

# Lecture Notes for Math 472: Statistical Inference

Last updated: February 5, 2026

## Contents

<b>0</b>	<b>Tentative course outline</b>	<b>3</b>
<b>1</b>	<b>2025-01-12   Week 01   Lecture 01</b>	<b>4</b>
1.1	What is probability? . . . . .	4
1.1.1	A general framework: sample space, events, etc . . . . .	4
1.1.2	Definition of probability measure . . . . .	5
<b>2</b>	<b>2026-01-14   Week 01   Lecture 02</b>	<b>6</b>
2.1	Independent events and conditional probabilities . . . . .	6
2.2	Random variables . . . . .	7
<b>3</b>	<b>2026-01-16   Week 01   Lecture 03</b>	<b>8</b>
3.1	Random variables . . . . .	8
3.1.1	Discrete vs continuous . . . . .	8
3.1.2	Expected value . . . . .	8
3.1.3	Joint distributions . . . . .	9
<b>4</b>	<b>2026-01-21   Week 02   Lecture 04</b>	<b>10</b>
4.1	Independence of random variables . . . . .	10
4.1.1	Definition and characterization . . . . .	10
4.1.2	Independence and expectations/variances . . . . .	10
4.1.3	Independence and long-term behavior: the weak law of large numbers . . . . .	11
<b>5</b>	<b>2026-01-23   Week 02   Lecture 05</b>	<b>12</b>
5.1	Proof of the weak law of large numbers . . . . .	12
5.2	Equality in distribution . . . . .	12
5.3	Populations and samples . . . . .	13
<b>6</b>	<b>2026-01-26   Week 03   Lecture 06</b>	<b>14</b>
6.1	Sampling . . . . .	14
6.2	What is a statistic? . . . . .	14
<b>7</b>	<b>2026-01-28   Week 03   Lecture 07</b>	<b>16</b>
7.1	Basic examples of statistics and estimators . . . . .	16
<b>8</b>	<b>2026-01-30   Week 03   Lecture 08</b>	<b>18</b>
8.1	The Gaussian distribution . . . . .	18

<b>9</b>	<b>2026-02-02   Week 04   Lecture 09</b>	<b>21</b>
9.1	Motivation: “Approximate” standardization . . . . .	21
9.2	The chi-squared distribution . . . . .	22
9.3	Definition of the Student t-distribution . . . . .	23
<b>10</b>	<b>2026-02-04   Week 04   Lecture 10</b>	<b>24</b>
10.1	Using the student t-distribution . . . . .	24
<b>11</b>	<b>2026-02-06   Week 04   Lecture 11</b>	<b>26</b>
11.1	The central limit theorem . . . . .	26
11.1.1	Point Estimation . . . . .	27
11.1.2	Mean square error . . . . .	29

## 0 Tentative course outline

This course is a problem-oriented introduction to the basic concepts of probability and statistics, providing a foundation for applications and further study.

1. **Weeks 1-2.** Sampling distributions (4 lessons).  
chi-squared, t, and F distributions, distributions of sample mean and variance
2. **Weeks 3-4.** Point estimation (5 lessons)  
properties and methods of point estimation
3. **Weeks 5-6.** Interval estimation (4 lessons)  
Confidence intervals for means, variances, proportions and differences
4. **Weeks 7-12.** Hypothesis Testing (19 lessons)  
Neyman-Pearson lemma, likelihood ratio test; tests concerning means and variances, tests based on count data, nonparametric tests, analysis of variance
5. **Weeks 13-14.** Regression and correlation (6 lessons)  
regression, bivariate normal distributions, method of least squares

# 1 2025-01-12 | Week 01 | Lecture 01

- give syllabus
- do activity with why you're in this course

*The nexus question of this lecture: What is a probability?*

**Reading assignment:** Sections 1.1, 1.2, 1.3, 2.1, 2.4 of the textbook.

## 1.1 What is probability?

### 1.1.1 A general framework: sample space, events, etc

We begin with a general framework and some terminology to formalize the notions of probability. This is based on section 2.4 in the textbook.

- An **experiment** is an activity or process whose outcome is subject to uncertainty, and about which an observation is made.

Examples include flipping a coin, rolling a dice, measuring the size of a wave, or the amount of rainfall, conducting a poll, performing a diagnostic test, opening a pack of Pokemon cards, etc.

- The **sample space**  $S$  of an experiment is the set of all possible outcomes. The elements of the sample space are called **sample points**.

We think of each sample point as representing a unique outcome of the experiment. In the case of rolling a dice, the sample points are 1, 2, 3, 4, 5 and 6, and the sample space is  $S = \{1, 2, 3, 4, 5, 6\}$ .

- We use the term **event** to refer to a collection of outcomes, i.e., a subset of  $S$ .

Example: if our experiment is rolling a 6-sided dice, here are some events

$A = [\text{observe an odd number}]$	$E_2 = [\text{observe a 2}]$
$B = [\text{observe an even number}]$	$E_3 = [\text{observe a 3}]$
$C = [\text{observe a number less than 5}]$	$E_4 = [\text{observe a 4}]$
$D = [\text{observe a 2 or a 3}]$	$E_5 = [\text{observe a 5}]$
$E_1 = [\text{observe a 1}]$	$E_6 = [\text{observe a 6}]$

- There are two types of events: **compound events**, which can be decomposed into other events, and **simple events**, which cannot.

In the above example, the events  $A, B, C$  and  $D$  are compound events.  $E_1, \dots, E_6$  are simple events.

- A sample space is **discrete** if it is countable (i.e., finite or countably infinite). In a discrete sample space  $S$ , the set of all possible events is the **power set** of  $S$ .<sup>1</sup>

In the dice-rolling example, the set of all possible events is  $\{E : E \subseteq \{1, 2, 3, 4, 5, 6\}\}$ .

$A = [\text{observe an odd number}] = \{1, 3, 5\}$	$E_2 = [\text{observe a 2}] = \{2\}$
$B = [\text{observe an even number}] = \{2, 4, 6\}$	$E_3 = [\text{observe a 3}] = \{3\}$
$C = [\text{observe a number less than 5}] = \{1, 2, 3, 4\}$	$E_4 = [\text{observe a 4}] = \{4\}$
$D = [\text{observe a 2 or a 3}] = \{2, 3\}$	$E_5 = [\text{observe a 5}] = \{5\}$
$E_1 = [\text{observe a 1}] = \{1\}$	$E_6 = [\text{observe a 6}] = \{6\}$

<sup>1</sup>If  $S$  is not discrete, a complication arises: in that case, some subsets of  $S$  are too wild and untameable for us to treat them mathematically as “events”. Resolving that issue requires introducing measure theory, which is beyond the scope of this class, so we will ignore it and simply steer clear of any setting where any issues might arise.

- Some observations about events:
    - The sample points are *elements* of  $S$ . The simple events are *singleton subsets* of  $S$ . In the dice example, we have:
      - \* Sample points: 1,2,3,4,5,6.
      - \* Simple events:  $\{1\}, \{2\}, \{3\}, \{4\}, \{5\}, \{6\}$ .
    - The empty set  $\emptyset$  and the whole sample space  $S$  are always both events:  $\emptyset$  is the event “nothing happens” and  $S$  is the event “something happens”.
    - Events satisfy the properties of a boolean algebra:
      - \* “**And**”: If  $E$  and  $F$  are events, then  $E \cap F$  is the event that  $E$  and  $F$  occur.
      - \* “**Or**”: If  $E$  and  $F$  are events, then  $E \cup F$  is the event that  $E$  or  $F$  occurs.
      - \* “**Not**”: If  $E$  is an event, then  $E^c = S \setminus E$  is the event that  $E$  does not occur.
  - Two events  $E$  and  $F$  are **mutually exclusive** if  $E \cap F = \emptyset$ . This means that  $E$  and  $F$  cannot both happen at the same time.
- In the dice example, the events  $A$  and  $B$  are mutually exclusive, since the dice roll cannot be both even and odd. But  $A$  and  $C$  are not mutually exclusive because  $A \cap C = \{1, 3\} \neq \emptyset$ . If a 1 or a 3 is rolled, then both  $A$  and  $C$  occur.

### 1.1.2 Definition of probability measure

**Definition 1** (Probability measure). Let  $S$  be a sample space associated with an experiment. A function  $\mathbb{P}$  is said to be a **probability measure** on  $S$  if it satisfies the following three axioms:

**A.1** (Nonnegativity) For every event  $E \subseteq S$ ,

$$\mathbb{P}[E] \geq 0.$$

**A.2** (Total mass one)  $\mathbb{P}[S] = 1$ .

**A.3** (Countable additivity) If  $E_1, E_2, \dots$  is a sequence of events which are pairwise mutually exclusive (meaning  $E_i \cap E_j = \emptyset$  if  $i \neq j$ ), then

$$\mathbb{P}[E_1 \cup E_2 \cup \dots] = \sum_{i=1}^{\infty} \mathbb{P}[E_i].$$

If  $\mathbb{P}$  is a probability measure, then for every event  $E \subseteq S$ , the number  $\mathbb{P}[E]$  is called the **probability** of  $E$ .

The above definition only tells us the conditions an assignment of probabilities must satisfy; it doesn't tell us how to assign specific probabilities to events.

Probability measures satisfy some basic properties:

**Proposition 2** (Basic properties of probability measure). *If  $\mathbb{P}$  is a probability measure, then the following properties hold:*

- (The null event has probability zero)  $\mathbb{P}[\emptyset] = 0$ .
- (Finite additivity) Let  $\{E_1, \dots, E_n\}$  be a finite sequence of events. If the sequence is pairwise disjoint, then

$$\mathbb{P}[E_1 \cup E_2 \cup \dots \cup E_n] = \mathbb{P}[E_1] + \mathbb{P}[E_2] + \dots + \mathbb{P}[E_n].$$

- (“With probability one, an event  $E$  either does occur or doesn't”)  $\mathbb{P}[E^c] = 1 - \mathbb{P}[E]$ .

- (Excision Property) If  $A, B$  are events and  $A \subseteq B$ , then

$$\mathbb{P}[B \setminus A] = \mathbb{P}[B] - \mathbb{P}[A].$$

- (“The particular is less likely than the general”) If  $A, B$  are events and  $A \subseteq B$ , then  $\mathbb{P}[A] \leq \mathbb{P}[B]$ .

- (“Probabilities are between 0 and 1”) For any event  $E$ ,  $\mathbb{P}[E] \in [0, 1]$ .

## 2 2026-01-14 | Week 01 | Lecture 02

*The topic of this lecture: independent events, conditional probabilities, random variables*

### 2.1 Independent events and conditional probabilities

*This section is based on section 2.7 in the textbook.*

**Definition 3** (Independence). Two events  $A$  and  $B$  are said to be **independent** if  $\mathbb{P}[A \cap B] = \mathbb{P}[A] \mathbb{P}[B]$ . Otherwise, the events are said to be dependent.

**Definition 4** (Conditional probability). Let  $A, B$  be events, and assume that  $\mathbb{P}[B] > 0$ . Then the **conditional probability of  $A$ , given  $B$** , denoted  $\mathbb{P}[A | B]$ , is given by the formula

$$\mathbb{P}[A | B] = \frac{\mathbb{P}[A \cap B]}{\mathbb{P}[B]}.$$

**Interpretation:**  $\mathbb{P}[A | B]$  is the probability of  $A$  when we know that event  $B$  happened.

**Definition 5.** We say that there exists a **positive relationship** between events  $A$  and  $B$  if

$$\mathbb{P}[A | B] > \mathbb{P}[A],$$

and a **negative relationship** if

$$\mathbb{P}[A | B] < \mathbb{P}[A].$$

**Remark 6.** Note the the conditions of Definition 5 are symmetric in the sense that

$$\mathbb{P}[A | B] > \mathbb{P}[A] \iff \mathbb{P}[B | A] > \mathbb{P}[B],$$

provided that both  $A$  and  $B$  have positive probability.

**Example 7.** Roll a 6-sided dice. Let  $A$  be the event that a ‘2’ was rolled, and  $B$  be the event that an even number was observed.

- The unconditional probability:  $\mathbb{P}[A] = 1/6$ .
- The conditional probability:  $\mathbb{P}[A | B] = 1/3$ .

Since  $\frac{1}{3} > \frac{1}{6}$ , we conclude there is a positive relationship between rolling a ‘2’ and rolling an even number.

End of Example 7.  $\square$

The notion of independence formalizes the idea of “no relationship”.

**Proposition 8.** *If  $A, B$  are events with positive probabilities then the following are equivalent:*

- (i.)  $A$  and  $B$  are independent.
- (ii.)  $\mathbb{P}[A | B] = \mathbb{P}[A]$  and  $\mathbb{P}[B | A] = \mathbb{P}[B]$ .

In words, independence means that the probabilities of each event are unaffected by whether or not the other event occurs. Proposition 8 simply formalizes this idea using conditional probabilities.

## 2.2 Random variables

Based on Sections 2.11, 4.2 in the textbook

**Definition 9** (Random variable). A **random variable** (or **rv**) is a real-valued function whose domain is a sample space.

The value of a random variable is thought of as varying depending on the outcome of the experiment (the sample point). Random variables are usually denoted with capital letters, like  $X, Y, Z$ .

**Example 10** (Sum 2d4). Roll a 4-sided dice twice (this is the **experiment**). There are 16 possible **outcomes**. The **sample space** is

$$S = \{(x, y) : x, y \in \{1, 2, 3, 4\}\}.$$

Let  $X$  be the sum of the two rolls. We can represent  $X$  by the following table:

		Dice 2			
		1	2	3	4
Dice 1	1	2	3	4	5
	2	3	4	5	6
	3	4	5	6	7
	4	5	6	7	8

**Events** are often defined using preimages of random variables. Most interesting take the form  $[X \in B]$ , where  $X$  is a random variable and  $B \subseteq \mathbb{R}$ . For example, the event that  $X = 6$  is:

$$\begin{aligned} [X = 6] &= \{\omega \in S : X(\omega) = 6\} \\ &= \{(1, 5), (2, 4), (3, 3), (4, 2), (5, 1)\}. \end{aligned}$$

The textbook uses the notation  $\{X = 6\}$  instead of  $[X = 6]$ .

Here's another example of an event. Let  $E = \{2, 4, 6, 8\}$ . Then

$$\begin{aligned} [X \text{ is even}] &= [X \in E] \\ &= \{\omega \in S : X(\omega) \in E\} \\ &= \{(1, 1), (1, 3), (2, 2), (2, 4), (3, 1), (3, 3), (4, 2), (4, 4)\}. \end{aligned}$$

When writing random variables, we usually suppress the arguments, e.g., writing  $X$  rather than  $X(\omega)$ .

End of Example 10.  $\square$

## 3 2026-01-16 | Week 01 | Lecture 03

### 3.1 Random variables

#### 3.1.1 Discrete vs continuous

**Definition 11** (Discrete random variable). We say that a random variable  $X$  is a **discrete random variable** if it can assume only a finite or countably infinite number of distinct values.

**Definition 12** (Probability mass function, pmf). Let  $X$  be a discrete random variable. The **probability mass function** (or **pmf**) of  $X$  is the function

$$p(x) = \mathbb{P}[X = x],$$

defined for every  $x \in \mathbb{R}$ .

**Example 13.** The pmf of  $X$  in Example 10 is

$$p(2) = 1/16 \quad p(3) = 2/16, \quad p(4) = 3/16, \quad p(5) = 4/16, \quad p(6) = 3/16, \quad p(7) = 2/16, \quad p(8) = 1/16$$

and  $p(x) = 0$  for all other  $x \in \mathbb{R}$ .

End of Example 13.  $\square$

**Definition 14** (Distribution function - section 4.2). Let  $X$  be any random variable. The **cumulative distribution function** (or **cdf**) of  $X$  is the function

$$F(x) = \mathbb{P}[X \leq x],$$

defined for all  $x \in \mathbb{R}$ .

**Remark 15.** The domain of a cdf is always  $\mathbb{R}$ , and it is always a nondecreasing function with  $F(-\infty) = 0$  and  $F(+\infty) = 1$ . The cdf of a discrete random variable is always a step function.

**Definition 16** (Continuous rv). Let  $Y$  be a random variable with distribution function  $F$ . We say that  $Y$  is a **continuous random variable** if there exists a nonnegative function  $f$  such that

$$F(y) = \int_{-\infty}^y f(t)dt \tag{1}$$

for all  $y \in \mathbb{R}$ . The function  $f$  is called the **probability density function** (or **pdf**) of  $Y$ .

**Remark 17.** For continuous random variables, the distribution function  $F$  is always continuous. Moreover, for a continuous random variable  $Y$ ,  $\mathbb{P}[Y = b] = 0$  for all  $b \in \mathbb{R}$ .

**Theorem 18** (Theorem 4.3 in textbook). *If  $Y$  is a continuous random variable with pdf  $f$ , then*

$$\mathbb{P}[a \leq Y \leq b] = \int_a^b f(t)dt$$

for all  $-\infty \leq a \leq b \leq +\infty$ .

#### 3.1.2 Expected value

**Definition 19** (Expectation of a continuous random variable). If  $Y$  is a random variable with pdf  $f$ , then the **expected value** of  $Y$ , denoted  $\mathbb{E}[Y]$ , is the quantity

$$\mathbb{E}[Y] = \int_{-\infty}^{\infty} yf(y)dy,$$

provided that  $\int_{-\infty}^{\infty} |y|f(y)dy < \infty$ .



**Remark 20.**  $\mathbb{E}[Y]$  is the long-run average of  $Y$ , if we were to repeat the experiment many times.

The next theorem is called the *Law of the unconscious statistician (LOTUS)*.

**Theorem 21** (LOTUS - single variable case). *Let  $g : \mathbb{R} \rightarrow \mathbb{R}$  be a function.*

(i.) *If  $X$  has pmf  $p$ , then*

$$\mathbb{E}[g(X)] = \sum_{\substack{x \in \mathbb{R} \\ p(x) > 0}} g(x)p(x).$$

(ii.) *If  $Y$  has pdf  $f$ , then*

$$\mathbb{E}[g(Y)] = \int_{-\infty}^{\infty} g(y)f(y)dy.$$

**Remark 22.** Often we wish to compute probabilities of functions of multiple random variables, for example:

- What is the probability that  $\frac{X_1 + \dots + X_n}{n} \in (0, 1)$ ? Here, the function is  $g(x_1, \dots, x_n) = \frac{x_1 + \dots + x_n}{n}$ .
- What is the probability that  $\max(X, Y) \leq 10$ ? Here the function is  $g(x, y) = \max(x, y)$ .
- Suppose we roll two dice and take the maximum. What is the expected value? In this case, our dice rolls are  $X, Y$  and we want to compute  $\mathbb{E}[g(X, Y)]$ , where  $g(x, y) = \max(x, y)$ .

To answer these sorts of questions, we need the notion of a “joint distribution”.

### 3.1.3 Joint distributions

*This subsection is based on section 5.4 in the textbook. Everything in this section generalizes naturally to  $n$  variables, but the results are simpler to state for just 2 random variables.*

**Definition 23** (Joint pmf). Let  $X_1$  and  $X_2$  be discrete random variables. The **joint probability mass function** for  $X_1$  and  $X_2$  is the function

$$p(x_1, x_2) = \mathbb{P}[X_1 = x_1, X_2 = x_2],$$

defined for all  $x_1, x_2 \in \mathbb{R}$ .

**Definition 24** (Joint pdf). Let  $Y_1$  and  $Y_2$  be continuous random variables. We say that  $Y_1$  and  $Y_2$  are **jointly continuous** if there exists a function  $f : \mathbb{R}^2 \rightarrow \mathbb{R}_{\geq 0}$  such that

$$\mathbb{P}[Y_1 \leq y_1, Y_2 \leq y_2] = \int_{-\infty}^{y_1} \int_{-\infty}^{y_2} f(t_1, t_2) dt_2 dt_1.$$

for all  $y_1, y_2 \in \mathbb{R}$ . The function  $f$  is called the **joint probability density function** for  $Y_1$  and  $Y_2$ .

**Theorem 25** (LOTUS - multivariable case). *Let  $g : \mathbb{R}^2 \rightarrow \mathbb{R}$ .*

- *If  $X_1, X_2$  have joint pmf  $p(x_1, x_2)$ , then*

$$\mathbb{E}[g(X_1, X_2)] = \sum_{\substack{(x_1, x_2) \in \mathbb{R}^2: \\ p(x_1, x_2) > 0}} g(x_1, x_2)p(x_1, x_2).$$

- *If  $Y_1, Y_2$  are jointly continuous random variables with joint pdf  $f(y_1, y_2)$ , then*

$$\mathbb{E}[g(Y_1, Y_2)] = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(y_1, y_2)f(y_1, y_2)dy_1dy_2.$$

**Remark 26.** Theorem 25 generalizes to  $n$  variables. It gives us a way to answer questions like the third question posed in Remark 22.

## 4 2026-01-21 | Week 02 | Lecture 04

*Question for this lecture: what does it mean for random variables to be independent, and what does it buy us?*

### 4.1 Independence of random variables

#### 4.1.1 Definition and characterization

The aim of this section is to define what it means for random variables to be independent.

**Definition 27.** We say that the random variables  $X_1, X_2, \dots, X_n$  are **independent** if the following holds for all possible values  $x_1, \dots, x_n$  in their range:

$$\mathbb{P}[X_1 \leq x_1, X_2 \leq x_2, \dots, X_n \leq x_n] = \mathbb{P}[X_1 \leq x_1] \mathbb{P}[X_2 \leq x_2] \cdots \mathbb{P}[X_n \leq x_n].$$

**Theorem 28** (Factorization theorem – Theorem 5.4 in textbook). *For discrete/continuous random variables, independence is equivalent to factorizability of the joint pmf/pdf. More formally, we have:*

- **Discrete case:** Let  $X_1, \dots, X_n$  be discrete random variables. Then  $X_1, \dots, X_n$  are independent if and only if

$$\mathbb{P}[X_1 = x_1, X_2 = x_2, \dots, X_n = x_n] = \mathbb{P}[X_1 = x_1] \mathbb{P}[X_2 = x_2] \cdots \mathbb{P}[X_n = x_n]$$

for all  $x_1, \dots, x_n \in \mathbb{R}$ .

- **Continuous case:** Let  $Y_1, \dots, Y_n$  be continuous random variables with pdfs  $f_1, \dots, f_n$ , and joint pdf  $f : \mathbb{R}^n \rightarrow \mathbb{R}$ . Then  $Y_1, \dots, Y_n$  are independent if and only if

$$f(y_1, \dots, y_n) = f_1(y_1) f_2(y_2) \cdots f_n(y_n)$$

for all  $y_1, \dots, y_n \in \mathbb{R}$ .

**Remark 29.** In this course, we will frequently work with “samples” of  $n$  independent random variables  $X_1, \dots, X_n$ . The intuition about independence for  $n$  variables is that observing any number of them doesn’t give you any information about the others.

#### 4.1.2 Independence and expectations/variances

Independence splits the expectation of a product into a product of expectations.

**Theorem 30.** If  $X_1, X_2, \dots, X_n$ , are independent, then

$$\mathbb{E}[X_1 X_2 \cdots X_n] = \mathbb{E}[X_1] \mathbb{E}[X_2] \cdots \mathbb{E}[X_n],$$

provided that the expectations exist.

*Proof.* This can be proven for continuous/discrete random variables by an application of Theorem 25 and Theorem 28.  $\square$

**Definition 31** (Variance of a random variable). Let  $X$  be a random variable. The **variance** of  $X$ , denoted  $\text{Var}(X)$ , is the quantity

$$\text{Var}(X) = \mathbb{E}[(X - \mu)^2].$$

where  $\mu = \mathbb{E}[X]$ . The positive square root of the variance is the **standard deviation** of  $X$ .

**Remark 32.** Variance is often denoted by  $\sigma^2$ . The textbook uses the notation  $V(X)$  instead of  $\text{Var}(X)$ .

**Theorem 33** (Properties of Variance). *Let  $X$  be a random variable and  $a, b$  be scalars. Then*

$$\text{Var}(aX + b) = a^2 \text{Var}(X).$$

*If  $X$  and  $Y$  are independent random variables then*

$$\text{Var}(X + Y) = \text{Var}(X) + \text{Var}(Y).$$

*Proof.* Follows by direct computation using the definition of variance. □

The second part of Theorem 33 says that for independent random variables, variance is additive.

### 4.1.3 Independence and long-term behavior: the weak law of large numbers

Combining many independent sources of randomness tends to produce predictable phenomena. Here we introduce one example of that.

**Theorem 34** (Weak Law of Large Numbers). *Let  $(X_n)_{n=1}^\infty$  be a sequence of independent random variables. Assume that for all  $n$ ,  $\mu = \mathbb{E}[X_n]$  and  $\text{Var}(X_n) \leq B$  for some fixed bound  $B < \infty$ . Let  $S_n = X_1 + \dots + X_n$ . Then for all  $\epsilon > 0$ ,*

$$\mathbb{P} \left[ \left| \frac{S_n}{n} - \mu \right| > \epsilon \right] \rightarrow 0 \text{ as } n \rightarrow \infty.$$

## 5 2026-01-23 | Week 02 | Lecture 05

### 5.1 Proof of the weak law of large numbers

We will need the following theorem, which says that if the average male height is 5 feet tall, then no more than 10% of men can be more than 50 feet tall.

**Theorem 35** (Markov's inequality). *Let  $X$  be a nonnegative random variable and let  $a > 0$ . Then*

$$\mathbb{P}[X \geq a] \leq \frac{\mathbb{E}[X]}{a} \quad (2)$$

*Proof.* Let  $A = [X \geq a]$ . Then  $X \cdot \mathbf{1}_A \leq X$ , so

$$\begin{aligned} \mathbb{E}[X] &\geq \mathbb{E}[X \cdot \mathbf{1}_A] \\ &\geq \mathbb{E}[a \mathbf{1}_A] \\ &\geq a \mathbb{E}[\mathbf{1}_A] \\ &= a \mathbb{P}[A] \\ &= a \mathbb{P}[X \geq a]. \end{aligned}$$

Dividing by  $a$  implies Eq. (2). □

**Theorem 36** (Weak Law of Large Numbers). *Let  $(X_n)_{n=1}^\infty$  be a sequence of independent random variables. Assume that for all  $n$ ,  $\mu = \mathbb{E}[X_n]$  and  $\text{Var}(X_n) \leq B$  for some fixed bound  $B < \infty$ . Let  $S_n = X_1 + \dots + X_n$ . Then for all  $\epsilon > 0$ ,*

$$\mathbb{P}\left[\left|\frac{S_n}{n} - \mu\right| > \epsilon\right] \rightarrow 0 \text{ as } n \rightarrow \infty.$$

*Proof.* First observe that by independence,

$$\text{Var}(S_n) = \text{Var}(X_1) + \dots + \text{Var}(X_n) \leq nB. \quad (3)$$

Next, let  $\epsilon > 0$  be arbitrary.

$$\begin{aligned} \mathbb{P}\left[\left|\frac{S_n}{n} - \mu\right| > \epsilon\right] &= \mathbb{P}[|S_n - n\mu| > n\epsilon] \\ &= \mathbb{P}[(S_n - n\mu)^2 > (n\epsilon)^2] \\ &\leq \frac{\mathbb{E}[(S_n - n\mu)^2]}{n^2\epsilon^2} && \text{by Theorem 35} \\ &= \frac{\text{Var}(S_n)}{n^2\epsilon^2} && \text{by definition of variance} \\ &\leq \frac{B}{\epsilon^2 n} && \text{by Eq. (3).} \end{aligned}$$

The right hand side tends to zero as  $n \rightarrow \infty$ , proving the theorem. □

### 5.2 Equality in distribution

**Definition 37** (Identically distributed). Two random variables  $X$  and  $Y$  are *identically distributed* if they have the same cdf.

**Remark 38.** Identically distributed random variables are said to “have the same distribution”. For discrete/continuous random variables, this is equivalent to them having the same pmf/pdf.

The next example shows that identically distributed random variables need not be equal as functions.

**Example 39.** Flip a coin. Define two random variables

$$X = \begin{cases} 1 & : \text{ coin is heads} \\ 0 & : \text{ coin is tails} \end{cases}$$

$$Y = \begin{cases} 0 & : \text{ coin is heads} \\ 1 & : \text{ coin is tails} \end{cases}$$

Then  $X$  and  $Y$  are identically distributed, since they have the same pmf:

$$\mathbb{P}[X = 1] = \mathbb{P}[Y = 1] = \frac{1}{2} \quad \text{and} \quad \mathbb{P}[X = 0] = \mathbb{P}[Y = 0] = \frac{1}{2}.$$

But of course  $X$  and  $Y$  are never equal, i.e.,  $\mathbb{P}[X \neq Y] = 1$ .

End of Example 39.  $\square$

### 5.3 Populations and samples

Here we introduce a conceptual framework for mathematical statistics.

A **population** is a large body of data that is the target of our interest. The subset collected from it is our **sample**.

**Example 40** (Populations). A population can be real or theoretical. Here are some examples

- The set of people in Hawai'i (real, finite)
- The set of voters in the 2026 Midterm elections (hypothetical, finite)
- The decimal expansion of  $\pi$  (countably infinite)
- The infinitely many observations that could be made during a laboratory experiment if the experiment were repeated over and over again (hypothetical)
- The lifetimes of light bulbs produced by a factory

Importantly, a population can also be a *probability distribution*, specified by a pdf, pmf, or cdf

- Observations made from an exponential distribution with mean  $\lambda > 0$  (i.e., the distribution with pdf  $f(x) = \lambda e^{-\lambda x} \mathbf{1}_{[x>0]}$ .)

End of Example 40.  $\square$

## 6 2026-01-26 | Week 03 | Lecture 06

### 6.1 Sampling

For discussions of “random sample”, see sections 2.12 and 6.1 in the textbook.

The simplest sampling procedure is called simple random sampling.

**Definition 41** (Simple random sampling). Let  $N$  and  $n$  denote the numbers of elements in the population and sample, respectively. If the sampling is conducted in such a way that each of the  $\binom{N}{n}$  samples has an equal probability of being selected, the sampling is called **simple random sampling**, and the result is a **simple random sample**.

More commonly in mathematical statistics, we think of the population as a distribution.

**Definition 42** (Random sample from a distribution). Consider a given probability distribution on  $\mathbb{R}$  that can be represented by a pdf or pmf  $f$ . We say that the random variables  $X_1, \dots, X_n$  form a **random sample** from this distribution if these random variables are independent and the distribution of each is given by  $f$ . Such random variables are also said to be **independent and identically distributed** (iid). The number of random variables  $n$  is the **sample size**.

*The objective of statistics is to make an inference about a population based on information contained in a sample from that population and to provide an associated measure of goodness for the inference.*

### 6.2 What is a statistic?

Section 7.1 in the textbook.

**Definition 43** (Statistic). A **statistic** is a function of the observable random variables in a sample and known constants.

In other words, if  $X_1, \dots, X_n$  is a random sample and  $T : \mathbb{R}^n \rightarrow \mathbb{R}$  is a function, then the random variable

$$Y = T(X_1, \dots, X_n)$$

is a statistic.<sup>2</sup> The probability distribution of such a statistic  $Y$  is called its **sampling distribution**.

Often, we have some quantity of interest, called a **target parameter**, and we want a single “best guess” of some quantity of interest. When this is the case, then we call a statistic an estimator:

**Definition 44** (Estimator). An **estimator** is a statistic, that is a function  $T(X_1, \dots, X_n)$  of a sample, that is used to approximate a target parameter. An **estimate** is the realized value of an estimator (e.g., a number) that is obtained when the sample is actually taken.

In words, an estimator is a rule, often expressed as a formula, that tells us how to calculate the value of an estimate based on the measurements contained in a sample. Here are two important examples of estimators.

**Definition 45** (Sample Mean, Sample Variance). Let  $X_1, \dots, X_n$  be a random sample. The **sample mean**, denoted  $\bar{X}$ , is the statistic

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

The **sample variance**, denoted  $S^2$ , is the statistic

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

The target parameters these are used to estimate are the mean and variance of the population. The following examples illustrate some of the terminology we’ve introduced.

---

<sup>2</sup>A statistic does not need to be real-valued, but we will focus on the case when it is.

**Example 46** (Estimating average lightbulb lifetime). Suppose the lifetime of each light bulb produced in a certain factory is distributed according to the following pdf

$$f(y) = \lambda e^{-\lambda y} \mathbf{1}_{[y>0]}.$$

for some parameter  $\lambda > 0$ , where  $y$  is measured in minutes. Here, the **population** is either the set of lightbulbs produced by the factory, which we idealize as the probability distribution given by  $f$ . Suppose we do not know  $\lambda$ , and we wish to estimate it. Hence  $\lambda$  is the **target parameter**. A random sample  $Y_1, \dots, Y_n$  is taken. (So the  $Y_i$ 's are independent and each as pdf  $f$ .)

In this case  $f$  is an exponential distribution with rate  $\lambda > 0$ . The exponential distribution is used to modeling lifetimes of systems that are not subject to degradation (e.g., lifetimes of light bulbs, not diesel engines) as well as waiting times (e.g., the length of time intervals between cars passing by a tree on an idyllic country road). In the road example, if the rate of cars passing is 2 cars per minute, then on average you have to wait only 1/2 of a minute for a car to pass. That is, the *rate* and *expected values* are reciprocals of each other. Let's prove this fact in the following claim:

**Claim 1:** If  $Y$  has pdf  $f$ , then  $\mathbb{E}[Y] = \frac{1}{\lambda}$ .

*Proof of Claim 1.* By definition of expected value for a continuous random variable,

$$\begin{aligned} \mathbb{E}[Y] &= \int_{-\infty}^{\infty} y \lambda e^{-\lambda y} \mathbf{1}_{[y>0]} dy \\ &= \int_0^{\infty} y \lambda e^{-\lambda y} dy \\ &= \int_0^{\infty} y \frac{d}{dy} [-e^{-\lambda y}] dy \\ &= [-ye^{-\lambda y}]_{y=0}^{y=\infty} - \int_0^{\infty} \frac{d}{dy} [y] (-e^{-\lambda y}) dy && \text{by integration by parts} \\ &= \int_0^{\infty} e^{-\lambda y} dy \\ &= \left[ \frac{1}{\lambda} e^{-\lambda y} \right]_{y=\infty}^{y=0} \\ &= \frac{1}{\lambda}. \end{aligned}$$

□ Claim

End of Example 46. □

## 7 2026-01-28 | Week 03 | Lecture 07

### 7.1 Basic examples of statistics and estimators

*This lecture is based on section 7.1 in the textbook.*

**Example 47** (Example 46 continued). We have a random sample of  $Y_1, \dots, Y_n$  from the distribution with pdf

$$f(y) = \lambda e^{-\lambda y} \mathbf{1}_{[y>0]},$$

where  $\lambda$  is a target parameter.

In the setting of this example, we interpret the random variables  $Y_1, \dots, Y_n$  as lifetimes (in, say, years) of lightbulbs produced by a certain factory.

In the last lecture, we used integration by parts to show that if  $Y$  has pdf  $f$ , then

$$\mathbb{E}[Y] = \frac{1}{\lambda}.$$

Consider the **statistic**

$$\bar{Y} = \frac{Y_1 + \dots + Y_n}{n}.$$

By Theorem 36 (The Weak Law of Large Numbers),  $\bar{Y}$  is likely to be close to  $\mathbb{E}[Y] = 1/\lambda$  when  $n$  is large. Therefore  $\frac{1}{\bar{Y}}$  is likely to be close to  $\lambda$ . Therefore a reasonable **estimator** for  $\lambda$  is

$$\frac{1}{\bar{Y}} = \frac{n}{Y_1 + \dots + Y_n}.$$

If  $n = 10$  and the observed values of  $Y_1, \dots, Y_{10}$  are

$$2, 0.8, 0.1, 2.3, 3.2, 5.4, 2, 0.4, 2.8, \text{ and } 3.4$$

then  $\bar{Y} = 2.24$ , and hence our **estimate** for  $\lambda$  would be  $\frac{1}{2.24} \approx 0.45$ .

End of Example 47.  $\square$

**Example 48** (Example 7.1 in textbook). Roll a dice three times. Let  $Y_1, Y_2, Y_3$  be the values of the rolls. The average number observed in this sample of size 3 is

$$\bar{Y} = \frac{Y_1 + Y_2 + Y_3}{3}.$$

This is the **sample mean**, it is function of the sample (and the known constant  $n$ ) and is therefore a **statistic**.

**Question:** What the mean  $\mu_{\bar{Y}}$  and standard deviation  $\sigma_{\bar{Y}}$  of the random variable  $\bar{Y}$ ?

First we compute the mean and variance of a single  $Y_i$ .

**Claim 1:**  $\mathbb{E}[Y_i] = 3.5$  and  $\text{Var}(Y_i) = 35/12 \approx 2.9167$ .

*Proof of Claim 1.* Fix  $i \in [3]$ . For simplicity, let  $Y = Y_i$ . Using the definition of expected value,

$$\mathbb{E}[Y] = \sum_{k=1}^6 k \mathbb{P}[Y = k] = \sum_{k=1}^6 k \frac{1}{6} = 3.5.$$

Next we compute the variance of  $Y$ :

$$\text{Var}(Y) = \mathbb{E}[(Y - 3.5)^2] \quad \text{Definition 31}$$

$$= \sum_{y=1}^6 (y - 3.5)^2 \mathbb{P}[Y = y] \quad \text{By Theorem 21 (LOTUS) using } g(y) = (y - 3.5)^2$$

$$= \sum_{k=1}^6 (y - 3.5)^2 \frac{1}{6} \quad \text{since } \mathbb{P}[Y = y] = 1/6 \text{ for all } k \in [6]$$
$$= 35/12.$$



□ Claim

**Claim 2:**  $\mu_{\bar{Y}} = \mathbb{E}[\bar{Y}] = 3.5$

*Proof of Claim 2.* We have:

$$\begin{aligned}
 \mathbb{E}[\bar{Y}] &= \mathbb{E}\left[\frac{Y_1 + Y_2 + Y_3}{3}\right] && \text{by definition of } \bar{Y} \\
 &= \frac{1}{3}(\mathbb{E}[Y_1] + \mathbb{E}[Y_2] + \mathbb{E}[Y_3]) && \text{by linearity of expectation} \\
 &= \frac{1}{3}(3.5 + 3.5 + 3.5) && \text{by Claim 1} \\
 &= 3.5.
 \end{aligned}$$

□ Claim

**Claim 3:**  $\sigma_{\bar{Y}}^2 = \text{Var}(\bar{Y}) = .9722$

*Proof of Claim 3.*

$$\begin{aligned}
 \text{Var}(\bar{Y}) &= \text{Var}\left(\frac{Y_1 + Y_2 + Y_3}{3}\right) \\
 &= \frac{1}{9}\text{Var}(Y_1 + Y_2 + Y_3) && \text{by Theorem 33} \\
 &= \frac{1}{9}(\text{Var}(Y_1) + \text{Var}(Y_2) + \text{Var}(Y_3)) && \text{by Theorem 33} \\
 &= \frac{1}{9}(2.9167 + 2.9167 + 2.9167) && \text{by Claim 1} \\
 &= \frac{2.9167}{3} && (*)
 \end{aligned}$$

and this is approximately .97224.

□ Claim

Since the standard deviation is the square root of the variance, the standard deviation is

$$\sigma_{\bar{Y}} = \sqrt{.9722} = .9860$$

Claim 3.

**Remark 49.** In equation (\*), we had  $\text{Var}(\bar{Y}) = \frac{2.9167}{3}$ . Notice how, if we computed the variance of four or five dice rolls, we'd get

$$\text{Var}(\bar{Y}) = \frac{2.9167}{4} \quad \text{or} \quad \text{Var}(\bar{Y}) = \frac{2.9167}{5}.$$

In general, for  $n$  dice rolls, we'd get

$$\text{Var}(\bar{Y}) = \frac{2.9167}{n}.$$

This quantity tends to zero as  $n \rightarrow \infty$ . In words, as the number of samples  $n$  grows, the variance of the sample mean decreases.

End of Example 49. □

## 8 2026-01-30 | Week 03 | Lecture 08

### 8.1 The Gaussian distribution

Begin section 7.2

**Definition 50** (Normal / Gaussian Distribution). A random variable  $Y$  is said to be **normally distributed** with mean  $\mu \in \mathbb{R}$  and variance  $\sigma^2 > 0$  if it has pdf

$$f(y) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left\{ -\frac{(y - \mu)^2}{2\sigma^2} \right\},$$

defined for all  $y \in \mathbb{R}$ . We abbreviate this by writing  $Y \sim \mathcal{N}(\mu, \sigma^2)$ . If  $Y \sim \mathcal{N}(0, 1)$ , we say  $Y$  has **standard normal distribution**.

**Remark 51.** Normal random variables/distributions are also called **Gaussian** random variables/distributions.

**Example 52.** Normal distributions are the classic “bell curve” distributions. Whenever a random quantity is the result of adding up many small, independent random effects, we expect it to be approximately normally distributed.

- A classic example is human height, which is influenced by the combined effects of thousands of genes together with environmental factors.
- Another example is repeated measurements of the same physical quantity (e.g., if we all went out and measured the temperature outside tomorrow at midday), this is because the total error is the sum of many small independent sources of noise (e.g., instrument precision, time, location, shade, wind, etc).

End of Example 52.  $\square$

**Remark 53** (Standardization). If  $Y \sim \mathcal{N}(\mu, \sigma^2)$  then the random variable

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

is a standard normal random variable. The transformation

$$X \mapsto \frac{X - \mu}{\sigma}$$

in which we subtract off the mean of  $X$  and then divide by its standard deviation is called **standardization**.

**Remark 54** (The Empirical Rule). The **Empirical Rule** (also called the **68-95-99.7 rule**; see textbook section 1.3) is summarized by the following figure, for normal distributions:

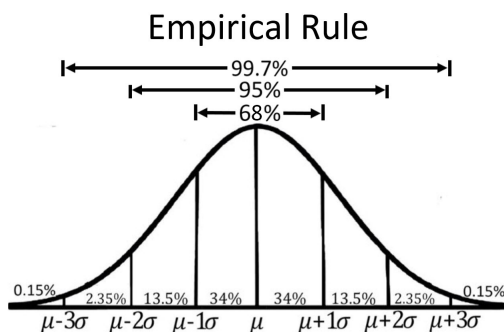


Image source: <https://andymath.com/wp-content/uploads/2019/12/empirical-rule-normdist2.jpg>

The next theorem says that if we have a sample of  $Y_1, \dots, Y_n$  normal random variables, then their sample mean is normally distributed as well.

**Theorem 55** (Mean and variance of a normal sample mean). Let  $Y_1, \dots, Y_n$  be a random sample of size  $n$  from a normal distribution with mean  $\mu$  and variance  $\sigma^2$ . Then

$$\bar{Y} = \frac{1}{n} \sum_{i=1}^n Y_i$$

is normally distributed with mean  $\mu_{\bar{Y}} = \mu$  and variance  $\sigma_{\bar{Y}}^2 = \sigma^2/n$ .

*Proof sketch.* The proof follows from three facts:

- Any linear combination of normal random variables is a normal random variable (this can be proved using moment generating functions).
- That  $\mathbb{E}[\bar{Y}] = \mu$  follows by linearity of expectation.
- The variance calculation follows by Theorem 33.

□

**Remark 56.** Applying the idea of standardization, observe that the random variable  $Z = \frac{\bar{Y} - \mu_{\bar{Y}}}{\sigma_{\bar{Y}}} = \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}}$  has a standard normal distribution.

**Example 57** (Example 7.2 in textbook). A bottling machine discharges an average of  $\mu$  ounces per bottle. It has been observed that the amount of liquid discharged is normally distributed with standard deviation  $\sigma = 1$  per ounce. A sample of  $n = 9$  filled bottles is randomly selected, and is measured.

**Question:** Find the probability that the sample mean will be within .3 ounces of the true mean  $\mu$ .

**Solution:** Let  $Y_1, \dots, Y_9$  be the ounces in each of the bottles. Then  $Y_i \sim \mathcal{N}(\mu, 1)$  for  $i \in [9]$ . By Theorem 55,  $\bar{Y} \sim \mathcal{N}(\mu, \sigma^2/n)$ , and  $\sigma^2/n = 1/9$ . We want to find

$$\begin{aligned} \mathbb{P}[|\bar{Y} - \mu| \leq .3] &= \mathbb{P}[-.3 \leq \bar{Y} - \mu \leq .3] \\ &= \mathbb{P}\left[-\frac{.3}{\sigma/\sqrt{n}} \leq \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \leq \frac{.3}{\sigma/\sqrt{n}}\right]. \end{aligned} \quad (4)$$

By Remark 56,  $Z = \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \sim \mathcal{N}(0, 1)$ , and plugging in  $\sigma = 1$  and  $n = 9$  and simplifying gives

$$\begin{aligned} \mathbb{P}[|\bar{Y} - \mu| \leq .3] &= \mathbb{P}[-.9 \leq Z \leq .9] \\ &= 1 - 2\mathbb{P}[Z > .9] \\ &= .6318. \end{aligned}$$

End of Example 57. □

**Example 58** (Example 7.3 in textbook). How many observations need to be included in the sample to ensure that  $\bar{Y}$  is within .3 ounces of  $\mu$  with probability .95?

Now we want

$$\mathbb{P}[|\bar{Y} - \mu| \leq .3] = .95.$$

By Eq. (4),

$$\mathbb{P}[|\bar{Y} - \mu| \leq .3] = \mathbb{P}\left[-\frac{.3}{\sigma/\sqrt{n}} \leq \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \leq \frac{.3}{\sigma/\sqrt{n}}\right].$$

Recalling that  $\sigma = 1$  and  $Z = \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \sim \mathcal{N}(0, 1)$ , we have

$$\mathbb{P}[|\bar{Y} - \mu| \leq .3] = \mathbb{P}[-.3\sqrt{n} \leq Z \leq .3\sqrt{n}].$$

So we need to find  $n$  such that  $\mathbb{P}[-.3\sqrt{n} \leq Z \leq .3\sqrt{n}] = .95$ .

It is a well-known fact that

$$\mathbb{P}[-1.96 \leq Z \leq 1.96] = .95.$$

So we need  $.3\sqrt{n} = 1.96$ , or equivalently,  $n = \left(\frac{1.96}{.3}\right)^2 = 42.68$ .

So we need at least 43 samples, since 42 is not quite enough.

End of Example 58.  $\square$

## 9 2026-02-02 | Week 04 | Lecture 09

This lecture is based on Section 7.2 in the textbook. I will be skipping the part about  $F$  statistics for now.

### 9.1 Motivation: “Approximate” standardization

In Example 57, we had a random sample  $Y_1, \dots, Y_n$  of normally distributed random variables, and we computed  $\mathbb{P}[|\bar{Y} - \mu| \leq .3]$  by rewriting the event  $[|\bar{Y} - \mu| \leq .3]$  using the standardization trick:

$$\begin{aligned} [|\bar{Y} - \mu| \leq .3] &= [-.3 \leq \bar{Y} - \mu \leq .3] \\ &= \left[ \frac{-.3}{\sigma/\sqrt{n}} \leq \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \leq \frac{.3}{\sigma/\sqrt{n}} \right] \\ &= \left[ \frac{-.3}{\sigma/\sqrt{n}} \leq Z \leq \frac{.3}{\sigma/\sqrt{n}} \right] \end{aligned}$$

where  $Z \sim \mathcal{N}(0, 1)$ . Hence,

$$\mathbb{P}[|\bar{Y} - \mu| \leq .3] = \left[ \frac{-.3}{\sigma/\sqrt{n}} \leq \underbrace{\frac{\bar{Y} - \mu}{\sigma/\sqrt{n}}}_Z \leq \frac{.3}{\sigma/\sqrt{n}} \right]. \quad (5)$$

In other words, we used standardization (see Remark 53) to rewrite the probability into something we could compute (or look up).

The problem with this approach is that the example is contrived and unrealistic because, in the problem statement, we assumed that we knew the true standard deviation to be  $\sigma = 1$ . In practice, this sort of thing is almost never known ahead of time, but instead must be estimated from the data.

A natural estimator of  $\sigma$  is  $S$ , the square root of the sample variance. This is because  $S^2 \rightarrow \sigma^2$  as  $n \rightarrow \infty$  by the law of large numbers, so  $S$  should be close to  $\sigma$  when  $n$  is large. In that case, we can “approximately” standardize. Replacing  $\sigma$  by  $S$  in the calculation above, we obtain

$$\mathbb{P}[|\bar{Y} - \mu| \leq .3] = \left[ \frac{-.3}{S/\sqrt{n}} \leq \underbrace{\frac{\bar{Y} - \mu}{S/\sqrt{n}}}_{\text{call it } T} \leq \frac{.3}{S/\sqrt{n}} \right].$$

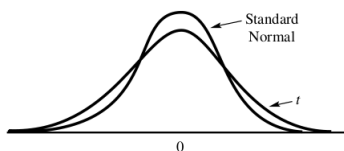
Here, the random variable  $T$  is not normally distributed, but it should be pretty close to  $\mathcal{N}(0, 1)$  when  $n$  is large. This is because  $S \approx \sigma$  when  $n$  is large, so

$$T = \left( \frac{\bar{Y} - \mu}{S/\sqrt{n}} \right) \approx \left( \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \right) = Z.$$

**Question:** What is the distribution of  $T$ ? Can we quantify “how close” it is to  $Z$ ?

**Short answer:** Assuming a sample size of  $n > 2$ ,  $T$  has a distribution called a  $t$ -distribution, which is well-known and widely used. It has expectation  $\mathbb{E}[T] = 0$  and variance  $\text{Var}(T) = \frac{\nu}{\nu-2}$ , where  $\nu = n - 1$  is called the “degrees of freedom”. It has a probability density function which is symmetric and bell-shaped, like the normal distribution, but the shape is a little more spread out than the standard normal:

FIGURE 7.3  
A comparison of the  
standard normal and  
 $t$  density functions.



The reason for this greater spread is that  $\text{Var}(T) > 1$  for all  $n > 2$ , whereas  $\text{Var}(Z) = 1$ .

**Long answer:** see the next two subsections.

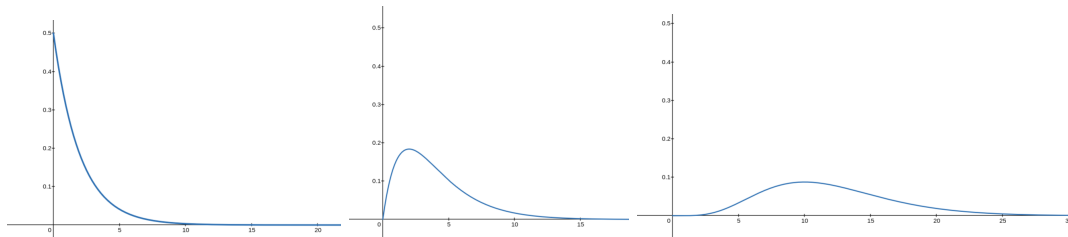
## 9.2 The chi-squared distribution

**Definition 59** (Chi-Squared Distribution). Let  $d$  be a positive integer. A nonnegative random variable  $X$  is said to have **chi-squared distribution with parameter  $d$**  if it has pdf

$$f(x) = \begin{cases} \frac{1}{2^{d/2}\Gamma(d/2)} x^{\frac{d}{2}-1} e^{-x/2} & : x \geq 0 \\ 0 & : x < 0 \end{cases}$$

The parameter  $d$  is usually called the **degrees of freedom** of  $X$ .

From left-to-right, here's what this looks like for  $d = 2$ ,  $d = 4$ , and  $d = 12$ :



**Proposition 60** (Properties of chi-squared distribution). A chi-squared random variable  $X$  with  $d$  degrees of freedom has

$$\mathbb{E}[X] = d \quad \text{and} \quad \text{Var}(X) = 2d$$

Chi-squared random variables are important in statistics because they arise as squared normal random variables:

**Theorem 61** (Chi-squared is sum of squared normals). Let  $n \geq 1$ . The following are equivalent

- (i.)  $X$  has chi-squared distribution with  $n$  degrees of freedom
- (ii.)  $X \stackrel{d}{=} Z_1^2 + \dots + Z_n^2$ , where  $Z_1, \dots, Z_n$  are independent standard normal random variables

A standard proof of Theorem 61 involves the use of moment generating functions. (See Example 6.11 in the textbook).

**Remark 62.** Taking  $n = 1$ , Theorem 61 implies that  $Z \sim \mathcal{N}(0, 1)$  implies  $Z^2$  is chi-squared with 1 degree of freedom.

**Corollary 63** (Theorem 7.2 in textbook). If  $Y_1, \dots, Y_n$  is a sample of  $\mathcal{N}(\mu, \sigma)$  random variables, then

$$\sum_{i=1}^n \left( \frac{Y_i - \mu}{\sigma} \right)^2$$

is a chi-squared random variable with  $\text{df} = n$ .

**Remark 64.** Usually, we use a table or a computer to compute probabilities with chi-squared random variables. But the fact that we usually can't do exact computations by hand doesn't make chi-squared random variables any less important to statistics, as they show up in sample variances, linear regression, distance estimates (pythagorean theorem has squares), etc.

The main example we will need is the following

**Theorem 65** (Theorem 7.3 in textbook). Let  $Y_1, \dots, Y_n$  be a random sample from  $\mathcal{N}(\mu, \sigma^2)$ . Then the random variable

$$\frac{(n-1)S^2}{\sigma^2}$$

has a chi-squared distribution with  $n - 1$  degrees of freedom. Also, the random variables  $\bar{Y}$  and  $S^2$  are independent.

See textbook for outline of the proof (for the case when  $n = 2$ ). The independence of  $\bar{Y}$  and  $S^2$  is rather technical to prove, but simply says that the knowledge of the center of location of a normal random variable does not contribute to knowledge of its variability.

### 9.3 Definition of the Student t-distribution

**Definition 66** (Student’s t-distribution). Let  $Z \sim \mathcal{N}(0, 1)$  and let  $\chi_\nu^2$  be an independent chi-squared distributed random variable with  $\text{df} = \nu$ . Then

$$T = \frac{Z}{\sqrt{\chi_\nu^2/\nu}}$$

is said to have a *t-distribution*<sup>3</sup> with  $\nu$  degrees of freedom.

**Remark 67.**

- To show that a random variable follows a  $T$  distribution, we must show that it can be written as a ratio of a standard normal random variable to the square root of an independent chi-squared random variable divided by its degrees of freedom.
- There are infinitely many t-distributions, one for every positive integral  $\nu$ .
- As  $\nu$  increases, the bell-curve distribution of  $T$  becomes less spread out, and approaches the standard normal curve as  $\nu \rightarrow \infty$ .

---

<sup>3</sup>This is also called “Student’s t distribution”. It was discovered by W. S. Gosset, an employee of the Guinness Brewery in Dublin, who wrote under the pseudonym “Student.”

## 10 2026-02-04 | Week 04 | Lecture 10

### 10.1 Using the student t-distribution

*This is based on section 7.2 of the textbook.*

The following theorem illustrates an important example of the  $t$ -distribution, which arises when we “approximately standardize” a sample mean with the transformation

$$\bar{Y} \mapsto \frac{\bar{Y} - \mu}{S/\sqrt{n}}$$

(where we’ve used the sample standard deviation  $S$  in place of the unknown population parameter  $\sigma$ ).

**Theorem 68.** *Let  $Y_1, \dots, Y_n$  be a random sample from  $\mathcal{N}(\mu, \sigma^2)$ . The random variable*

$$\frac{\bar{Y} - \mu}{S/\sqrt{n}}$$

*follows a Student  $t$ -distribution with  $n - 1$  degrees of freedom.*

*Proof.* Observe that

- $Z := \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}}$  is a standard normal by Remark 53 and Theorem 55.
- $\chi_{n-1}^2 := (n-1)S^2/\sigma^2$  has a  $\chi^2$  distribution with  $n - 1$  degrees of freedom by Theorem 65.
- Since  $\bar{Y} \perp\!\!\!\perp S^2$  by Theorem 65, it follows that  $Z \perp\!\!\!\perp \chi_{n-1}^2$  as well.

Hence

$$\begin{aligned} \frac{\bar{Y} - \mu}{S/\sqrt{n}} &= \frac{\frac{\bar{Y} - \mu}{\sigma/\sqrt{n}}}{\sqrt{[(n-1)S^2/\sigma^2]/(n-1)}} \\ &:= \frac{Z}{\sqrt{\chi_{n-1}^2/(n-1)}}, \end{aligned}$$

And the right hand satisfies the definition of a  $t$ -distribution with  $\nu = n - 1$  degrees of freedom.  $\square$

The third observation in the proof of Theorem 68 uses the following theorem

**Theorem 69.** *Let  $X$  and  $Y$  be independent random variables. Let  $g(x)$  be a function only of  $x$  and  $h(y)$  a function only of  $y$ . Then the random variables  $U = g(X)$  and  $V = h(Y)$  are independent.*

*Proof idea.* We’ll show the case where  $X, Y$  are discrete random variables, as this illustrates the idea of the general proof. [In lecture, I only sketched this proof, but am including a more detailed version here in the notes for fun.]

We need to show that for all  $u, v \in \mathbb{R}$ , we have

$$\mathbb{P}[U = u, V = v] = \mathbb{P}[U = u] \mathbb{P}[V = v],$$

as this will establish that  $U$  and  $V$  are independent.

Let  $S_X \subseteq \mathbb{R}$  be the set of values that the random variable  $X$  can take, and define  $S_Y$  similarly. Let  $A_u = \{x \in S_X : g(x) = u\}$  and  $B_v = \{y \in S_Y : h(y) = v\}$ . Note that the sets  $A_u$  and  $B_v$  are defined in such a way that

$$[U = u] = [X \in A_u] \quad \text{and} \quad [V = v] = [Y \in B_v] \tag{6}$$



for all  $u, v \in \mathbb{R}$ . The result then follows from the following calculation:

$$\begin{aligned}
\mathbb{P}[U = u, V = v] &= \mathbb{P}[X \in A_u, Y \in B_v] && \text{by Eq. (6)} \\
&= \mathbb{E}[\mathbf{1}_{[X \in A_u, Y \in B_v]}] \\
&= \sum_{x \in S_X} \sum_{y \in S_Y} \mathbf{1}_{[X \in A_u, Y \in B_v]} \mathbb{P}[X = x, Y = y] && \text{by Theorem 25} \\
&= \sum_{x \in S_X} \sum_{y \in S_Y} \mathbf{1}_{[X \in A_u, Y \in B_v]} \mathbb{P}[X = x] \mathbb{P}[Y = y] && \text{by Theorem 28} \\
&= \sum_{x \in S_X} \sum_{y \in S_Y} \mathbf{1}_{[X \in A_u]} \mathbf{1}_{[Y \in B_v]} \mathbb{P}[X = x] \mathbb{P}[Y = y] && \text{since } \mathbf{1}_{E \cap F} = \mathbf{1}_E \mathbf{1}_F \text{ for any events } E, F \\
&= \left( \sum_{x \in S_X} \mathbf{1}_{X \in A_u} \mathbb{P}[X = x] \right) \left( \sum_{y \in S_Y} \mathbf{1}_{Y \in B_v} \mathbb{P}[Y = y] \right) \\
&= \mathbb{P}[X \in A_u] \mathbb{P}[Y \in B_v] && \text{by Theorem 21} \\
&= \mathbb{P}[U = u] \mathbb{P}[V = v] && \text{by Eq. (6).}
\end{aligned}$$

Since  $u, v \in \mathbb{R}$  are arbitrary, this show that  $U$  and  $V$  are independent.  $\square$

**Example 70** (Example 7.6 in the textbook). The tensile strength of a type of wire is normally distributed with unknown mean  $\mu \in \mathbb{R}$  and variance  $\sigma^2 > 0$ . Six pieces of wire are selected from a roll. Let

$$Y_i := \text{the tensile strength for portion } i, \quad i \in [6].$$

We can estimate  $\mu$  and  $\sigma^2$  with  $\bar{Y}$  and  $S^2$ . Because  $\sigma_{\bar{Y}}^2 = \sigma^2/n$ , it follows that  $\sigma_{\bar{Y}}^2$  can be estimated by  $S^2/n$ .

**Question:** Find the probability that  $\bar{Y}$  is within  $2S/\sqrt{n}$  of  $\mu$ .

$$\begin{aligned}
\mathbb{P}\left[|\bar{Y} - \mu| \leq \frac{2S}{\sqrt{n}}\right] &= \mathbb{P}\left[-\frac{2S}{\sqrt{n}} \leq \bar{Y} - \mu \leq \frac{2S}{\sqrt{n}}\right] \\
&= \mathbb{P}\left[-2 \leq \left(\frac{\bar{Y} - \mu}{S/\sqrt{n}}\right) \leq 2\right] \\
&= \mathbb{P}[-2 \leq T \leq 2],
\end{aligned}$$

where  $T$  has a t-distribution with  $\text{df} = 5$  (i.e., one less than the number of samples).

A computer tells us that when  $\text{df} = 5$ ,

$$\mathbb{P}[-2.015 \leq T \leq 2.015] = .9$$

Hence,  $\mathbb{P}\left[|\bar{Y} - \mu| \leq \frac{2S}{\sqrt{n}}\right]$  is slightly less than .9. In words, the probability that  $\bar{Y}$  will be within 2 estimated standard deviations of its mean is slightly less than .90.

Note that if  $\sigma^2$  were known, the probability that  $\bar{Y}$  will fall within  $2\sigma_{\bar{Y}}$  of its mean would be given by

$$\begin{aligned}
\mathbb{P}\left[|\bar{Y} - \mu| \leq 2\left(\frac{\sigma}{\sqrt{n}}\right)\right] &= \mathbb{P}\left[-2 \leq \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \leq 2\right] \\
&= \mathbb{P}[-2 \leq Z \leq 2] \\
&\approx .95.
\end{aligned}$$

End of Example 70.  $\square$

Section 7.2 ends with a discussion about comparing variances of two populations using  $F$  statistics. We will skip this, but return to  $F$  statistics later.

## 11 2026-02-06 | Week 04 | Lecture 11

### 11.1 The central limit theorem

*This is based on Section 7.3 and 7.5. The central limit theorem :)*

We've seen that if  $Y_1, \dots, Y_n$  is a random sample of normal random variables, then  $\bar{Y}$  is normally distributed.

What if the population is not normally distributed?

**Main idea of the central limit theorem:** If  $X_1, \dots, X_n$  is a random sample from (almost) any distribution, then  $\bar{X}$  will be approximately normal when  $n$  is large.

**Theorem 71** (Central Limit Theorem). *Let  $X_1, \dots, X_n$  be independent identically distributed random variables with  $\mathbb{E}[X_i] = \mu$  and  $\text{Var}(X_i) = \sigma^2 < \infty$ . Let*

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

*Then*

$$U_n \rightarrow \mathcal{N}(0, 1) \text{ as } n \rightarrow \infty,$$

*in the sense that*

$$\lim_{n \rightarrow \infty} \mathbb{P}[U_n \leq u] = \int_{-\infty}^u \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt \text{ for all } u \in \mathbb{R}.$$

**Remark 72.** In practice, this means that when  $n$  is large we have  $\mathbb{P}[a \leq U_n \leq b] \approx \mathbb{P}[a \leq Z \leq b]$  for any  $a, b \in \mathbb{R}$  with  $a \leq b$ .

The conclusion of the central limit can be summarized in words as the following:  $\bar{X}$  is *asymptotically normally distributed* with mean  $\mu_{\bar{X}} = \mu$  and variance  $\sigma_{\bar{X}}^2 = \sigma^2/n$ .

**Example 73** (Example 7.9 in the textbook). A Ukrainian munitions factory produces a 155mm artillery shell every 1.5 minutes, with the production time having a variance of 1.

**Question:** Find the probability that the factory will produce more than 100 shells in the next two hours.

**Solution:** We don't need to assume that the production times of the shells are normal, but we'll assume that they are independent. Let

$$Y_i = (\text{time required to produce the } i^{\text{th}} \text{ shell}).$$

With this notation, we want to find the probability of the event  $[Y_1 + \dots + Y_{100} \leq 120]$ .

$$\begin{aligned} \mathbb{P}[Y_1 + \dots + Y_{100} \leq 120] &= \mathbb{P}\left[\bar{Y} \leq \frac{120}{100}\right] \\ &= \mathbb{P}[\bar{Y} \leq 1.2]. \end{aligned}$$

Because the sample size is large, the central limit theorem tells us that  $\bar{Y}$  is approximately normally distributed with mean  $\mu_{\bar{Y}} = 1.5$  and variance  $\sigma_{\bar{Y}}^2 = 1/100$ . Standardizing  $\bar{Y}$ , we have

$$\begin{aligned} \mathbb{P}[\bar{Y} \leq 1.2] &= \mathbb{P}\left[\frac{\bar{Y} - 1.5}{1/\sqrt{100}} \leq \frac{1.2 - 1.5}{1/\sqrt{100}}\right] \\ &\approx \mathbb{P}[Z \leq -3] \\ &= .0013. \end{aligned}$$

Therefore it is very unlikely that the factory will produce more than 100 shells in the next two hours.

End of Example 73.  $\square$

**Example 74** (Example 7.10 in the textbook). A candidate believes that she can win a city election if she can earn at least 55% of the votes in precinct 1. She also believes that about 50% of the city's voters favor her. If  $n = 100$  voters show up to vote at precinct 1, what is the probability that she will receive at least 55% of their votes?

**Solution:** If we think of the  $n = 100$  voters as a random sample from the city, we have random variables

$$X_i = \begin{cases} 1 & : \text{voter } i \text{ votes for her} \\ 0 & : \text{otherwise} \end{cases}$$

and the proportion of votes she receives is

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

We need to find  $\mathbb{P}[\bar{X} \geq .55]$ . First observe that

$$\mu := \mathbb{E}[X_i] = .5 \quad \text{and} \quad \sigma^2 := \text{Var}(X_i) = p(1-p) = (.5)(.5) = .25.$$

By the central limit theorem, since  $n$  is large,  $\bar{X}$  is approximately normally distributed with mean  $\mu_{\bar{X}} = .5$  and variance  $\sigma_{\bar{X}}^2 = \sigma^2/n = .25/100 = .0025$ . Therefore, standardizing  $\bar{X}$ , we have

$$\begin{aligned} \mathbb{P}[\bar{X} \geq .55] &= \mathbb{P}\left[\frac{\bar{X} - .5}{\sqrt{.0025}} \geq \frac{.55 - .5}{\sqrt{.0025}}\right] \\ &\approx \mathbb{P}\left[Z \geq \frac{.55 - .5}{\sqrt{.0025}}\right] \\ &\approx \mathbb{P}[Z \geq 1] \\ &= .1587. \end{aligned}$$

End of Example 74.  $\square$

### 11.1.1 Point Estimation

*This section is based on section 8.2 in the textbook.*

Suppose we wish to estimate a target parameter  $\theta$ , say, the fraction of people living in Hawai'i who like broccoli.

**Remark 75.** If our target parameter is  $\theta$ , we often denote our estimator for that parameter using a “hat”, i.e., as  $\hat{\theta}$ .

Recall that the distribution of an estimator  $\hat{\theta}$  is called the **sampling distribution**. It is desirable for the sampling distribution to cluster around the target parameter.

One criterion of the “goodness” of an estimator is to ask whether it exhibits “bias”.

**Definition 76** (Biased and unbiased). Let  $\hat{\theta}$  be a point estimator for a parameter  $\theta \in \mathbb{R}$ .

If  $\mathbb{E}[\hat{\theta}] = \theta$  then  $\hat{\theta}$  is **unbiased**.

If  $\mathbb{E}[\hat{\theta}] \neq \theta$ , then  $\hat{\theta}$  is said to be **biased**.

The **bias** of an estimator  $\hat{\theta}$ , denoted  $B(\hat{\theta})$  or  $\text{Bias}(\hat{\theta})$ , is the number  $B(\hat{\theta}) = \mathbb{E}[\hat{\theta}] - \theta$ .

**Remark 77.** Since  $\hat{\theta}$  is a statistic, it is a function of a random sample. So when we write  $\mathbb{E}[\hat{\theta}]$ , we really mean  $\mathbb{E}[\hat{\theta}(X_1, \dots, X_n)]$ , where  $X_1, \dots, X_n$  is a random sample from the population.

**Remark 78.** Confusingly, when given an estimator  $\hat{\theta} = \hat{\theta}(X_1, \dots, X_n)$  (a random variable which depends on the sample), we also sometimes denote the value of resulting estimate by  $\hat{\theta}$ .

**Example 79.** Suppose I roll a dice behind a screen, shouting out the number rolled each time. Your job is to estimate the number of sides of the dice, which we will call  $\theta$ .

Given  $n$  rolls, the sample  $n$  random variables

$$X_1, \dots, X_n$$

where  $X_i$  is the  $i^{\text{th}}$  dice roll. We'll give two examples of estimators:

- Our first example is called the *running maximum*, and it is defined as

$$\hat{\theta} = \max(X_1, \dots, X_n).$$

For example, if I roll the dice four times and obtain 3, 11, 7, and 4, then your estimate would be that the dice has 11 sides.

This sounds silly, but with enough data this estimator will give you the correct answer with high probability. This is because, if I roll the dice enough times, then I will eventually roll the highest number; hence,

$$\lim_{n \rightarrow \infty} \hat{\theta}(X_1, \dots, X_n) = \theta.$$

One drawback is that this estimator is biased because  $\mathbb{E}[\hat{\theta}] < \theta$ . This is because it will “usually” be less than the true number of sides, and will never be more.

- Our second example is what is called the *method of moments estimator*. In this setting, it's defined as

$$\hat{\theta} = 2 \left( \frac{X_1 + \dots + X_n}{n} \right) - 1.$$

Let's demystify this estimator. We know that since the dice has  $\theta$  sides, it has expected value

$$\mathbb{E}[X] = \frac{1}{\theta} (1 + 2 + \dots + \theta) = \frac{\theta + 1}{2}.$$

Rearranging, we get

$$\theta = 2\mathbb{E}[X] - 1. \tag{7}$$

We also know that by the law of large numbers,

$$\frac{X_1, \dots, X_n}{n} \approx \mathbb{E}[X].$$

Combining this with Eq. (7) implies

$$\theta \approx 2 \left( \frac{X_1, \dots, X_n}{n} \right) - 1.$$

The right hand side is what we've chosen to be our  $\hat{\theta}$ , and hopefully this calculation makes it seem like a reasonable choice.

This estimator is unbiased. To see why, observe that

$$\begin{aligned} \mathbb{E}[\hat{\theta}] &= \mathbb{E} \left[ 2 \left( \frac{X_1 + \dots + X_n}{n} \right) - 1 \right] \\ &= 2\mathbb{E} \left[ \frac{X_1 + \dots + X_n}{n} \right] - 1 \\ &= 2\mathbb{E}[X] - 1 \\ &= \theta \end{aligned} \quad \text{by Eq. (7).}$$

In our example, with dice rolls 3, 11, 7, and 4, our estimator  $\hat{\theta}$  returns the estimate

$$2 \left( \frac{3 + 11 + 7 + 4}{4} \right) - 1 = 2 \left( \frac{25}{4} \right) - 1 = 11.5.$$

So your estimate would be that the dice has 11.5 sides.

End of Example 79.  $\square$

Given two unbiased estimators, then *ceteris paribus*, we would typically prefer the estimator which has lower variance.

### 11.1.2 Mean square error

Here we present another criterion for whether an estimator is “good”.

**Definition 80** (Mean square error). The *mean square error* (MSE) of a point estimator  $\hat{\theta}$  is

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

This is the average square of the distance between the estimator and the target parameter. We want the MSE to be small.

The next theorem says that MSE is a combined measure of both the estimator’s variance and its bias.

**Theorem 81.** Let  $\hat{\theta}$  be an estimator such that  $\mathbb{E} \left[ \hat{\theta} \right]$  is defined. Then,

$$\text{MSE}(\hat{\theta}) = \text{Var}(\hat{\theta}) + \text{Bias}(\hat{\theta})^2.$$