

Summation Notation

ECON 340: Economic Research Methods

Instructor: Div Bhagia

The capital sigma (Σ) stands for summing everything on the right.

$$\sum_{i=1}^N X_i = X_1 + X_2 + \dots + X_N$$

When we have sets, the index i denotes the i -th position in the set.

Example: For $X = \{1, 3, 5, 1\}$, we have $\sum_{i=1}^3 X_i = X_1 + X_2 + X_3 = 1 + 3 + 5 = 9$

Note: Another way of using a summation sign is to write $\sum_{x \in A} x$, which refers to summing up all elements in A . Similarly, to sum up x for all possible values x , we can simply write $\sum_x x$.

Things you CAN do to summations:

1. Pull constants out of them or into them.

$$\sum_{i=1}^N bX_i = b \sum_{i=1}^N X_i$$

Example: $\sum_{i=1}^2 bX_i = bX_1 + bX_2 = b(X_1 + X_2) = b \sum_{i=1}^2 X_i$

2. Split apart (or combine) sums (addition) or differences (subtraction)

$$\sum_{i=1}^N (bX_i + cY_i) = b \sum_{i=1}^N X_i + c \sum_{i=1}^N Y_i$$

Example: $\sum_{i=1}^2 (X_i - 2Y_i) = (X_1 - 2Y_1) + (X_2 - 2Y_2) = X_1 + X_2 - 2(Y_1 + Y_2)$. So we can write

$$\sum_{i=1}^2 (X_i - 2Y_i) = \sum_{i=1}^2 X_i - 2 \sum_{i=1}^2 Y_i$$

3. Multiply through constants by the number of terms in the summation

$$\sum_{i=1}^N (a + bX_i) = aN + b \sum_{i=1}^N X_i$$

Example: $\sum_{i=1}^3 a = a + a + a = 3a$.

Things you CAN NOT do to summations:

1. Split apart (or combine) products (multiplication) or quotients (division).

$$\sum_{i=1}^N X_i Y_i \neq \sum_{i=1}^N X_i \times \sum_{i=1}^N Y_i$$

Example: Note that $\sum_{i=1}^2 X_i Y_i = X_1 Y_1 + X_2 Y_2$, while $(\sum_{i=1}^2 X_i) \cdot (\sum_{i=1}^2 Y_i) = (X_1 + X_2)(Y_1 + Y_2) = X_1 Y_1 + X_2 Y_2 + X_1 Y_2 + X_2 Y_1$.

2. Move the exponent out of or into the summation.

$$\sum_{i=1}^N X_i^a \neq \left(\sum_{i=1}^N X_i \right)^a$$

Example: Note that $\sum_{i=1}^2 X_i^2 = X_1^2 + X_2^2$, while $\left(\sum_{i=1}^2 X_i \right)^2 = (X_1 + X_2)^2 = X_1^2 + X_2^2 + 2X_1 X_2$.

Describing Data

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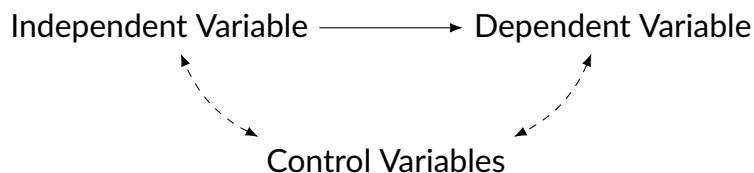
1 What is a variable?

A *variable* is multiple observations of the same measurement. Variables may be classified into two main categories: continuous and categorical (or discrete).

- *Continuous*: can take any value in an interval (e.g., income, age, GPA, rent, etc.)
- *Categorical (or discrete)*: assigns observations in different groups (e.g., gender, race, religious affiliation, educational attainment, etc.)

A categorical variable with two categories is called a *binary* variable.

Many questions in economics and other social sciences are concerned with cause-and-effect relationships. When studying such questions, we refer to the cause as the *independent* variable. The *dependent* variable is the effect. Its value depends on changes in the independent variable. Finally, a *control* variable is a variable that might be associated with both the *dependent* and the *independent* variables, and we might want to account for it while studying our causal relationship of interest.



The dependent variable is also called the *outcome* or *response* variable. In contrast, the independent variable is also called the *predictor* or *explanatory* variable. We will also refer to *control* variables as *confounding* variables.

2 Empirical Distribution of a Variable

A useful way to learn about a variable is by looking at how often different values of this variable occur. This information is summarized by a variable's empirical *distribution*. We can look at the proportion of observations in each category for categorical variables. In particular, we can calculate the *relative frequency* as follows:

$$\text{Relative frequency} = \frac{\text{Number of observations in a category}}{\text{Total number of observations}}$$

If n denotes the total number of observations and n_k denotes the number of observations that fall in category k , then we can calculate the relative frequency f_k as follows:

$$f_k = \frac{n_k}{n}$$

The relative frequency f_k tells us the proportion of observations in category k .

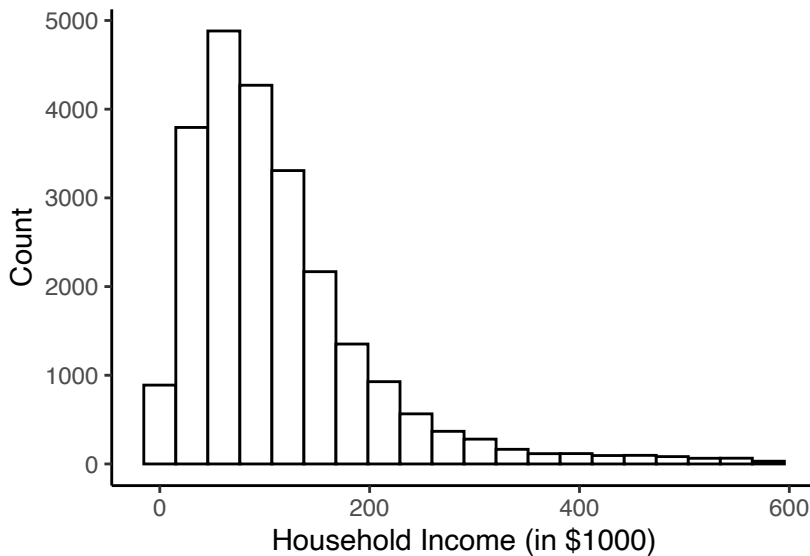
The following is an example of a *frequency distribution table* for the outcome from 100 die rolls.

Outcome	Count	Proportion	Cumulative
1	18	0.18	0.18
2	18	0.18	0.36
3	12	0.12	0.48
4	16	0.16	0.64
5	21	0.21	0.85
6	15	0.15	1
Total	100	1	

The cumulative frequency is calculated by adding each frequency from a frequency distribution table to the sum of its predecessors.

Continuous variables can take many different values, so it is not possible to look at how many observations take each possible value. Instead, we can look at how many observations fall in a particular interval.

The graphical version of the frequency distribution table is a *histogram*. The x -axis of a histogram presents the possible outcomes or intervals for the variable, while the y -axis presents the number or proportion of outcomes in each group. Below is a histogram of household income.



Note that the distribution is skewed to the right due to a small number of outliers with really high incomes.

3 Measures of Central Tendency

While a frequency distribution table or a histogram is a good way to learn about a variable, we only sometimes want to present a long table or a figure. We want a single number that can summarize this variable. A few options:

Mean: the average value

Median: the middle value

Mode: the most frequent value

To calculate the median, you find the middle value. If the number of observations is even, you take the average of the two middle values.

Mean and median are frequently employed in applied work. While the mean suffices for most purposes, it is more sensitive to outliers than the median because it considers all values, not just the middle values. For the distribution of household income above, the mean is \$112,900, and the median is \$91,600. Mean earnings are higher than the median, reflecting that the mean is pushed upwards as it is more affected by the outliers with really high incomes in the data.

To calculate the mean, you add up all the observations and divide by the number of observations. A sample mean is usually denoted by \bar{X} and can be calculated as:

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

Here n is the sample size.

The population mean is denoted by μ .

Some things to note about the mean:

- $\sum_{i=1}^n X_i = n\bar{X}$
- Deviations from the mean are always zero

$$\sum_{i=1}^n (X_i - \bar{X}) = \sum_{i=1}^n X_i - n\bar{X} = n\bar{X} - n\bar{X} = 0$$

- We can always write

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

Mean from Grouped Data

If data are grouped, we can use the frequency distribution table to calculate the mean. In particular, for K groups, we use the following formula:

$$\bar{X} = \frac{\sum_{k=1}^K n_k X_k}{n} = \sum_{k=1}^K f_k X_k$$

Example. Say, we have the following observations on a variable X :

1, 1, 3, 3, 3, 4, 5

One way to find the mean:

$$\frac{1 + 1 + 3 + 3 + 3 + 4 + 5}{7} = \frac{20}{7}$$

Another way to find the mean:

X_k	n_k	f_k	$f_k X_k$
1	2	2/7	2/7
3	3	3/7	9/7
4	1	1/7	4/7
5	1	1/7	5/7
Total	7	1	20/7

Note that both approaches are equivalent, as all we do by using the frequency distribution table is group observations with the same values.

$$\begin{aligned} \frac{1 + 1 + 3 + 3 + 3 + 4 + 5}{7} &= \frac{(2 \times 1) + (3 \times 3) + (1 \times 4) + (1 \times 5)}{7} \\ &= 2 \cdot \frac{1}{7} + 3 \cdot \frac{3}{7} + 4 \cdot \frac{1}{7} + 5 \cdot \frac{1}{7} \end{aligned}$$

Weighted Mean

The *weighted mean* of a set of data is given by:

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

where ω_i is the weight of the i^{th} observation. When weights sum up to 1 (i.e. $\sum_{i=1}^n \omega_i = 1$)

1) we can simply write the weighted mean as:

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

When we calculate the unweighted mean, we put equal weight on all observations in the data. However, sometimes we want to put a higher weight on some observations than others; in such cases, we use the weighted mean.

4 Percentiles

The P^{th} percentile is a value such that $P\%$ of observations are at or below that number.

The 50th percentile is called the median. The 25th and 75th percentiles are called the 1st and 3rd quartiles, respectively.

5 Measures of Variance

Measures of central tendency tell us about the average observation in the data. However, it doesn't say anything about this variable's dispersion or variation. One way to learn about dispersion would be to look at the minimum and maximum values a variable takes. This is called the *range* of the variable. Another way is to look at how far observations are away from the mean, so calculate the variance as follows.

Population Variance

$$\sigma_X^2 = \frac{1}{N} \sum_{i=1}^N (X_i - \mu_X)^2$$

Sample Variance

$$S_X^2 = \frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2$$

If there is more dispersion in the data, the variance will be higher. This is because we

calculate the mean by taking the average of square deviations from the mean. If many observations are further below or above the mean, the sum of square deviations will be larger.

For the sample variance, the denominator is $n - 1$ instead of n . This is because observations in the sample are closer to the sample mean than the population mean. The variance estimator uses the sample mean and hence underestimates the actual variance of the population. Dividing by $n - 1$ instead of n corrects for that bias.

However, it isn't easy to interpret the variance since it is in *squared units*. So we often convert the variance back to its original units by taking the square root of it. This quantity is called the standard deviation.

Standard Deviation

$$\sigma_X = \sqrt{\sigma_X^2} \quad S_X = \sqrt{S_X^2}$$

Example.

X_i	$X_i - \mu$	$(X_i - \mu)^2$
2	-3	9
5	0	0
8	3	9
Total	0	18

We can calculate the variance as follows:

$$\sigma_X^2 = \frac{1}{3} \sum_{i=1}^3 (X_i - \mu_X)^2 = \frac{18}{3} = 6$$

The standard deviation is $\sigma_X = 2.45$.

Note that we can use the frequency distribution table for grouped data to calculate the variance. In which case,

$$\sigma_X^2 = \sum_{k=1}^K f_k (X_k - \mu_X)^2$$

For the sample variance, we will need to do the $n - 1$ correction as follows:

$$S_X^2 = \frac{n}{n-1} \sum_{k=1}^K f_k (X_k - \bar{X})^2$$

6 Z-Score

Z-score is defined as:

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

Z-score tells us how many standard deviations any particular observation is away from the mean.

Example. Say we have two hypothetical countries Mushroom Kingdom (MK) and Bowser's Kingdom (BK). Now say

$$\mu_{MK} = 50,000 \quad \mu_{BK} = 50,000$$

$$\sigma_{MK} = 3,000 \quad \sigma_{BK} = 5,000$$

Someone earning \$ 45,000 in MK is $5000/3000 = 1.66$ standard deviations below the mean. While someone earning \$ 45,000 in BK is $5000/5000 = 1$ below the mean. Why the difference? Z-score standardizes both distributions and tells us how many people are between the person who earns 50K and 45K.

7 Correlation and Covariance

While so far, we have been talking about describing one variable. Most often, we are interested in the relationship between two different variables. For instance, we might be interested in whether cars with better fuel economy have lower horsepower. To learn about such relationships, we can calculate the *covariance*:

$$\sigma_{XY} = \frac{1}{N} \sum_{i=1}^N (X_i - \mu_X)(Y_i - \mu_Y) \quad (\text{Population})$$

$$S_{XY} = \frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y}) \quad (\text{Sample})$$

Covariance indicates whether there is a positive or negative relationship between two variables.

Why does this formula work? If it is, in fact, true that there is a negative relationship between fuel economy as measured by MPG and horsepower. Then for many observations in our data, $(X_i - \mu_X)(Y_i - \mu_Y)$ will be negative. $(X_i - \mu_X)(Y_i - \mu_Y)$ is negative every time X_i is above its mean but Y_i is below its mean or vice versa.

Similarly, $(X_i - \mu_X)(Y_i - \mu_Y)$ is positive for any observation if both X_i and Y_i are above the mean. The covariance is positive if $(X_i - \mu_X)(Y_i - \mu_Y)$ is positive on average. If there is no clear relationship between the two variables, for some observations, $(X_i - \mu_X)(Y_i - \mu_Y)$ will be negative, while for some, it will be positive, leading the covariance to go towards 0.

In other words, if two variables tend to be above average at the same time or below average at the same time, then we add a positive number to the numerator for the covariance for most observations, increasing the covariance. If they have nothing to do with each other, we add a positive number sometimes and a negative number other times, canceling each other and giving us a covariance of 0.

The upper and lower limits for the covariance depend on the variances of the variables involved. These variances, in turn, can vary with the scaling of the variables, so even a change in the units of measurement can change the covariance. Thus, covariance is only helpful in finding the direction of the relationship between two variables and not the magnitude.

We can obtain the *correlation coefficient* of two variables by dividing the covariance of these variables by the product of the standard deviations of both variables. Correlation also indicates the strength of the relationship in addition to the direction.

$$\rho_{XY} = \frac{\sigma_{XY}}{\sigma_X \sigma_Y} \quad (\text{Population})$$

$$r_{XY} = \frac{S_{XY}}{S_X S_Y} \quad (\text{Sample})$$

Things to note about the correlation coefficient:

- Measures the strength and direction of the linear relationship between two variables
- Bounded between -1 and 1
- If $\rho = 0$, there is no linear relationship between the two variables. If $\rho = 1$ or $\rho = -1$, there is a perfect linear relationship.
- If $\rho > 0$, then when X is above (below) \bar{X} , Y is above (below) \bar{Y} .
- If $\rho < 0$, then when X is above (below) \bar{X} , Y is below (above) \bar{Y} .

Finally, correlation is not causation! Particularly for two reasons:

1. Reverse causality: A high correlation between education and household income could come from either “more education \rightarrow higher household income” or “higher household income \rightarrow more education.”
2. Other factors: It could be another factor like generational wealth is correlated with both the likelihood of getting more education and having a higher household income.

Random Variables

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1 Single Random Variable

A random variable is a variable that takes different values under different scenarios. The likelihood of these different scenarios is summarized by the distribution of the random variable. We will denote a random variable by X and realizations of it by x .

Random variables can either be discrete or continuous. A *discrete* random variable has a countable number of possible values. While *continuous* random variables can take any value in a given interval.

1.1 Discrete Random Variables

The *probability distribution function* (PDF) for a discrete random variable X is given by:

$$f(x) = Pr(X = x)$$

where $0 \leq f(x) \leq 1$ for all x and $\sum_x f(x) = 1$.

The *cumulative distribution function* (CDF) for a discrete random variable X is given by:

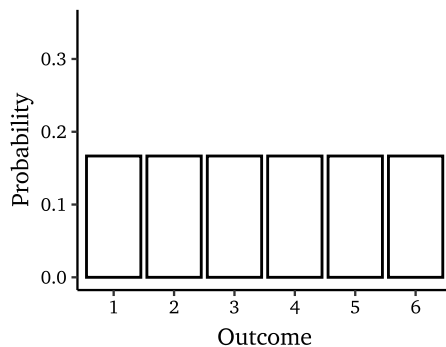
$$F(x_0) = Pr(X \leq x_0) = \sum_{x \leq x_0} f(x)$$

Example. X is the outcome of rolling a die.

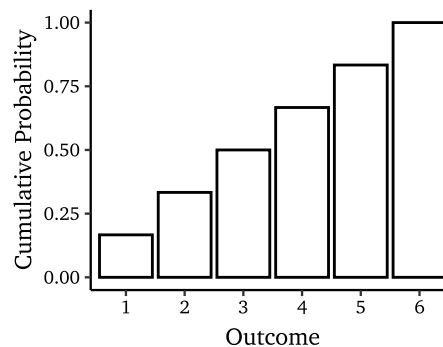
x	$f(x)$	$F(x)$
1	1/6	1/6
2	1/6	2/6
3	1/6	3/6
4	1/6	4/6
5	1/6	5/6
6	1/6	1

Figure 1: Outcome from a Die Roll

(a) Probability Distribution Function



(b) Cumulative Distribution Function



Bernoulli Random Variable is a special type of discrete random variable that only takes two values 1 and 0. It is also called a *binary* variable.

$$X = \begin{cases} 1 & \text{with probability } p \\ 0 & \text{with probability } 1 - p \end{cases}$$

1.2 Continuous Random Variables

Because of continuum of possible values, it is not feasible to list the probability of each possible value of a continuous random variable. So we instead have the *probability density function* (PDF), denoted by $f(x)$. The area under the curve $f(x)$ gives us the probability of X falling in certain intervals. The *probability density function* is defined as:

$$Pr(a \leq x \leq b) = \int_a^b f(x) \partial x$$

where $f(x) > 0$ for all x and $\int_{-\infty}^{\infty} f(x) \partial x = 1$.

Note that for continuous random variables, $Pr(X = x) = 0$. This is just to say that it is very very unlikely that any particular value will be realized because there are infinite possibilities.

The integral \int_a^b is the continuous analog of the sum. You don't need to know how to solve an integral, but remember it is like taking a sum over continuous values. The limits

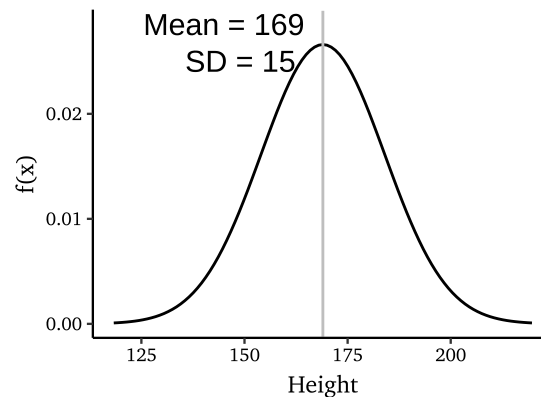
of the integral, a and b , define the interval over which we are taking this sum.

The *cumulative density function* (CDF) for a continuous random variable X is given by:

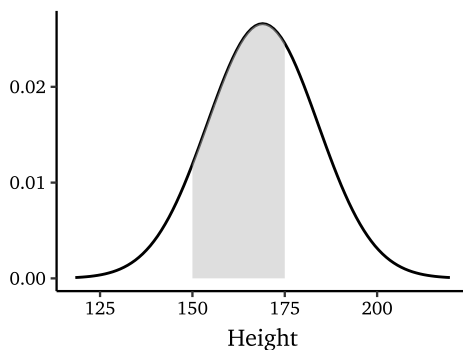
$$F(x_0) = Pr(X \leq x_0) = \int_{-\infty}^{x_0} f(x) \partial x$$

Note that, $Pr(a \leq x \leq b) = F(b) - F(a)$.

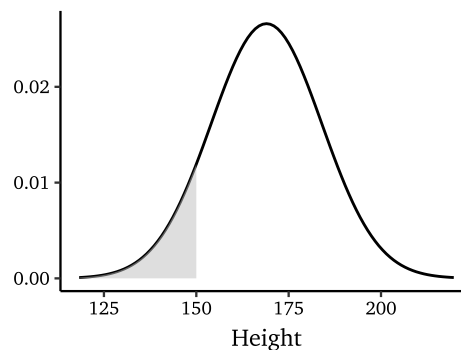
Example. Let's say the distribution for the height of individuals in the world is given by the following probability density function:



We need to find the corresponding area under the curve to find the probability of height being in particular intervals.

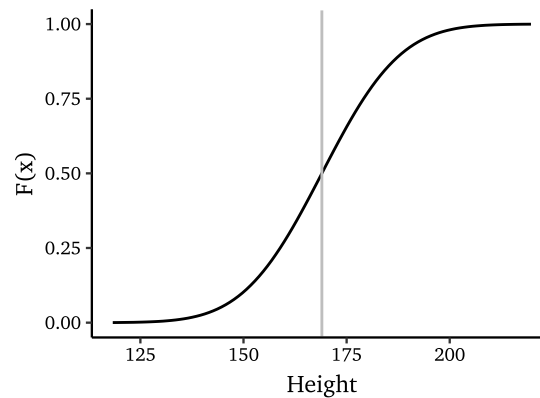


(a) $Pr(150 < X < 175)$



(b) $Pr(X < 150)$

The CDF corresponding to the above PDF looks like:



1.3 Expectation and Variance of Random Variables

The *expectation* or *expected value* or the *mean* of a random variable gives us the average value of this variable over many repeated trials or occurrences. We can compute the expectation as a weighted average of possible outcomes, where the weights are probabilities.

The expectation of a discrete random variable is given by:

$$\mu_X = E(X) = \sum_x x f(x)$$

The expected value for a continuous random variable is given by:

$$\mu_X = E(X) = \int_x x f(x) dx$$

The *variance* measures the dispersion or the “spread” of a probability distribution. The variance for a random variable is given by:

$$\sigma_X^2 = \text{Var}(X) = E[(X - \mu_X)^2]$$

In other words, variance is the expected value of the square of deviations of X from its mean.

Using the definition of expectation for a discrete random variable, we can write:

$$\sigma_X^2 = \text{Var}(X) = E[(X - \mu_X)^2] = \sum_x (x - \mu_X)^2 f(x)$$

Alternative formula for the variance: $\text{Var}(X) = E[(X - \mu_X)^2] = E(X^2) - \mu_X^2$.

Variance is in units of the square of X . Therefore we use *standard deviation*, which is the square-root of variance:

$$\sigma_X = \sqrt{\sigma_X^2}$$

Example. We can calculate the expected value and variance for the outcome of rolling a die as follows:

x	$f(x)$	$xf(x)$	$(x - \mu_X)^2 f(x)$
1	1/6	1/6	(-2.5) ² /6
2	1/6	2/6	(-1.5) ² /6
3	1/6	3/6	(-0.5) ² /6
4	1/6	4/6	(0.5) ² /6
5	1/6	5/6	(1.5) ² /6
6	1/6	6/6	(2.5) ² /6
Total	-	21/6	17.5/6

$$\mu_X = E(X) = \sum_x xf(x) = \frac{21}{6} = 3.5$$

$$\text{Var}(X) = \sum_x (x - \mu_X)^2 f(x) = \frac{17.5}{6}$$

Example. The expected value and variance for a binary random variable that takes value 1 with probability p and 0 with probability $1 - p$ is given by:

$$\mu_X = E(X) = \sum_x xf(x) = 1 \cdot p + 0 \cdot (1 - p) = p$$

$$\text{Var}(X) = \sum_x (x - \mu_X)^2 f(x) = (1 - p)^2 \cdot p + (0 - p)^2 \cdot (1 - p) = p(1 - p)$$

Using the alternative formula for variance:

$$\text{Var}(X) = E(X^2) - \mu_X^2 = 1^2 \cdot p + 0^2 \cdot (1 - p) - \mu_X^2 = p - p^2 = p(1 - p)$$

2 Normal and Standard Normal Distribution

2.1 Normal Distribution

There are lots and lots of probability distributions that are used for modeling different variables. For example, *uniform* distribution is a distribution with constant probability. There are many more, Bernoulli, binomial, gamma, beta, Poisson, and so on.

However, one distribution that appears over and over again is the *normal distribution*. The distribution of a lot of things like height, birthweight, IQ, etc. is normal. The normal distribution is symmetric (i.e., the left and right tails are the same sizes and there's no skew). For this reason, sometimes it is informally referred to as a bell curve. We express normal distribution with mean μ and variance σ^2 as follows:

$$N(\mu, \sigma^2)$$

Figure 2 presents normal distributions with different means and variances.

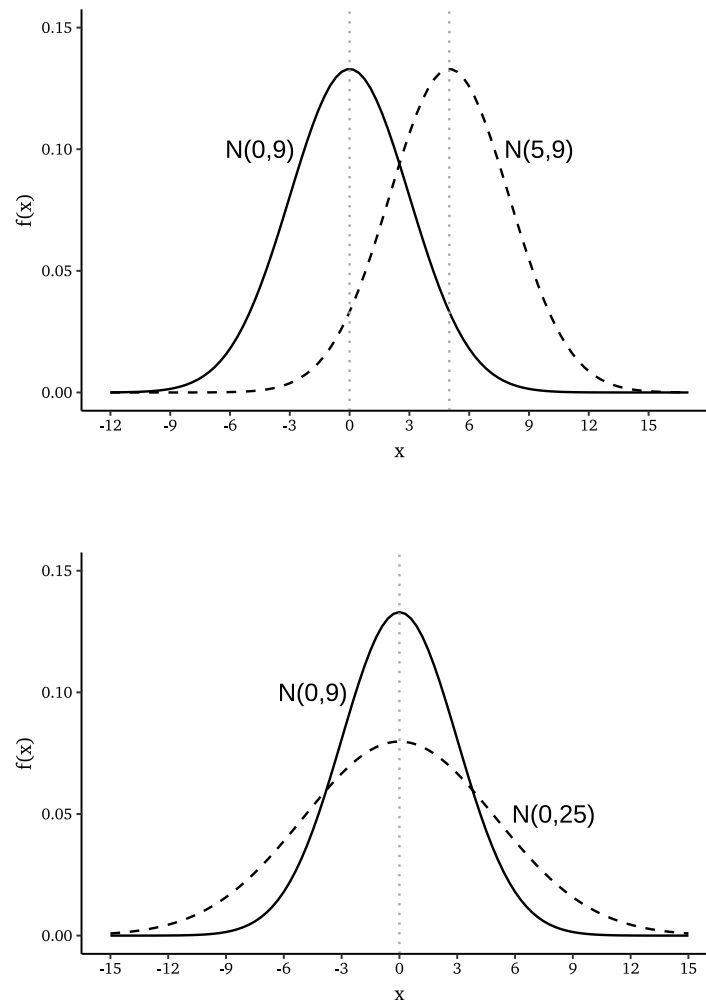
The distribution of height that we saw in the above example was a normal distribution with a mean of 169 and a variance of 225. In which case, we can write *height* $\sim N(169, 225)$, which is short-form for saying height is normally distributed with mean 169 and variance 225.

2.2 Standard Normal Distribution

The normal distribution with mean 0 and variance 1 is called the *standard normal distribution* and is denoted by $N(0, 1)$. Random variables that have a $N(0, 1)$ distribution are often denoted by Z .

In fact, we can standardize any normally distributed variable into a standard normal

Figure 2: Normal distributions with different means and variances



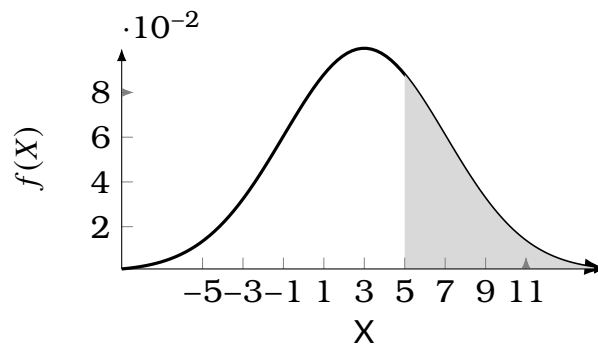
variable by subtracting the mean of the normal variable from each value in the distribution and then dividing by the standard deviation of the distribution. Given $X \sim N(\mu, \sigma^2)$, the standardized random variable is given by:

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

Here, $Z \sim N(0, 1)$. To see why this is the case, note that when we standardize X , we subtract the mean μ from each value of X . This has the effect of shifting the distribution so that its center is at 0. Next, we divide each value by the standard deviation σ . This has the effect of scaling the distribution so that its spread equals 1.

2.3 Finding the area under the curve

We are often interested in finding the probability that a random variable lies in a particular interval. For example, say $X \sim N(3, 16)$, and we want to calculate $Pr(X \geq 5)$. As we said before, to find this probability, we need to calculate the following area under the curve:



However, it can be difficult and time-consuming to calculate the area by hand. Instead, we can standardize this variable and use the *standard normal table* to find this area. The standard normal table provides the area under the standard normal distribution curve for different values of Z .

Given $X \sim N(3, 16)$,

$$Z = \frac{X - 3}{4} \sim N(0, 1)$$

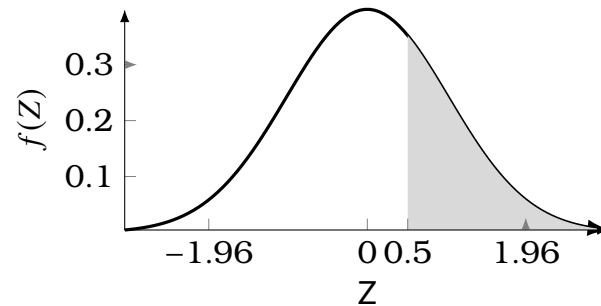
Note that,

$$Pr(X \geq 5) = Pr\left(\frac{X - 3}{4} \geq \frac{5 - 3}{4}\right) = Pr(Z \geq 0.5)$$

We can now refer to the standard normal table and find that $Pr(Z \geq 0.5)$ equals 0.3085. The figure below presents this probability as the area under the curve standard normal curve.

Given $X \sim N(\mu, \sigma^2)$, general recipe to find $Pr(x_0 < X < x_1)$:

- Find $z_0 = (x_0 - \mu)/\sigma$ and $z_1 = (x_1 - \mu)/\sigma$
- Use standard normal table to find $Pr(z_0 < Z < z_1)$



Example. Given $X \sim N(3, 16)$, we want to find $Pr(2 < X < 5)$. Here $x_0 = 2, x_1 = 5$, we can find that $z_0 = (2 - 3)/4 = -0.25$ and $z_1 = (5 - 3)/4 = 0.5$. Now we just need to look at the standard normal table and find $Pr(-0.25 < Z < 0.5)$.

Alternatively, sometimes we wish to identify the value of x for which the probability $Pr(X < x)$ or $Pr(X > x)$ equals a specific value p . This can be achieved in a similar manner by using the standard normal table. In particular, we need to find the corresponding value z that satisfies $Pr(Z < z)$ or $Pr(Z > z)$, and then transform it back to obtain x .

Given $X \sim N(\mu, \sigma^2)$ and $Pr(X < x) = p$, to find x :

- Use standard normal table to find z where $Pr(Z < z) = p$
- Find $x = \mu + z \cdot \sigma$

This follows analogously for when we are given $Pr(X > x) = p$.

3 Multiple Random Variables

3.1 Joint and Marginal Distribution

The *joint probability distribution* of two discrete random variables X and Y , is the probability that the random variables simultaneously take on certain values.

$$f(x, y) = Pr(X = x, Y = y)$$

Example. The table below gives us the probability of possible commute times and rain on a given day.

	Rain ($X = 1$)	No Rain ($X = 0$)	Total
60-min commute ($Y = 60$)	0.3	0.2	0.5
30-min commute ($Y = 30$)	0.1	0.4	0.5
Total	0.4	0.6	1

The *marginal probability distribution* of a random variable Y is just another name for its probability distribution. In particular,

$$f(y) = Pr(Y = y) = \sum_x Pr(X = x, Y = y)$$

For example, the probability of having a 60-minute commute is given by the sum of probability of having a 60-minute commute and no rain and the probability of having a 60-minute commute and rain.

$$Pr(Y = 60) = Pr(X = 1, Y = 60) + Pr(X = 0, Y = 60) = 0.3 + 0.2 = 0.5$$

3.2 Conditional Probability and Bayes Rule

The distribution of a random variable Y conditional on another random variable X taking on a specific value is called the *conditional distribution* of Y given X .

$$f(y|x) = Pr(Y = y|X = x) = \frac{Pr(X = x, Y = y)}{Pr(X = x)} = \frac{f(x, y)}{f(x)}$$

For example, the probability of having a 60-minute commute conditional on rain is given by:

$$Pr(Y = 60|X = 1) = \frac{Pr(X = 1, Y = 60)}{Pr(X = 1)} = \frac{0.3}{0.4} = \frac{3}{4}$$

While the probability of having a 60-minute commute conditional on no rain is given

by:

$$Pr(Y = 60|X = 0) = \frac{Pr(X = 0, Y = 60)}{Pr(X = 0)} = \frac{0.2}{0.6} = \frac{1}{3}$$

Remember, the unconditional probability of having a 60-minute commute was given by 0.5.

The *conditional expectation* of Y given X is the mean of the conditional distribution of Y given X .

$$E(Y|X = x) = \sum_y y Pr(Y = y|X = x)$$

For the example above,

$$E(Y|X = 1) = 60 \cdot Pr(Y = 60|X = 1) + 30 \cdot Pr(Y = 30|X = 1) = 60 \cdot \frac{3}{4} + 30 \cdot \frac{1}{4} = 52.5$$

Similarly,

$$E(Y|X = 0) = 60 \cdot Pr(Y = 60|X = 0) + 30 \cdot Pr(Y = 30|X = 0) = 60 \cdot \frac{1}{3} + 30 \cdot \frac{2}{3} = 40$$

So by comparing $E(Y|X = 1)$ and $E(Y|X = 0)$, we can find out how rain affects the average commute time.

Bayes' rule says that the conditional probability of Y given X is the conditional probability of X given Y times the relative marginal probabilities of Y and X :

$$Pr(Y = y|X = x) = \frac{Pr(X = x|Y = y)Pr(Y = y)}{Pr(X = x)}$$

This is a very useful law because it says that we can deduce conditional probabilities from the reverse conditional probability with the help of marginal probabilities.

3.3 Law of Iterated Expectations

The mean of Y is the weighted average of the conditional expectation of Y given X , weighted by the probability distribution of X .

$$E(Y) = \sum_x E(Y|X = x)Pr(X = x)$$

More compactly,

$$E(Y) = E(E(Y|X))$$

E.g. the mean height of adults is the weighted average of the mean height of men and women, weighted by their proportions.

3.4 Independence and Uncorrelatedness

Two random variables X and Y are independently distributed, or *independent*, if knowing the value of one of the variables provides no information about the other. That is,

$$Pr(Y = y|X = x) = Pr(Y = y)$$

Then by Bayes' rule:

$$Pr(X = x, Y = y) = Pr(X = x)Pr(Y = y)$$

Example: Two consecutive coin tosses.

Note: We can equivalently say that X and Y are independent if $E(Y|X) = E(Y)$.

Covariance is a measure of the extent to which two random variables move together. Let X and Y be a pair of random variables, then the *covariance* of X and Y is given by:

$$\sigma_{XY} = Cov(X, Y) = E[(X - \mu_X)(Y - \mu_Y)] = E(XY) - \mu_X\mu_Y$$

The *correlation* between X and Y is given by:

$$\rho_{XY} = corr(X, Y) = \frac{Cov(X, Y)}{\sigma_X\sigma_Y} \quad \text{where } -1 \leq \rho \leq 1$$

X and Y are uncorrelated if $\rho_{XY} = \sigma_{XY} = 0$ i.e. $E(XY) = E(X)E(Y)$.

If X and Y are independent, then they are also uncorrelated.

$$E(Y|X) = E(Y) \rightarrow \rho_{XY} = 0$$

However, it is not necessarily true that if X and Y are uncorrelated, then they are also independent.

4 Linear Functions of Random Variables

4.1 Linear Functions of a Single Random Variable

If X is a random variable and $Y = a + bX$, then Y is also a random variable with

$$E(Y) = a + bE(X) \quad \text{Var}(Y) = b^2\text{Var}(X)$$

In addition, a linear transformation of a random variable does not change the shape of the distribution. So if X is normal, Y will also be normal.

Example. Let us calculate the expectation and variance for the Z score:

$$Z = \frac{X - \mu_X}{\sigma_X}$$

Note that we can write,

$$Z = -\frac{\mu_X}{\sigma_X} + \frac{1}{\sigma_X} \cdot X$$

So $a = -\frac{\mu_X}{\sigma_X}$ and $b = \frac{1}{\sigma_X}$, then by the above formulas:

$$E(Z) = a + bE(X) = -\frac{\mu_X}{\sigma_X} + \frac{1}{\sigma_X}\mu_X = 0$$

$$\text{Var}(Z) = b^2\text{Var}(X) = \frac{1}{\sigma_X^2} \cdot \sigma_X^2 = 1$$

So if $X \sim N(\mu_X, \sigma_X^2)$, then $Z \sim N(0, 1)$.

4.2 Linear Combination of Two Random Variables

X and Y is a pair of random variables, define

$$W = aX + bY$$

Then the expectation of W is given by:

$$E(W) = aE(X) + bE(Y)$$

And the variance of W is given by:

$$\text{Var}(W) = a^2\text{Var}(X) + b^2\text{Var}(Y) + 2ab\text{Cov}(X, Y)$$

If X and Y are independent then $\text{Cov}(X, Y) = 0$, so in that case $\text{Var}(W) = a^2\text{Var}(X) + b^2\text{Var}(Y)$.

4.3 Linear Combination of Several Random Variables

For random variables, X_1, X_2, \dots, X_n :

$$E(X_1 + X_2 + \dots + X_n) = E(X_1) + E(X_2) + \dots + E(X_n)$$

$$\text{Var}(X_1 + X_2 + \dots + X_n) = \sum_{i=1}^n \text{Var}(X_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{Cov}(X_i, X_j)$$

If X_1, X_2, \dots, X_n are independent random variables, then $\text{Var}(\sum_i X_i) = \sum_i \text{Var}(X_i)$.

Note that a linear combination of several normally distributed random variables will also be normal.

Sampling and Estimation

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Instructor: Div Bhagia

We often want to make inferences about a population. But a lot of times, it is only possible to collect data from some individuals in the population. Therefore, we collect data from a smaller subset of the population, called a sample. However, the sample must be selected carefully to ensure that the inferences we make from the sample accurately reflect the characteristics of the population.

One way to achieve a representative sample is through the use of *random sampling*. In a random sample, each individual in the population has an equal chance of being selected for the sample. This helps reduce bias that could be introduced if individuals were chosen based on specific characteristics.

Sample statistics, such as the sample mean or sample standard deviation, are quantities calculated from a sample of data. Because the sample is only a subset of the entire population, sample statistics vary from sample to sample. This variability means that *sample statistics are random variables*.

To see why sample statistics are random variables, consider the sample mean as an example. Suppose we take multiple random samples of the same size from a population and calculate the mean for each sample. We expect these sample means to vary from sample to sample due to the variability inherent in the sampling process. Thus, the sample mean is a random variable since it can take on different values depending on the sample that is selected.

1 Distribution of Sample Mean

Let X_1, X_2, \dots, X_n denote independent random draws (random sample) from a population with mean μ and variance σ^2 . We can calculate the sample mean as follows:

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

We can show that the expectation and the variance of the sample mean are given by¹:

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

The expected value of the sample mean is equal to the population mean, which means that if we were to take an infinite number of random samples and calculate the mean of each sample, the average of these sample means would be equal to the population mean.

The variance of the sample mean refers to the amount of variability or spread that we would expect to see in the sample means that we would obtain if we were to take multiple random samples from a population.

The variance of the sample mean is equal to the population variance divided by the sample size. From this formula, we can see that when sample size increases, the variance of the sample mean decreases, and the sample mean becomes a more precise estimator of the population mean. This is because by increasing the sample size, we can reduce the effects of random variation and sampling error.

On the other hand, variance of the sample mean increases with the variance of the population. This means that when we take repeated random samples of a fixed size from a highly variable population, we are likely to observe more variability in the sample means from sample to sample.

The distribution of the sample mean is normal if *either* of the following is true:

- The underlying population is normal
- The sample size is large, say $n \geq 100$

The first one follows from the sample mean being a linear combination of normally distributed variables. The latter is implied by the *Central Limit Theorem*.

¹Derivations at the end.

Central Limit Theorem

Central Limit Theorem (CLT) states that if X_1, X_2, \dots, X_n are drawn randomly from a population with mean μ and variance σ^2 , sample mean \bar{X} is normally distributed with mean μ and variance σ^2/n as long as n is large.

$$\bar{X} \sim N(\mu, \sigma^2/n)$$

In other words, CLT states that as we increase the sample size, the distribution of the sample means tends to approximate a normal distribution, regardless of the underlying distribution of the population.

2 Estimators

An estimator $\hat{\theta}$ for the population parameter θ is said to be *unbiased* if

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

Examples: \bar{X} for μ , s^2 for σ^2 But lots of estimators are unbiased. For example, say our estimator is X_1 , then $E(X_1) = \mu$. This doesn't sound right. What else should we be looking for?

When choosing between two unbiased estimators $\hat{\theta}_1$ and $\hat{\theta}_2$, we prefer the lower variance estimator. We say the lower variance estimator is more *efficient*.

3 Confidence Intervals

Since the sample mean is a random variable, we cannot expect it to be exactly equal to the true population mean in any particular sample. However, if we have a large and random sample, we can use the sample mean as an estimate of the population mean with some degree of confidence. The sample variance measures how much the sample mean deviates from the population mean on average. Confidence intervals are another way to summarize this uncertainty by providing a range of values that contains the population mean with a certain probability.

Essentially our goal is to create an interval around the sample mean that gives us a range of plausible values for the population mean. We can have confidence intervals of varying levels of confidence, most common are 90%, 95%, or 99%. The level of confidence is the probability that a calculated confidence interval contains the true population parameter.

Say we are interested in creating a 95% confidence interval for the true population mean. If we can conclude that $\bar{X} \sim N(\mu, \sigma_{\bar{X}}^2)$, then

$$Z = \frac{\bar{X} - \mu}{\sigma_{\bar{X}}^2} = \frac{\bar{X} - \mu}{\sigma^2/\sqrt{n}} \sim N(0, 1)$$

Note that from the formula for the variance of the sample mean $\sigma_{\bar{X}}^2 = \sigma^2/\sqrt{n}$.

From the standard normal table we can see that $Pr(-1.96 < Z < 1.96) = 0.95$. This implies that

$$P\left(\mu - 1.96 \cdot \frac{\sigma^2}{\sqrt{n}} < \bar{X} < \mu + 1.96 \cdot \frac{\sigma^2}{\sqrt{n}}\right) = 0.95$$

The above implies that the sample mean \bar{X} is within 1.96 standard deviations of the population mean μ with a 95% probability. We can now push this reasoning further and say that in that case, it must be that the population mean μ is within 1.96 standard deviations of any realization of the sample mean \bar{X} with a 95% probability. In other words, if we observe a sample mean \bar{x} , then there is a 95% chance that the population mean μ is within 1.96 standard deviations of \bar{X} . This gives us a way to construct a 95% confidence interval for μ based on \bar{x} as follows:

$$\bar{x} \pm 1.96 \cdot \frac{\sigma}{\sqrt{n}}$$

Confidence Interval: Known Population Variance

Let $z_{\alpha/2}$ be the z -value that leaves area $\alpha/2$ in the upper tail of the normal distribution. Then $1 - \alpha$ confidence interval is given by

$$\bar{x} \pm \underbrace{z_{\alpha/2} \frac{\sigma}{\sqrt{n}}}_{\text{Margin of Error}}$$

The margin of error is influenced by two main factors: the standard deviation of the sample mean, which in turn is affected by both the population standard deviation and the sample size, and the level of confidence. As the level of confidence increases, the margin of error also increases, resulting in a wider interval. If greater confidence is desired, a wider range of values must be considered. Additionally, if the sample variance is higher, there is more uncertainty, which leads to a wider interval.

Unknown Population Variance

Until now, we have made the assumption that the population variance is known, but this is often not the case in practice. However, we can rely on the sample variance as an unbiased estimator for the population variance. As a result, we can no longer construct the Z statistic, but we can use the T statistic instead, which is essentially the same as the Z statistic, but utilizes the sample standard deviation instead of the population standard deviation. This T statistic is defined as:

$$T = \frac{\bar{X} - \mu}{S/\sqrt{n}} \sim t_{n-1}$$

It has been shown that this statistic follows a t distribution with $n - 1$ degrees of freedom. The t -distribution is similar to the normal distribution, but it has thicker tails to account for the greater uncertainty in smaller sample sizes. In larger sample sizes, the t -distribution can be approximated by the standard-normal distribution.

To construct a confidence interval using the T statistic, we can use the same approach as before, but we now need to use the critical value for the t -distribution, denoted as $t_{\alpha/2, n-1}$.

Confidence Interval: Unknown Population Variance

Let $t_{\alpha/2, n-1}$ be the t -value that leaves area $\alpha/2$ in the upper tail of the t -distribution with $n - 1$ degrees of freedom. Then $1 - \alpha$ confidence interval is given by

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

However, if the sample size is larger than or equal to 100, the t -distribution can be

approximated by the standard-normal distribution. In this case, we can continue to use the standard-normal table for the critical values.

4 Hypothesis Testing

So far, we have discussed that when we use a sample to make inferences about the population, the sample statistic is not necessarily equal to the population parameter. However, we might be interested in knowing how plausible it is that the population parameter takes a particular value given our realization of the sample mean. To do this, we can formally test the hypothesis that the population parameter takes a particular value.

Say, we are interested in determining whether the population mean μ is equal to a particular value μ_0 . We found a sample mean of \bar{x} . We can formally test our hypothesis $\mu = \mu_0$ by following a set of steps. However, before we proceed, we need to choose a significance level. The significance level is the probability of rejecting the null hypothesis when it is actually true. Common significance levels are 0.01, 0.05, or 0.1, which correspond to a 1%, 5%, or 10% chance of rejecting the null hypothesis when it is actually true.

The steps for testing the hypothesis $\mu = \mu_0$ are as follows:

1. *Formulate the null and alternative hypothesis*

$$H_0 : \mu = \mu_0 \quad H_1 : \mu \neq \mu_0$$

The null hypothesis assumes that the population mean is equal to the specified value μ_0 , while the alternative hypothesis assumes that it is not.

2. *Determine the distribution of the test statistic under the null.* If we can conclude that the sample mean is normally distributed around the true population mean, then *under the null* $\bar{X} \sim N(\mu_0, \sigma^2/n)$. This implies that under the null, and T -statistic is distributed according to t_{n-1} (or the Z statistic is distributed according to the

standard normal distribution).

$$T = \frac{\bar{X} - \mu_0}{S/\sqrt{n}} \sim t_{n-1}$$

3. *Determine the rejection region.* We reject the null hypothesis when the calculated test statistic falls in the $\alpha\%$ most extreme outcomes of its distribution. This is because we started by assuming the null hypothesis to be true, and if we find a value that is too far in the tails, it suggests that the null hypothesis is unlikely to be true. Thus, we reject the null hypothesis in favor of the alternative hypothesis.
4. Calculate the test statistic (T or Z depending on if you know the population variance or not) and reject or fail to reject the null.

$$t = \frac{\bar{x} - \mu_0}{S/\sqrt{n}}$$

If the test statistic falls in the rejection region, we reject the null hypothesis in favor of the alternative hypothesis. So reject the null if $|t| > t_{n-1, \alpha/2}$ where $t_{n-1, \alpha/2}$ is the critical value of the t-distribution with $n - 1$ degrees of freedom at a significance level of α .

p-value

In hypothesis testing, the p-value is the probability of observing a test statistic as extreme or more extreme than the one calculated from the sample data, assuming the null hypothesis is true. We can calculate it by finding the area in the tails of the distribution beyond the absolute value of the observed test statistic and doubling it. In particular,

$$p = 2Pr(T \geq |t| | H_0 : \mu = \mu_0)$$

To put it simply, the p-value measures the strength of evidence against the null hypothesis. A small p-value indicates that the observed data is unlikely to have occurred by chance alone, and provides evidence in favor of the alternative hypothesis. On the

other hand, a large p -value suggests that the observed data could have occurred by chance, and there is not enough evidence to reject the null hypothesis.

We can use the significance level α and p -value to make a decision about whether to reject or fail to reject the null hypothesis. In particular, if the p -value is smaller than the significance level, we reject the null hypothesis, and if the p -value is greater than or equal to the significance level, we fail to reject the null hypothesis.

It is important to note that the p -value does not give any information about the size of the effect or the practical significance of the result. It only provides information on the statistical significance of the result.

Additional Derivations

The expectation of the sample mean can be derived as follows:

$$\begin{aligned} E(\bar{X}) &= E\left(\frac{1}{n} \sum_{i=1}^n X_i\right) \\ &= \frac{1}{n} E\left(\sum_{i=1}^n X_i\right) \\ &= \frac{1}{n} \sum_{i=1}^n E(X_i) \\ &= \frac{1}{n} n\mu = \mu \end{aligned}$$

The variance of the sample mean can be derived as follows:

$$\begin{aligned} \text{Var}(\bar{X}) &= \text{Var}\left(\frac{1}{n} \sum_{i=1}^n X_i\right) \\ &= \frac{1}{n^2} \sum_{i=1}^n \text{Var}(X_i) \\ &= \frac{1}{n^2} n\sigma^2 \\ &= \frac{\sigma^2}{n} \end{aligned}$$

Confidence Intervals: Example

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Example: Blood Pressure in Massachusetts

We picked a random sample of 100 people from Massachusetts and took their blood pressure. The average diastolic blood pressure in our sample was 75. We don't know the true underlying population mean and want to use our sample estimate to make inferences about it. For now assume that even though we don't know the population mean, we do know that the population variance is $\sigma^2 = 552.25$.

In addition, we know that $E(\bar{X}) = \mu$ and $Var(\bar{X}) = \frac{\sigma^2}{n}$. In this example:

$$Var(\bar{X}) = \frac{552.25}{100} = 5.52$$

and the standard deviation of \bar{X} , $\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} = \frac{23.5}{10} = 2.35$.

The sample mean is useful but not so much without its standard deviation. Every time we pick a random sample, it is one out of many samples we could have picked. In which case, the sample mean of 75 we got above is one of the many sample means we could have got. We know that despite this sampling variation, the sample mean is an unbiased estimator of μ . So we could get numbers larger or smaller than the true μ but on average, they will cancel out.

The standard deviation tells us how much further from μ our realizations could be. In other words, the standard deviation tells us how good or precise our estimate is. The standard deviation of the sample mean is lower if the underlying population is more similar (lower σ) or if we have a larger sample size (higher n) since both of these reduce the scope of sampling variation affecting our estimate.

Going a step further, if we know the distribution of the sample mean, we can attach probabilities to certain intervals of outcomes. In our example, since $n \geq 100$ we can invoke the Central Limit Theorem (CLT) and conclude that \bar{X} is normally distributed. So,

$$\bar{X} \sim N(\mu, 5.52)$$

Knowing the distribution of the sample mean helps us calculate areas under the curve that correspond to probabilities of outcomes in certain intervals.

90% Confidence Interval

Say we are interested in constructing a 90% confidence interval (CI) around the mean.

A $1 - \alpha$ CI is given by

$$\bar{X} \pm z_{\alpha/2} \frac{\sigma}{n}$$

where $z_{\alpha/2}$ leaves area $\alpha/2$ in the upper tail of the normal distribution. Here $1 - \alpha = 0.90$, so $\alpha = 0.10$. We need to find $z_{0.05}$ which is equal to 1.645 (from the standard normal table). So our 90% CI in this example is given by

$$75 \pm 1.645 \times 2.35$$

Interpretation: We are 90% confident that the true mean diastolic blood pressure in Massachusetts is between 71.13 and 78.86. Although the true mean may or may not be in this interval, 90% of intervals formed in this manner will contain the true mean.

A 95% CI would be wider as the margin of error has to be larger when we want to be 95% confident vs 90% confident. The margin of error will also be larger if the standard deviation of the sample mean is larger.

Hypothesis Testing: Example

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Example: Blood Pressure in Massachusetts (Continued.)

We picked a random sample of 100 people from Massachusetts and took their blood pressure. The average diastolic blood pressure in our sample was 75. We think that the true average blood pressure in the population should have been 78. We would like to test this hypothesis formally.

Hypothesis Testing: Two-Tailed Test

Step 1: State the null hypothesis and the alternative hypothesis.

$$H_0 : \mu = 78 \quad H_1 : \mu \neq 78$$

This will imply a two-tailed hypothesis test as values far above and far below 78 will cause us to reject the null hypothesis.

Step 2: Find the distribution of the test statistic under the null.

Here we have $n \geq 100$, so by CLT we know that \bar{X} is normally distributed. In addition, we are assuming we know that the population variance is $\sigma^2 = 552.25$. So we can calculate the variance of the sample mean $\sigma_{\bar{X}}^2 = \frac{\sigma^2}{n} = \frac{552.25}{100} = 5.52$. Under the null $\bar{X} \sim N(78, 5.52)$. So test statistic constructed as follows

$$Z = \frac{\bar{X} - \mu_0}{\sigma_{\bar{X}}}$$

is distributed normal with mean 0 and variance 1 i.e. $Z \sim N(0, 1)$.

Step 3: Determine the rejection region.

At 10% level of significance, we find the 5% of outcomes that are furthest above and

5% of outcomes that are furthest below zero.

$$z_{\alpha/2} = z_{0.05} = 1.64$$

We reject the null if our test statistic $z > 1.64$ or if $z < -1.64$.

Step 4: Find the test statistic and decide whether to reject the null.

$$z = \frac{75 - 78}{2.35} = -1.28$$

As $-1.64 < -1.28 < 1.64$, we do not reject the null. This automatically implies that we would not have rejected this null at 1% or 5% either.

P-Value

What is the p-value associated with our test statistic? In other words, what is the probability that we would randomly select a sample mean that is 1.28 standard deviations or more away from the (hypothesized) population mean?

$$p = 2P(Z > |z| | H_0 : \mu = 78) = 2P(Z > 1.28) = 2 \times 0.10 = 0.20$$

You should recognize that this is really $Pr(Z > 1.28) + Pr(Z < -1.28)$. Due to the symmetry properties of the Normal distribution, this is the same as $2P(Z > 1.28)$.

The p-value implies that our test statistic is (just barely) in the 20% percent of most surprising outcomes given that our null hypothesis is true. It is not in the 10% percent of outcomes that are most surprising if the null is true. Therefore, our null cannot be rejected at a 10% significance level. Put another way, the probability of being at least 1.28 standard deviations away from the mean is approximately 20% and thus higher than the 10% significance level.

One-Tailed Test

This topic was not included in our classroom instruction and is not necessary for the exam. The information is simply provided for your personal interest.

Now

$$H_0 : \mu > 78 \quad H_1 : \mu \leq 78$$

The only thing that changes in this case from when we were doing a two-tailed test is the rejection region. Test statistic outcomes far above 0 would be surprising, but obtaining a sample mean many standard deviations above 78 would not cause us to reject this null hypothesis. This implies a one-tailed test.

As we are using a 10% significance level, we find the 10% of outcomes that are furthest below zero. Our critical value here is $z_\alpha = z_{0.10} = -1.28$, which tells us the cutoff for leaving 10 percent probability on the negative side tail. We will reject our null hypothesis if $z < -1.28$. Here $z = -1.28$, so we fail to reject the null.

Note: In the one-tailed test we did here, any $\mu_0 < 75$ would automatically never be rejected. (Finding an average of 75 does not make me reject the idea that the average is greater than 70)