 | 350 | 349 | 349 | 351 | 362 | 351 | 361 | 351.47 |
| F38C-13 | 350 | 347 | 350 | 351 | 347 | 353 | 348 | 348 | 348 | 345 | 348 | 347 | 348 | 361 | 349 | 358 | 349.93 |
| F38C-13 | 350 | 347 | 351 | 350 | 348 | 353 | 348 | 349 | 348 | 345 | 348 | 347 | 348 | 360 | 349 | 351 | 349.47 |
| F38C-13 | 350 | 349 | 350 | 351 | 348 | 349 | 354 | 350 | 360 | 350 | 350 | 352 | 351 | 354 | 349 | 350 | 351.73 |
| F38C-13 | 350 | 344 | 344 | 348 | 343 | 349 | 346 | 344 | 344 | 342 | 345 | 347 | 343 | 353 | 344 | 353 | 345.93 |
| F38C-13 | 350 | 351 | 351 | 354 | 351 | 354 | 342 | 342 | 343 | 340 | 344 | 352 | 350 | 360 | 350 | 361 | 349.07 |
| F38C-13 | 350 | 352 | 352 | 354 | 351 | 354 | 349 | 349 | 349 | 347 | 351 | 350 | 350 | 352 | 348 | 352 | 351.33 |
| F38C-13 | 350 | 350 | 349 | 353 | 349 | 354 | 349 | 348 | 348 | 347 | 350 | 351 | 350 | 360 | 352 | 360 | 351.33 |
| F38C-13 | 350 | 352 | 352 | 354 | 351 | 355 | 349 | 349 | 348 | 347 | 349 | 349 | 349 | 359 | 349 | 359 | 350.73 |
| F38C-13 | 350 | 350 | 350 | 354 | 349 | 355 | 349 | 349 | 349 | 346 | 349 | 353 | 351 | 362 | 351 | 362 | 352.07 |
| F38C-13 | 350 | 348 | 348 | 352 | 347 | 351 | 339 | 340 | 341 | 338 | 342 | 351 | 349 | 358 | 351 | 358 | 347.53 |
| F38C-13 | 350 | 350 | 351 | 353 | 349 | 355 | 350 | 350 | 348 | 347 | 351 | 351 | 352 | 361 | 352 | 360 | 352.00 |
| F38C-13 | 350 | 349 | 349 | 352 | 348 | 354 | 349 | 350 | 349 | 349 | 351 | 351 | 353 | 360 | 353 | 361 | 351.87 |
| F38C-13 | 350 | 351 | 351 | 353 | 351 | 354 | 343 | 343 | 342 | 342 | 344 | 354 | 355 | 362 | 355 | 362 | 352.00 |
| F38C-13 | 350 | 352 | 353 | 355 | 352 | 355 | 342 | 344 | 345 | 342 | 342 | 356 | 355 | 364 | 356 | 364 | 352.00 |
| F38C-13 | 350 | 351 | 352 | 353 | 350 | 357 | 350 | 350 | 349 | 348 | 350 | 351 | 350 | 360 | 351 | 360 | 352.07 |
| F38C-13 | 350 | 350 | 350 | 353 | 350 | 357 | 350 | 350 | 349 | 348 | 350 | 352 | 351 | 360 | 351 | 360 | 352.07 |
| F38C-13 | 350 | 352 | 352 | 354 | 351 | 354 | 345 | 345 | 345 | 345 | 345 | 355 | 355 | 364 | 355 | 364 | 352.33 |
| F38C-13 | 350 | 350 | 351 | 353 | 349 | 353 | 349 | 349 | 350 | 347 | 350 | 349 | 347 | 357 | 348 | 359 | 350.67 |
| F38C-13 | 350 | 350 | 350 | 354 | 350 | 355 | 351 | 351 | 350 | 348 | 352 | 350 | 349 | 359 | 350 | 350 | 351.87 |
| F38C-13 | 350 | 348 | 348 | 345 | 348 | 353 | 350 | 350 | 350 | 348 | 351 | 349 | 348 | 357 | 349 | 358 | 350.80 |
| F38C-13 | 350 | 348 | 348 | 345 | 348 | 349 | 345 | 346 | 355 | 345 | 356 | 348 | 347 | 348 | 349 | 351 | 347.53 |
| F38C-13 | 350 | 348 | 348 | 346 | 347 | 349 | 345 | 346 | 354 | 346 | 355 | 348 | 347 | 349 | 350 | 351 | 347.87 |
| F38C-13 | 350 | 346 | 346 | 349 | 344 | 351 | 348 | 345 | 348 | 346 | 348 | 345 | 346 | 345 | 346 | 355 | 347.87 |

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Frequency Distribution

- Example: frequency distribution is calculated for 85 readings of SiO₂ average

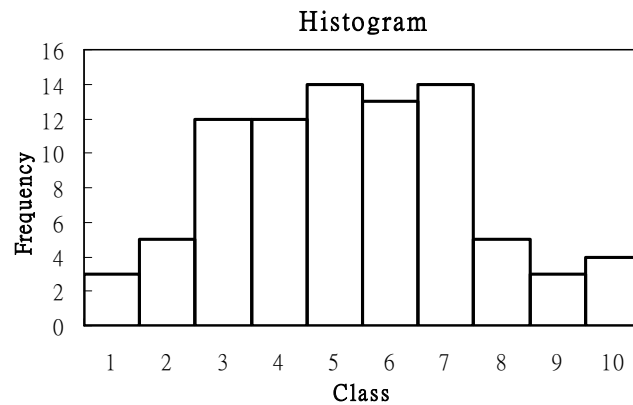
| | Class Interval | Frequency= <i>fi</i> | Relative Freq.= <i>fi</i> /Total |
|----|----------------|----------------------|----------------------------------|
| 1 | ~346.5 | 3 | 0.0353 |
| 2 | 346.6~347.5 | 5 | 0.0588 |
| 3 | 347.6~348.5 | 12 | 0.1412 |
| 4 | 348.6~349.5 | 12 | 0.1412 |
| 5 | 349.6~350.5 | 14 | 0.1647 |
| 6 | 350.6~351.5 | 13 | 0.1529 |
| 7 | 351.6~352.5 | 14 | 0.1647 |
| 8 | 352.6~353.5 | 5 | 0.0588 |
| 9 | 353.6~354.5 | 3 | 0.0353 |
| 10 | 354.6~ | 4 | 0.0471 |
| | Total | 85 | |

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Histograms

- Example: 350Å SiO₂ thickness data



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The Box Plot

The Five-Number Summary:

Min ----- Q₁ ----- Median ----- Q₃ ----- Max

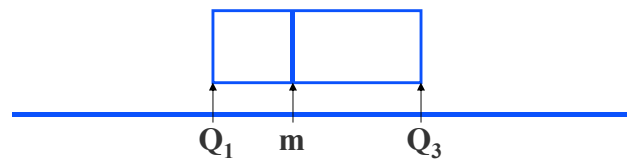
- Divides the data into 4 sets containing an equal number of measurements.
- A quick summary of the data distribution.
- Use to form a **box plot** to describe the **shape** of the distribution and to detect **outliers**.

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Constructing a Box Plot

- ✓ Calculate Q_1 , the median, Q_3 and $IQR(=Q_3-Q_1)$.
- ✓ Draw a horizontal line to represent the scale of measurement.
- ✓ Draw a box using Q_1 , the median m , Q_3 .

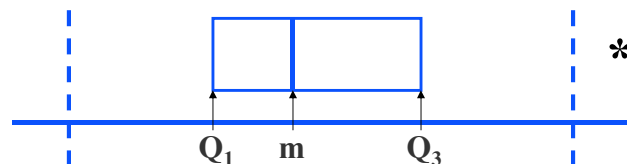


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Constructing a Box Plot

- ✓ Isolate outliers by calculating
 - ✓ Lower fence: $Q_1 - 1.5 IQR$ (or $Q_1 - 3(m - Q_1)$)
 - ✓ Upper fence: $Q_3 + 1.5 IQR$ (or $Q_3 + 3(Q_3 - m)$)
- ✓ Measurements beyond the upper or lower fence are outliers and are marked with *.

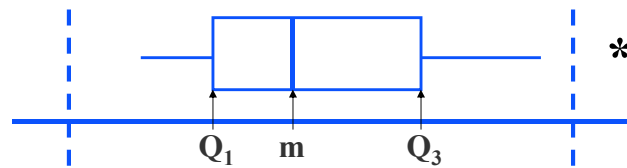


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Constructing a Box Plot

✓ Draw “whiskers” connecting the largest and smallest measurements that are NOT outliers to the box.



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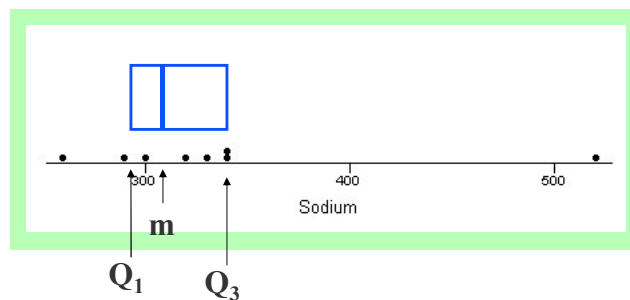
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Example

Amt of sodium in 8 brands of cheese:

260 290 300 320 330 340 340 520

$Q_1 = 292.5$ $m = 325$ $Q_3 = 340$



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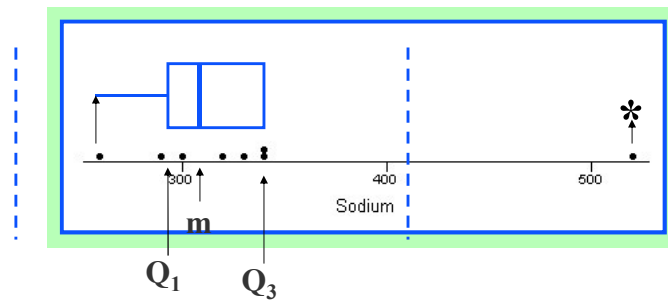
Example

$$\text{IQR} = 340 - 292.5 = 47.5$$

$$\text{Lower fence} = 292.5 - 1.5(47.5) = 221.25$$

$$\text{Upper fence} = 340 + 1.5(47.5) = 411.25$$

Outlier: $x = 520$



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Interpreting Box Plots

- ✓ Median line in center of box and whiskers of equal length—symmetric distribution
- ✓ Median line left of center and long right whisker—skewed right
- ✓ Median line right of center and long left whisker—skewed left



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Statistic

- A **statistic** is any function of the random variables constituting one or more samples, provided that the function does not depend on any unknown parameter values

Examples: sample mean, sample variance

- Sample data:
 - A **sample** = A set of sample observations $[x_1, x_2, \dots, x_i, \dots, x_n]$ and **sample size**= n
 - A sample **observation** = A piece of data vector $x_i = [x_{i1}, x_{i2}, \dots, x_{ij}, \dots, x_{im}]$

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What does Statistics do?

- **Point estimate:**
 - To estimate the parameters of the probability models with sample data
 - To evaluate how good the estimators are
- **Hypothesis test:**
 - To check/test whether the model parameter(s) has changed.
 - To evaluate how good the tests are (two types errors?)
- **Mathematical modeling of sampling statistics for performance evaluation:**
 - Modeling the “point estimate” and “hypothesis testing” for their performance evaluation

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Point Estimate

- A **point estimate** of a parameter θ is a single number that can be regarded as the most plausible value of θ . A point estimate is obtained by selecting a **suitable statistic** and computing its value from the given sample data. The selected statistic is called the **point estimator** of θ

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A Point Estimate of Mean: Sample Mean (Average)

- A statistic of point estimate, say sample mean, is a random variable. For example

$$\text{1st sampling: } \bar{x}_{1st} = \frac{\sum_{i=1}^n x_{1st,i}}{n} \quad \text{2nd: } \bar{x}_{2nd} = \frac{\sum_{j=1}^n x_{2nd,j}}{n}$$

$$\Rightarrow \bar{x}_{1st} \neq \bar{x}_{2nd}$$

- **Modeling sample mean by random variables:**

Assuming iid X_1, X_2, \dots, X_n

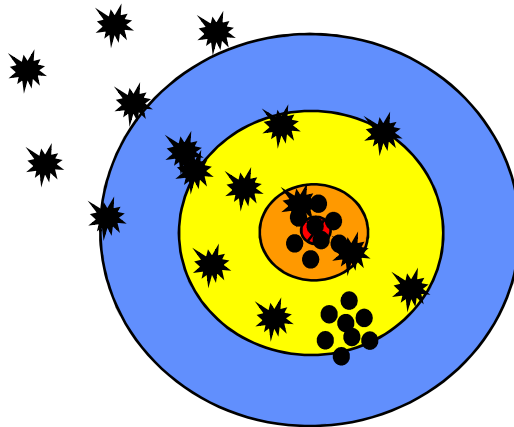
$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n}$$

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Performance of Point Estimate and Bull's Eye Aiming

- Parameter to be estimated: bull's eye **Center**
- Two estimators: 57 Rifle and M16 Rifle



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Unbiased Point Estimate

- A point estimator is itself a random variable with a distribution \Rightarrow Probability model of $\hat{\theta}$
- 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 . If not unbiased, the difference $E(\hat{\theta}) - \theta$ is called the **bias** of θ
- Example: Is sample mean \bar{X} the unbiased estimate of μ ?

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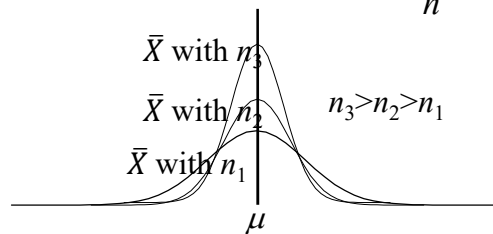
Is sample mean an Unbiased Estimator of mean?

- We model our observations x_1, x_2, \dots, x_n as independent and identically distributed (iid) X_1, X_2, \dots, X_n with μ and σ and sample mean can be modeled as a random variable:

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

- Recall Mean and Variance of sample mean:

$$E(\bar{X}) = \mu \text{ and } V(\bar{X}) = \frac{\sigma^2}{n}$$



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Is Sample Variance an Unbiased Estimator of Variance? $E(S^2) = \sigma^2$?

Assuming iid X_1, X_2, \dots, X_n with mean= μ and variance= σ^2

$$\begin{aligned} E\left[\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2\right] &= \frac{1}{n-1} E\left[\sum_{i=1}^n X_i^2 - \sum_{i=1}^n 2X_i \bar{X} + \sum_{i=1}^n \bar{X}^2\right] \\ &= \frac{1}{n-1} \left\{ \sum_{i=1}^n E[X_i^2] - E\left[2n \frac{\sum_{i=1}^n X_i}{n} \bar{X} - \sum_{i=1}^n \bar{X}^2\right] \right\} = \frac{1}{n-1} \left\{ nE[X_i^2] - E[2n\bar{X}^2 - n\bar{X}^2] \right\} \\ &= \frac{1}{n-1} \left\{ n[\sigma^2 + \mu^2] - nE[\bar{X}^2] \right\} = \frac{1}{n-1} \left\{ n\sigma^2 + n\mu^2 - n\left[\frac{\sigma^2}{n} + \mu^2\right] \right\} \\ &= \frac{1}{n-1} [(n-1)\sigma^2 + n\mu^2 - n\mu^2] = \sigma^2 \end{aligned}$$

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Example: Point Estimate of Binomial Distribution Parameter

- Let x be the number of heads observed from n tosses of coin. What would be the most plausible estimate of p for the Binomial distribution model?

$$\hat{p} = \frac{x}{n}$$

- To evaluate the performance of \hat{p} , we model x to be a random variable X following a (n, p) Binomial distribution. Is \hat{p} an unbiased estimate of p ?

$$E(\hat{p}) = E\left(\frac{X}{n}\right) = \frac{E(X)}{n} = \frac{np}{n} = p$$

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Standard Error

- Remember:** an estimator is itself a random variable with a distribution
- Standard Error** of an estimator $\hat{\theta}$ is its S.D.

$$\sigma_{\hat{\theta}} = \sqrt{V(\hat{\theta})}$$

- Estimated Standard Error** is the estimate of $\sigma_{\hat{\theta}}$ often denoted by $\hat{\sigma}_{\hat{\theta}}$ or $s_{\hat{\theta}}$
- Example: standard error of \bar{X} : $\sqrt{V(\bar{X})} = \sqrt{\frac{\sigma^2}{n}} = \frac{\sigma}{\sqrt{n}}$
- Example: Binomial experiment

$$\sigma_{\hat{p}} = \sqrt{V(\hat{p} = X/n)} = \sqrt{\frac{V(X)}{n^2}} = \sqrt{\frac{np(1-p)}{n^2}} = \sqrt{\frac{p(1-p)}{n}}$$

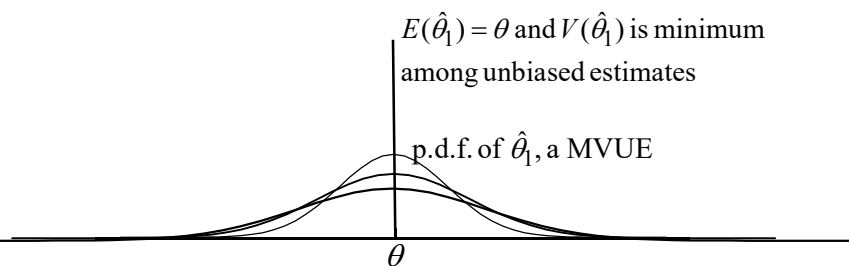
$$\hat{\sigma}_{\hat{p}} = s_{\hat{p}} = \sqrt{\frac{\hat{p}(1-\hat{p})}{n}} = \sqrt{\frac{(x/n)(1-x/n)}{n}} = \sqrt{\frac{x(n-x)}{n^2}}$$

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Performance of Point Estimate

- How good is an estimate?
 - On target? Unbiased?
 - Very certain? Minimum variance?
- Minimum Variance Unbiased Estimator (MVUE)
 - Among all unbiased estimators, the one with the minimum variance
- Example: sample mean is a MVUE for normally distributed populations

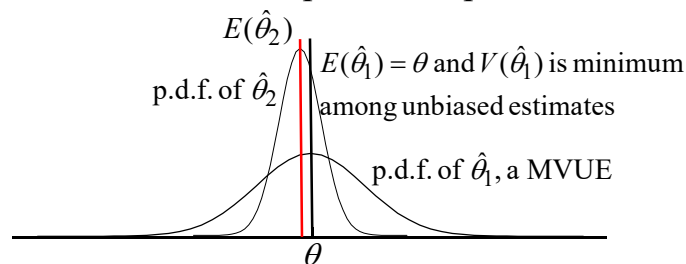


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Preferable Point Estimate

- Is a MVUE the most preferable point estimate?



- There are different point estimates for the same model parameter
- Different models requires different estimates
- Different point estimates serve different needs

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Example: Different Point Estimates of Mean

- Point estimates: $\bar{X}, \tilde{X}, \bar{X}_e, \bar{X}_{tr(m)}$
- \bar{X} is the arithmetic average called sample mean
- \tilde{X} is the median that is the center observation of the entire sample
- \bar{X}_e is the extreme mean (an average of two extreme observations)
- $\bar{X}_{tr(m)}$ is a trimmed mean that trims $m\%$ of observations from each end of the sample

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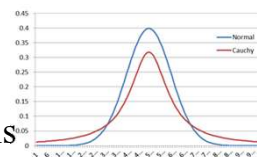
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Different Mean Point Estimates for Different Distributions

- Point estimates: $\bar{X}, \tilde{X}, \bar{X}_e, \bar{X}_{tr(m)}$
- \bar{X} is the best for Normal distribution
- How about an estimator for Cauchy distribution:

$$f(x) = \frac{1}{\pi[1 + (x - \mu)^2]}$$

Cauchy is bell-shaped with heavier tails



- \bar{X}, \bar{X}_e are terrible since they are sensitive to outlying observations; \tilde{X} is quite good
- For Uniform distribution (no tails), \bar{X}_e is the best
- $\bar{X}_{tr(m)}$ is not the best in all three situations, but it works reasonably well in all three!

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Methods of Point Estimate

- Most often used methods:
 - moment estimator
 - maximum likelihood estimator (MLE)
- Where do you learn all these? Theories of Statistical Inference
- BUT don't worry! Most of reasonable estimators are from your intuitions
- Example: Binomial experiment

$$\hat{p} = X / n$$

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Moment Estimator

- Moments of distribution models:
 - 1st moment= $E(X)$, 2nd moment= $E(X^2)$,...
 - m^{th} moment= $E(X^m)$
- Let X_1, X_2, \dots, X_n are **independent** random sample observations from a population following an **identical** probability model with p.m.f. or p.d.f. $f(X=x; \theta_1, \theta_2, \dots, \theta_m)$. Then, the moment estimator of $\theta_1, \theta_2, \dots, \theta_m$ are obtained by equating the first m sample moments to the corresponding first m model moments and solve for the estimators

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Example of Moment Estimator: Gamma Distribution

- To estimate the α and β of the Gamma distribution, equating the 1st and 2nd sample and model moments:

$$\text{sample mean} = \alpha\beta = E(X)$$

$$\text{sample variance} = \alpha\beta^2 = E(X^2) - E^2(X)$$

$$\Rightarrow \hat{\beta} = (\text{sample variance}) / (\text{sample mean}) \\ = S^2 / \bar{X}$$

$$\hat{\alpha} = (\text{sample mean})^2 / (\text{sample variance}) \\ = \bar{X}^2 / S^2$$

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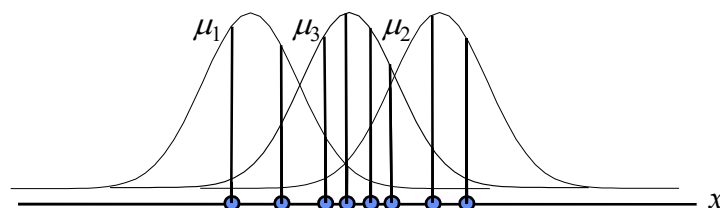
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Maximum Likelihood Estimate (MLE)

- The better the estimate of the parameter of a distribution model, the higher the value of the likelihood function substituted by the observed sample value.
- Let X_1, X_2, \dots, X_n are **independent** random sample observations from a population following an **identical** probability model with likelihood function $P(X)$ (discrete) or $f(X)$. Then, the joint joint likelihood for $X_1=x_1, X_2=x_2, \dots, X_n=x_n$ is:

$$P(X_1=x_1, X_2=x_2, \dots, X_n=x_n) = P(X=x_1)P(X=x_2) \dots P(X=x_n) \text{ or} \\ f(X_1=x_1, X_2=x_2, \dots, X_n=x_n) = f(X=x_1)f(X=x_2) \dots f(X=x_n)$$

- MLE is the estimate of a parameter that maximizes the joint likelihood function:



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MLE for p of Binomial Distribution

- Let X follow a (n, p) binomial distribution and p is unknown.
 - we observe the number of successes x from n trials.
 - What is the MLE of p ?

$$P(X=x) = C_x^n p^x (1-p)^{n-x}$$

- To maximize $P(x)$ w.r.t. p , take derivative of $P(x)$ w.r.t. p and set it to zero:

$$x\hat{p}^{x-1}(1-\hat{p}) - (n-x)\hat{p}^x(1-\hat{p})^{n-x-1} = 0$$

$$\Rightarrow x(1-\hat{p}) = (n-x)\hat{p}$$

$$\Rightarrow \hat{p} = x/n$$

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MLE for μ of Normal Distribution

- Let X follow a (μ, σ^2) normal distribution and μ is unknown.
 - we take a sample of n observed values x_1, x_2, \dots, x_n .
 - the joint likelihood function

$$f(x_1, \dots, x_n | \mu) = \prod_{i=1}^n \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x_i - \mu)^2}{2\sigma^2}\right] = \left(\frac{1}{2\pi}\right)^{n/2} \frac{1}{\sigma^n} \exp\left[-\frac{\sum (x_i - \mu)^2}{2\sigma^2}\right]$$

- Maximizing $f(x_1, \dots, x_n)$ is equivalent to maximizing $\log f(x_1, \dots, x_n)$. Take derivative of $\log f(x_1, \dots, x_n)$ and set it to zero:

$$\frac{d}{d\mu} \log f(x_1, \dots, x_n | \mu) = \frac{\sum_{i=1}^n (x_i - \hat{\mu})}{\sigma^2} = 0 \Rightarrow \hat{\mu} = \frac{\sum_{i=1}^n x_i}{n}$$

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Which Probability Model Fits Best?

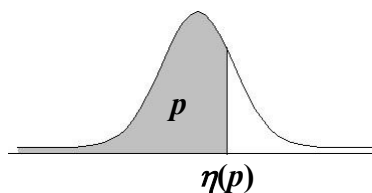
- Sample observations can be used to estimate parameters of any given probability model.
 - MLE can be used to estimate p of Geometric distribution as well as λ of Poisson distribution
- Which probability distribution model fits best to the sample observed data?
 - Goodness-of-Fit Tests
 - **Q-Q (P-P) plot: an effective visualized goodness of fit**

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Percentile and Sample Percentile

- Cumulative probability $F(\eta(p))=p$
 $\eta(p)$ is called the **(100p)th percentile (Quantile)**
 $= F^{-1}(p)$



- Sort the n sample observations from the smallest to the largest and the **sample cumulative probability** of the i th smallest observation $= 100(i-0.5)/n$
- The i th smallest observation $= [100(i-0.5)/n]$ th **sample percentile is an estimate of $[100(i-0.5)/n]$ th percentile**

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Probability Plot (Q-Q Plot)

Step 1: Sort the data from the smallest to the largest

Step 2: Calculate the sample cumulative probabilities $=100(i-0.5)/n$

Step 3: Assume a probability distribution model (F) and estimate probability distribution parameters

Step 4: Calculate the percentiles of the sample cumulative probabilities $= F^{-1}((i-0.5)/n)$

Step 5: Plot $\left(\begin{array}{cc} [100(i-0.5)/n] \text{th percentile,} & i \text{th smallest} \\ \text{of the distribution} & \text{sample observation} \end{array} \right)$

on the X-Y plane. If the observations follow the assumed distribution, the points form roughly a 45° line

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Example: 350Å SiO₂ Assumed to Follow Normal Distribution

Step 1: Sort the thickness data from 345.6 to 355.6 (X_i)

Step 2: Calculate the sample cumulative probabilities

$$\hat{p}_i = (i-0.5)/n$$

Step 3: Assume a **normal** probability distribution and estimated mean=349.91 and sample s.d.=2.235

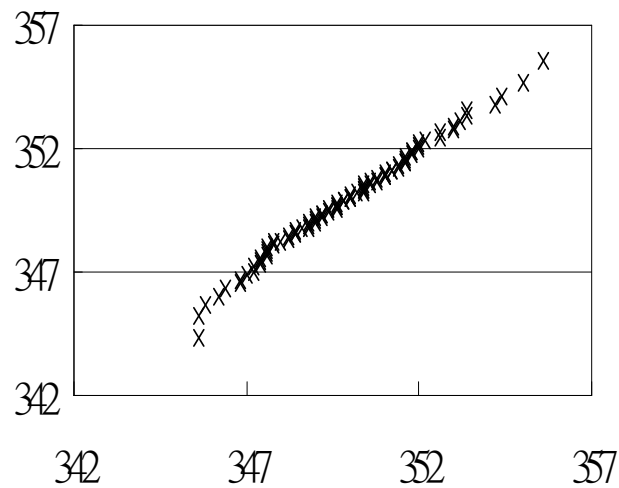
Step 4: Calculate the *percentiles* of the sample cumulative probabilities $N^{-1}(\hat{p}_i; 349.91, 2.235)$

Step 5: Plot $[N^{-1}(\hat{p}_i; 349.91, 2.235), X_i]$

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Example: 350Å SiO₂ Assumed to Follow Normal Distribution



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Normal Probability Plot

- $X \sim N(\mu, \sigma)$
- $Z = (X - \mu) / \sigma \sim N(0, 1)$

([100($i - .5$)/ n]th z percentile, i th smallest obs. x)

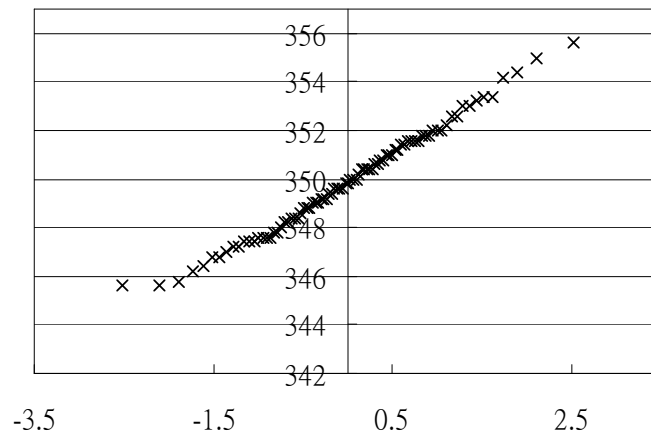
\Rightarrow form a line: $X = \sigma Z + \mu$

is a line with slop σ and intercept μ

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Example: 350Å SiO₂ Normal Probability Plot

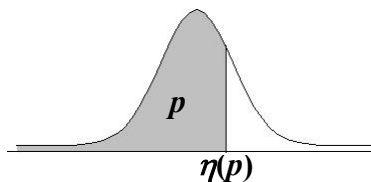


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Percentile and Sample Percentile

- Cumulative probability $F(\eta(p))=p$
 $\eta(p)$ is called the **(100p)th percentile (Quantile)**
 $= F^{-1}(p)$



- Sort the n sample observations from the smallest to the largest and the **sample cumulative probability** of the i th smallest observation $= 100(i-0.5)/n$
- The i th smallest observation $= [100(i-0.5)/n]$ th **sample percentile is an estimate of $[100(i-0.5)/n]$ th percentile**

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Probability Plot (Q-Q Plot)

Step 1: Sort the data from the smallest to the largest

Step 2: Calculate the sample cumulative probabilities
 $=100(i-0.5)/n$

Step 3: Assume a probability distribution model (F) and estimate probability distribution parameters

Step 4: Calculate the percentiles of the sample cumulative probabilities $= F^{-1}(100(i-0.5)/n)$

Step 5: Plot

$$\left(\begin{array}{cc} [100(i-0.5)/n] \text{th percentile,} & i \text{th smallest} \\ \text{of the distribution} & \text{sample observation} \end{array} \right)$$

on the X-Y plane. If the observations follow the assumed distribution, the points form roughly a 45° line

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Example: 350Å SiO₂ Assumed to Follow Normal Distribution

Step 1: Sort the thickness data from 345.6 to 355.6 (X_i)

Step 2: Calculate the sample cumulative probabilities (\hat{p}_i)

Step 3: Assume a **normal** probability distribution and estimated mean=349.91 and sample s.d.=2.235

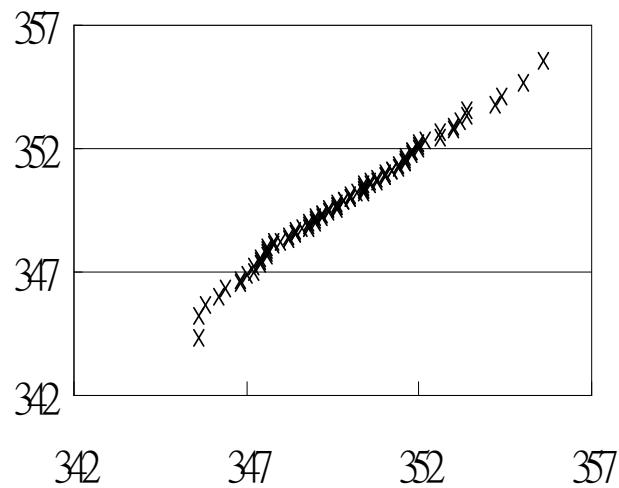
Step 4: Calculate the *percentiles* of the sample cumulative probabilities $N^{-1}(\hat{p}_i; 349.91, 2.235)$

Step 5: Plot $[N^{-1}(\hat{p}_i; 349.91, 2.235), X_i]$

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Example: 350Å SiO₂ Assumed to Follow Normal Distribution



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Normal Probability Plot

- $X \sim N(\mu, \sigma)$
- $Z = (X - \mu) / \sigma \sim N(0, 1)$

($[100(i-0.5)/n]$ th z percentile, i th smallest obs. x)

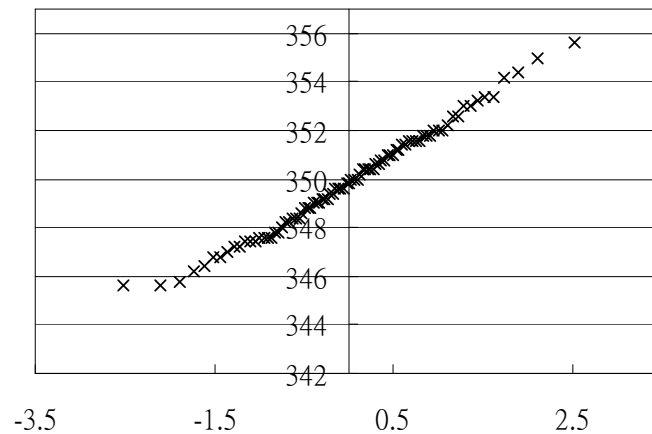
\Rightarrow form a line: $X = \sigma Z + \mu$

is a line with slop σ and intercept μ

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Example: 350Å SiO₂ Normal Probability Plot



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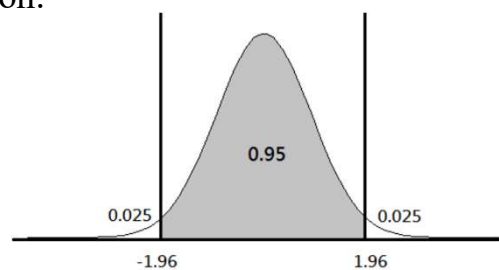
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Probability Interval of Normal Sample Mean

- Actual sample observations x_1, x_2, \dots, x_n from random sample X_1, X_2, \dots, X_n following $N(\mu, \sigma)$. Then, \bar{X} follows $N(\mu, \sigma / \sqrt{n})$

- Standardization:

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



$$\Rightarrow P(-1.96 < \frac{\bar{X} - \mu}{\sigma / \sqrt{n}} < 1.96) = .95$$

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Confidence Interval (C.I.) of Normal Mean

$$P(-1.96 < \frac{\bar{X} - \mu}{\sigma/\sqrt{n}} < 1.96) = .95$$

$$\Rightarrow P(\bar{X} - 1.96 \frac{\sigma}{\sqrt{n}} < \mu < \bar{X} + 1.96 \frac{\sigma}{\sqrt{n}}) = .95$$

- What does this mean?
- Remember that the sample mean is an estimator of the mean and is itself a *random variable* with uncertainty.
- With confidence interval, you are about 95% sure that the true mean will be in the range of

$$(\bar{x} - 1.96 \frac{\sigma}{\sqrt{n}}, \bar{x} + 1.96 \frac{\sigma}{\sqrt{n}})$$

- What if I would like to be **99%** sure?

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100(1- α)% Confidence Interval

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

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

- Example: 99%, $Z_{\alpha/2}$ =?
- In reality, what is the difficulty? σ is usually unknown!

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Large-sample Confidence Interval

- If sample size n is sufficiently large

$$Z \cong \frac{\bar{X} - \mu}{S/\sqrt{n}} \quad (S: \text{sample S.D.})$$

- Z is then approximately $N(0, 1)$

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

is a **large-sample confidence interval** for μ with confidence level approximately $100(1-\alpha)\%$

Example: 350Å SiO₂ Thickness

- Sample size $n=85$
- Sample mean=349.91 and sample s.d.=2.235
- 95% confidence interval of the thickness mean?
- 95%=100(1-0.05)% $\Rightarrow \alpha=0.05$
- Thickness mean 95% confidence interval:

$$\left(349.91 + z_{0.025} \frac{2.235}{\sqrt{85}}, 349.91 + z_{0.975} \frac{2.235}{\sqrt{85}} \right) =$$

$$(349.91 - 1.96 \cdot 0.2424, 349.91 + 1.96 \cdot 0.2424) =$$

$$(349.435, 350.385)$$

- What if n is considered small or the sample s.d. is not considered reliable?

***t* statistics: C.I. Interval for Unknown σ**

- \bar{X} is the average of a random sample of size n from a normal distribution with mean μ , Then, the random variable

$$T = \frac{\bar{X} - \mu}{S / \sqrt{n}}$$

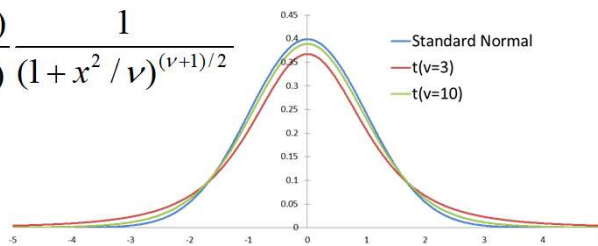
follows a probability distribution called a ***t*** distribution with $n-1$ degrees of freedom

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***t*-Distribution**

$$f_{\nu}(x) = \frac{\Gamma((\nu+1)/2)}{\sqrt{\nu\pi}\Gamma(\nu/2)} \frac{1}{(1+x^2/\nu)^{(\nu+1)/2}}$$



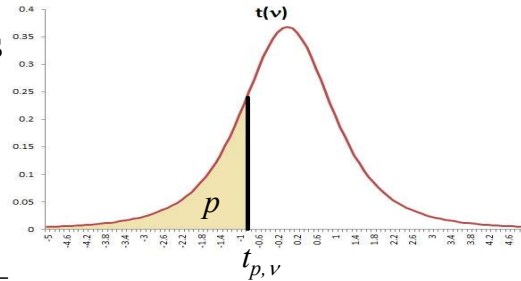
- Bell-shaped & centered at 0
- $\nu \uparrow$ distribution spread \downarrow
- The distribution spreads wider than the normal distribution (heavier tails)
- $\nu \rightarrow \infty$ $t_{\nu} \rightarrow$ standard normal $N(0, 1)$

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Confidence Interval using t -Statistic

- Let $t_{p,v}$ denotes



$$\Rightarrow P(t_{\alpha/2,v} < \frac{\bar{X} - \mu}{S/\sqrt{n}} < t_{1-\alpha/2,v}) = 1 - \alpha$$

Then a $100(1-\alpha)\%$ confidence interval for μ

is: $(\bar{x} + t_{\alpha/2,n-1} \frac{S}{\sqrt{n}}, \bar{x} + t_{1-\alpha/2,n-1} \frac{S}{\sqrt{n}})$

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Example: 350Å SiO₂ Thickness

- Sample size $n=85$
- Sample mean=349.91 and sample s.d.=2.235
- 95% confidence interval of the thickness mean?
- 95%=100(1-0.05)% $\Rightarrow \alpha=0.05$
- Thickness mean 95% confidence interval using Z:

$$(349.91 + z_{0.025} \frac{2.235}{\sqrt{85}}, 349.91 + z_{0.975} \frac{2.235}{\sqrt{85}}) =$$

$$(349.91 - 1.96 \cdot 0.2424, 349.91 + 1.96 \cdot 0.2424) = (349.435, 350.385)$$

- Thickness mean 95% confidence interval using t:

$$(349.91 + t_{0.025,84} \frac{2.235}{\sqrt{85}}, 349.91 + t_{0.975,84} \frac{2.235}{\sqrt{85}}) =$$

$$(349.91 - 1.9886 \cdot 0.2424, 349.91 + 1.9886 \cdot 0.2424) = (349.428, 350.392)$$

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Tests of Hypotheses

- The motivation: to reject an initial claim and to statistically prove that a scientific effort really makes differences
- Example: Medical experiment
- Initial claim
Null hypothesis H_0
- Claim otherwise
Alternative hypothesis H_1

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Errors in Hypothesis Tests

- Type I error: rejecting the null hypothesis H_0 when it is true
- Type II error: not rejecting H_0 when H_0 is false
- Probability of type I error (α)
- Probability of type II error (β)

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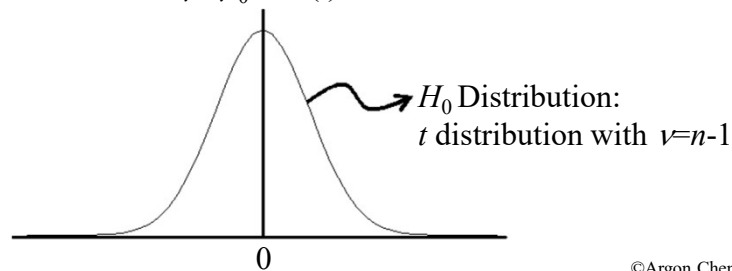
Test Statistic and Distribution under H_0 (Example: Testing Normal Mean)

$$H_0 : \mu = \mu_0$$

$$\text{Test statistic: } t\text{-test} = \frac{\bar{x} - \mu_0}{s / \sqrt{n}}$$

Distribution under H_0 : **t -Distribution with $\nu=n-1$**

$$\mu = \mu_0 \Rightarrow E(t) = 0$$



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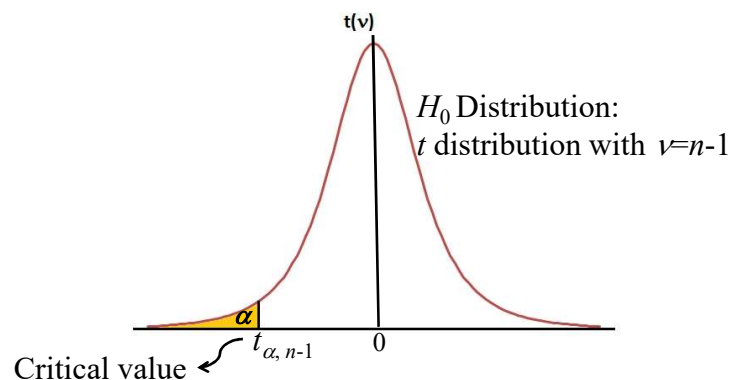
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Criteria to Reject H_0 : Reject Region

$$H_0 : \mu = \mu_0 \quad \text{Test statistic: } t\text{-test} = \frac{\bar{x} - \mu_0}{s / \sqrt{n}}$$

Distribution under H_0 : t -distribution

Reject H_0 when $t\text{-test} \leq t_{\alpha, n-1} \Rightarrow H_1: \mu < \mu_0$



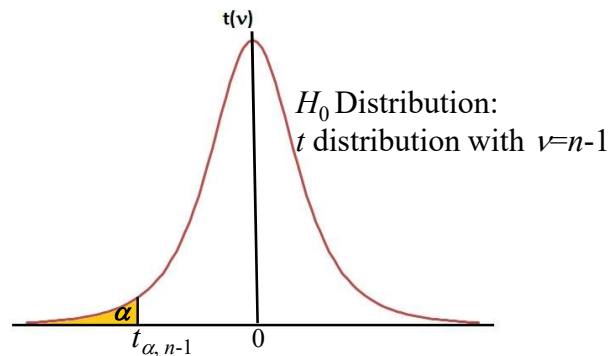
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Type I Error Probability of Rejecting the Null Hypothesis

Reject H_0 when $t\text{-test} \leq t_{1-\alpha, n-1} \Rightarrow H_1: \mu < \mu_0$

Probability ($\mu = \mu_0$ but you reject H_0 and accept H_1)
 $= \alpha$



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Hypothesis Test Procedure

- 1 Choose a test statistic: a function of the sample data with a known probability distribution model under H_0
- 2 Choose the Type I error probability (significance level) α to find the reject region and critical value based on the distribution of the test statistic under H_0
- 3 The H_0 will then be rejected if and only if the observed or computed test statistic values falls in the reject region

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Test about Population Mean

$$H_0: \mu = \mu_0$$

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

| H_1 | Reject Region |
|------------------|--|
| $\mu > \mu_0$ | $t \geq t_{1-\alpha, n-1}$ |
| $\mu < \mu_0$ | $t \leq t_{\alpha, n-1}$ |
| $\mu \neq \mu_0$ | $t \geq t_{1-\alpha/2, n-1}$ or $t \leq t_{\alpha/2, n-1}$ |
| | <div style="display: flex; align-items: center;"> <div style="font-size: 3em; margin-right: 10px;">{</div> <div> one-tailed test two-tailed test </div> </div> |

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Another View of Reject Region

Let H_1 be $\mu \neq \mu_0$ then reject H_0 when $t \leq t_{\alpha/2, n-1}$ or $t \geq t_{1-\alpha/2, n-1}$

$$\Rightarrow \frac{\bar{x} - \mu_0}{s / \sqrt{n}} \leq t_{\alpha/2, n-1} \text{ or } \frac{\bar{x} - \mu_0}{s / \sqrt{n}} \geq t_{1-\alpha/2, n-1}$$

$$\mu_0 \leq \bar{x} - t_{1-\alpha/2, n-1} \frac{s}{\sqrt{n}} \text{ or } \mu_0 \geq \bar{x} - t_{\alpha/2, n-1} \frac{s}{\sqrt{n}}$$

$$\mu_0 \leq \bar{x} + t_{\alpha/2, n-1} \frac{s}{\sqrt{n}} \text{ or } \mu_0 \geq \bar{x} + t_{1-\alpha/2, n-1} \frac{s}{\sqrt{n}}$$

\Rightarrow when μ_0 is outside the $100(1-\alpha)\%$ confidence interval of mean estimated by \bar{x} :

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

we reject it and accept $\mu \neq \mu_0$ with Type I error

probability = α

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***p*-value in Hypothesis Tests**

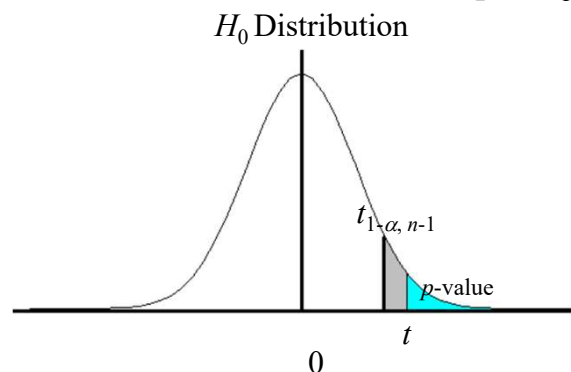
- Another way of presenting the test result
- The ***p*-value** is the smallest level of significance at which H_0 would be rejected when a specified test procedure is used on a given data set. Once the *p*-value has been determined, the conclusion at any particular level α results from comparing the *p*-value to α :

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***p*-value in one-tailed Hypothesis Tests**

- ***p*-value for one-tailed test:** (example: $H_1: \mu > \mu_0$)



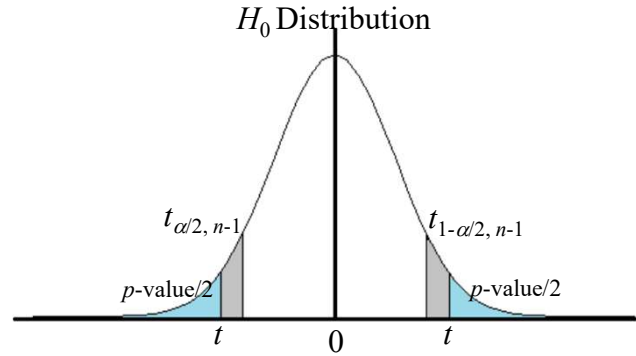
- $t > t_{1-\alpha, n-1} \Rightarrow P(t\text{-test} \geq t) = p\text{-value} \leq \alpha \Rightarrow \text{Reject } H_0$
- $p\text{-value} > \alpha \Rightarrow \text{Accept } H_0$

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***p*-value in two-tailed Hypothesis Tests**

- *p*-value for two-tailed test: (example: $H_1: \mu \neq \mu_0$)



- a. $t \geq t_{1-\alpha/2, n-1} \Rightarrow P(t\text{-test} \geq t) \leq \alpha/2 \Rightarrow 2P(t\text{-test} \geq t) = p\text{-value} \leq \alpha$
 or $t \leq t_{\alpha/2, n-1} \Rightarrow P(t\text{-test} \leq t) \leq \alpha/2 \Rightarrow 2P(t\text{-test} \leq t) = p\text{-value} \leq \alpha$
 \Rightarrow Reject H_0

- ⁷⁵ b. $p\text{-value} > \alpha \Rightarrow$ Accept H_0

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Testing 350Å SiO₂ Thickness Mean

- Null hypothesis: Thickness Mean= Target
 $H_0: \mu=350$
- Sample size $n=85$
- $\bar{x}=349.91$ and $s=2.235 \Rightarrow H_1: \mu < 350$
- Test statistic= $\frac{349.91 - 350}{2.235 / \sqrt{85}} = -0.37$
- Type I error prob.=0.05 $\Rightarrow \alpha=0.05$
- Reject $\mu=350$ if $t\text{-test} \leq t_{0.05, 84} = -1.663$
 but $-0.37 > -1.663 \Rightarrow \mu=350$ can't be rejected
- $p\text{-value}=0.356157 > 0.05 \Rightarrow$ do not reject H_0

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Testing A Pair of Means

- Testing problem: are the means the same?
 - That is: $H_0: \mu_x = \mu_y \Rightarrow \mu_x - \mu_y = 0$
- Choice of the test statistic:
 - Compare two sample means \bar{X} with sample size m and \bar{Y} with sample size n : $\bar{X} - \bar{Y}$
 - Question: what would be the distribution of $\bar{X} - \bar{Y}$?
 - Assuming X and Y are normally distributed with the same mean and a common variance σ^2 , then $\bar{X} - \bar{Y}$ follows a normal distribution with mean $= \mu_x - \mu_y$ and variance $= \sigma^2/m + \sigma^2/n = \sigma^2(\frac{1}{m} + \frac{1}{n})$
 - S.D. of $\bar{X} - \bar{Y}$: $\sigma \sqrt{\frac{1}{m} + \frac{1}{n}}$, how to estimate σ ?

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Pooled Estimator of σ^2

- The pooled estimator of the common variance σ^2 , denoted by S_p^2 , is the weighted average of the individual sample variances **weighted by the degree of freedom, i.e., $m-1$ and $n-1$:**

$$S_p^2 = \frac{m-1}{m-1+n-1} S_x^2 + \frac{n-1}{m+n-2} S_y^2$$

- Estimate of $\bar{X} - \bar{Y}$ S.D.: $S_p \sqrt{\frac{1}{m} + \frac{1}{n}}$

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Testing Mean Difference

$H_0: \mu_x - \mu_y = \Delta$ ($\Delta=0$ for testing the same means)

Test statistic:
$$t = \frac{(\bar{x} - \bar{y}) - \Delta}{s_p \sqrt{\frac{1}{m} + \frac{1}{n}}}$$

| H_1 | Reject Region |
|-----------------------------|--|
| $\mu_x - \mu_y > \Delta$ | $t \geq t_{1-\alpha, m+n-2}$ { one-tailed test |
| $\mu_x - \mu_y < \Delta$ | |
| $\mu_x - \mu_y \neq \Delta$ | $t \geq t_{1-\alpha/2, m+n-2}$ { two-tailed test |
| | or $t \leq t_{\alpha/2, m+n-2}$ } |

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Testing 350Å SiO₂ Means at Different Sites

- Null hypothesis:

$$H_0: \mu_{center} = \mu_{top}$$

- Sample size $m=n=86$

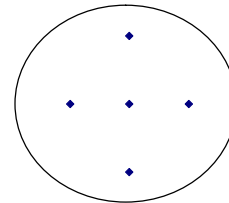
- $\bar{x}_{center} = 349.09$ and $s_{center}^2 = 5.12$

$$\bar{x}_{top} = 348.48 \text{ and } s_{top}^2 = 5.52$$

| Center | Top | Bottom | Left | Right |
|--------|-----|--------|------|-------|
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- Pooled estimate of σ : $s_p = \sqrt{\frac{85s_{center}^2 + 85s_{top}^2}{86+86-2}} = 2.31$

- Test statistic = $\frac{349.09 - 348.48}{2.31 \sqrt{\frac{1}{86} + \frac{1}{86}}} = 1.752$



- Type I error prob. = 0.05 \Rightarrow two-tailed $\alpha/2 = 0.025$; $1-\alpha/2 = 0.975$

- Do not reject $\mu_{center} = \mu_{top}$ as $t\text{-test} = 1.752 < t_{0.975, 86+86-2} = 1.974$

\Rightarrow do not accept $\mu_{center} \neq \mu_{top}$

- $p\text{-value} = 2 \times \text{Prob}(t_{86+86-2} > 1.752) = 0.0816 > 0.05 \Rightarrow$ do not reject H_0

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Testing Variance

- Testing problem: is the variance unchanged?
 - That is: $H_0: \sigma^2 = \sigma_0^2$
- Choice of the test statistic:
 - Sample variance S^2 seems to be a good test statistics since it's an unbiased estimate of variance
 - Question: what would be the distribution of S^2 under H_0 ($\sigma^2 = \sigma_0^2$)?

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Distribution of Sample Variance

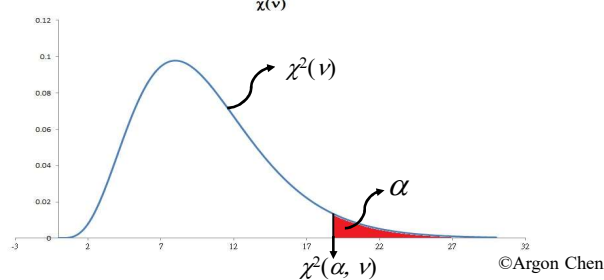
- To establish a hypothesis, one must know the assumed distribution model behind the sample. What would be the distribution model behind the variance?
- Recall: If $X_i \sim N(0, 1)$ then $\sum_n X_i^2 \sim \chi^2(n)$
- Recall: $(X - \mu)/\sigma \sim N(0, 1)$
- Therefore: $\sum_n [(X_i - \mu)/\sigma]^2 = \sum_n (X_i - \mu)^2 / \sigma^2 \sim \chi^2(n)$
- Recall: $S^2 = \sum_n (X_i - \bar{X})^2 / (n-1)$
- Result: $(n-1) S^2 / \sigma^2 = \sum_n (X_i - \bar{X})^2 / \sigma^2 \sim \chi^2(n-1)$
- If X_1, X_2, \dots, X_n is a sample from a normal population with mean μ and variance σ^2 , then $(n-1) S^2 / \sigma^2$ follows a χ^2 distribution with $\nu = n-1$.

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Testing $H_0: \sigma^2 = \sigma_0^2$

- Test statistic: $(n-1)S^2/\sigma_0^2$
- Under H_0 ($\sigma^2 = \sigma_0^2$), $(n-1)S^2/\sigma_0^2$ follows $\chi^2(n-1)$
- Reject region: determine critical value $\chi^2(\alpha, \nu)$ (CHISQ.INV.RT(α, ν) in Excel) and reject region based on α
- $H_1: \sigma^2 > \sigma_0^2$



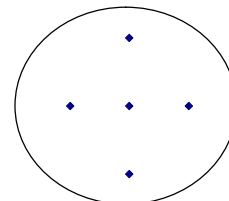
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Testing 350Å SiO₂ Thickness Variance

- Null hypothesis:
 $H_0: \sigma_{top}^2 = 5.0$
- Sample size $n=86$
- $\bar{x}_{top} = 348.48$ and $s_{top}^2 = 5.52$
- Test statistic = $(86 - 1) \frac{5.52}{5.0} = 93.89$
- Type I error prob. $\alpha=0.05$
- $\chi^2(0.05, 86-1)=107.52$
- Do not reject $\sigma_{top}^2 = 5.0$ as test-stat = $93.89 < 107.52$
 \Rightarrow do not accept $\sigma_{top}^2 > 5.0$
- $p\text{-value} = \text{Prob}(\chi_{85}^2 > 93.89) = 0.238 > 0.05 \Rightarrow$ do not reject H_0

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Testing A Pair of Variances

- Testing problem: are the variances the same?
 - That is: $H_0: \sigma_x^2 = \sigma_y^2$
- Choice of the test statistic:
 - Compare two sample variances S_x^2 with sample size n_1 and S_y^2 with sample size n_2 :

$$S_x^2/S_y^2$$

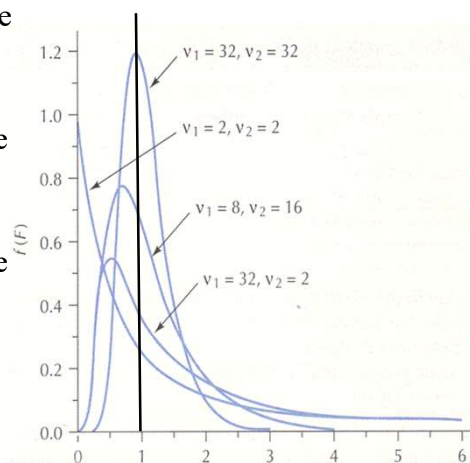
- Question: what would be the distribution of S_x^2/S_y^2 under H_0 ($\sigma_x^2 = \sigma_y^2$)?

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Distribution of Sample Variance Ratio

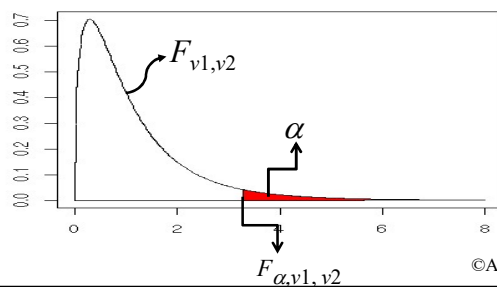
- Two **normal** populations have the **same variance**
- S_x^2 : sample variances from population 1 with sample size n_1
- S_y^2 : sample variances from population 2 with sample size n_2
- Then, S_x^2/S_y^2 follows F_{v_1, v_2} distribution with $v_1 = n_1 - 1$; $v_2 = n_2 - 1$
- $E(S_x^2/S_y^2) = v_2/(v_2 - 2)$ if $v_2 > 2$
- $E(S_x^2/S_y^2) \rightarrow 1$ as $v_2 \rightarrow$ large number



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Testing $H_0: \sigma_x^2 = \sigma_y^2$

- Test statistic: S_x^2/S_y^2
- Under H_0 ($\sigma_x^2 = \sigma_y^2$), S_x^2/S_y^2 follows $F_{v1,v2}$
- Reject region: determine critical value $F_{\alpha,v1,v2}$ (F.INV.RT(α , v1, v2) in Excel) and reject region based on α
- $H_1: \sigma_x^2 > \sigma_y^2$



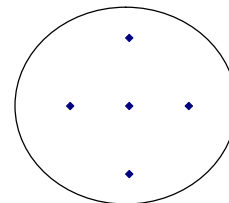
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Testing Variances at Different Sites

- Null hypothesis:
 $H_0: \sigma_{bottom}^2 = \sigma_{center}^2$
- Sample size $m=n=86$
- $s_{bottom}^2=7.88$
 $s_{center}^2=5.12$
- F-test statistic $= \frac{7.88}{5.12} = 1.538$
- Type I error prob. $\alpha=0.05$
- $F_{0.05, 86-1, 86-1}=1.432$
- Reject $\sigma_{bottom}^2 = \sigma_{center}^2$ as $F\text{-test}=1.538 > 1.432$
 \Rightarrow accept $\sigma_{bottom}^2 > \sigma_{center}^2$
- $p\text{-value}=\text{Prob}(F_{86-1, 86-1} > 1.538)=0.024 < 0.05 \Rightarrow \text{Reject } H_0$

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Testing a Proportion

- Testing problem: is the proportion of occurrences equal to p_0 ?
 - That is: $H_0: p=p_0$
- Choice of the test statistic:
 - X : number of occurrences in n trials
 - X follows Binomial distribution $b(x; p_0, n)$ under null hypothesis
- Given significance level (type I error prob.) α and $H_1: p > p_0$
 - Reject region: $x > k^*$ where k^* is the smallest value of k for which $\sum_{i=k}^n C_i^n p_0^i (1-p_0)^{n-i} \leq \alpha$.

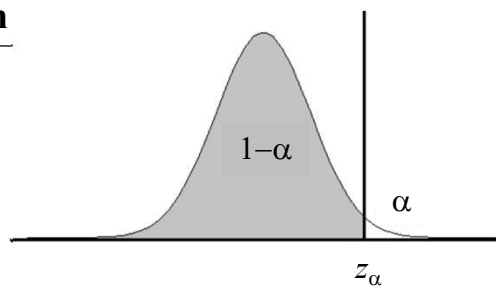
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Testing the Proportion with Large n

- $H_0: p=p_0$
- Test statistic: $Z = \frac{X - np_0}{\sqrt{np_0(1-p_0)}} \sim \text{standard normal}$ with a large n (recall: $E(X)=np$, $\text{Var}(X)=np(1-p)$) under null hypothesis

| H_1 | Reject Region |
|--------------|--|
| $p > p_0$ | $z \geq z_\alpha$ |
| $p < p_0$ | $z \leq -z_\alpha$ |
| $p \neq p_0$ | $z \geq z_{\alpha/2}$ or $z \leq -z_{\alpha/2}$ |

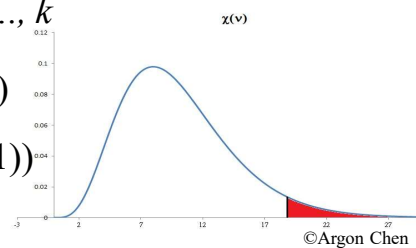


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Testing Proportions

- Testing problem: do the occurrences of different classes agree with the hypothesis that the occurrence probability of class i (for $i=1, \dots, k$) equals to p_i and $\sum p_i = 1$
- Let observed occurrences of class i be X_i (for $i=1, \dots, k$) in a total of n observations ($\sum X_i = n$)
- Test statistic: $C^2 = \sum_{i=1}^k \frac{(X_i - np_i)^2}{np_i}$ follows $\chi^2(v=k-1)$ under null hypothesis
- Reject H_0 : $P(\text{Class}=i) = p_i, i=1, \dots, k$

if $c^2 = \sum_{i=1}^k \frac{(x_i - np_i)^2}{np_i} \geq \chi^2(\alpha, k-1)$
(In Excel, CHISQ.INV.RT($\alpha, k-1$))



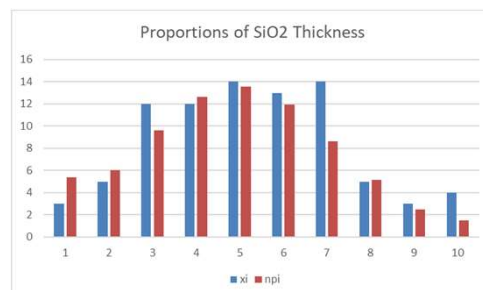
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Testing the Frequency Distribution

- Example: Is the frequency distribution for 85 readings of SiO_2 average fit the proportions based on Normal distribution $N(349.91, 2.235)$?

| | Class Interval | x_i | Relative Freq. | np_i |
|----|----------------|-------|----------------|--------|
| 1 | ~346.5 | 3 | 0.0353 | 5.40 |
| 2 | 346.6~347.5 | 5 | 0.0588 | 6.05 |
| 3 | 347.6~348.5 | 12 | 0.1412 | 9.64 |
| 4 | 348.6~349.5 | 12 | 0.1412 | 12.61 |
| 5 | 349.6~350.5 | 14 | 0.1647 | 13.54 |
| 6 | 350.6~351.5 | 13 | 0.1529 | 11.93 |
| 7 | 351.6~352.5 | 14 | 0.1647 | 8.63 |
| 8 | 352.6~353.5 | 5 | 0.0588 | 5.13 |
| 9 | 353.6~354.5 | 3 | 0.0353 | 2.50 |
| 10 | 354.6~ | 4 | 0.0471 | 1.53 |



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Testing the Proportions

- $H_0: P(\text{Class}=i)=p_i, i=1, \dots, 10$

| | Class Interval | x_i | Relative Freq. | np_i | $(x_i - np_i)^2 / np_i$ |
|----|----------------|-------|----------------|----------------------|-------------------------|
| 1 | ~346.5 | 3 | 0.0353 | 5.40 | 1.067 |
| 2 | 346.6~347.5 | 5 | 0.0588 | 6.05 | 0.181 |
| 3 | 347.6~348.5 | 12 | 0.1412 | 9.64 | 0.580 |
| 4 | 348.6~349.5 | 12 | 0.1412 | 12.61 | 0.029 |
| 5 | 349.6~350.5 | 14 | 0.1647 | 13.54 | 0.016 |
| 6 | 350.6~351.5 | 13 | 0.1529 | 11.93 | 0.096 |
| 7 | 351.6~352.5 | 14 | 0.1647 | 8.63 | 3.340 |
| 8 | 352.6~353.5 | 5 | 0.0588 | 5.13 | 0.003 |
| 9 | 353.6~354.5 | 3 | 0.0353 | 2.50 | 0.101 |
| 10 | 354.6~ | 4 | 0.0471 | 1.53 | 4.008 |
| | Total | 85 | | c^2 | 9.421 |
| | | | | p-value | 0.399 |
| | | | | $\chi^2(0.05, 10-1)$ | 16.919 |

- $c^2=9.421 < \chi^2(0.05, 10-1)=16.919$
- Do not reject the H_0 : the SiO_2 thickness proportions are the same as the normal distribution proportions