

# Probability Theory

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**Definition 5.** The **complement** of a set  $A$  is everything not in  $A$ .

**Definition 6.** A **finite set** is a set with finite number of elements.

**Definition 7.** The **cartesian** product of two sets  $A$  and  $B$  denoted  $A \times B$  is

$$\{(a, b) : a \in A \wedge b \in B\}.$$

Then,  $|A \times B| = |A| \cdot |B|$ .

## Lecture 1: Intro to Probability

### 1 Basics of Probability

What data do you need to specify probability? You need the **set of all outcomes**, a list of everything that could possibly occur as a consequence, and the likelihood of each event.

**Example.** For a roll of a dice, the set of all outcomes would be  $\{1, 2, 3, 4, 5, 6\}$ . The list could include things like “the result is 3”, or “the result is  $\geq 4$ ”, and the likelihood would be  $\frac{1}{6}$  for each of the results.

#### 1.1 Basics of Set Theory

**Definition 1.** A **set** is an unordered collection of elements. **Elements** are objects within sets.

**Definition 2.** A set  $A$  is a **subset** of a set  $B$  if  $a \in A \Rightarrow a \in B$

**Definition 3.** The **union** of two sets  $A$  and  $B$  is the collection of elements that are in  $A$  or  $B$ .

**Definition 4.** The **intersection** of two sets  $A$  and  $B$  is the collection of elements that are in both  $A$  and  $B$ .

#### 1.2 Back to Probability

**Definition 8.** A **sample space** is the set of all possible outcomes in an experiment.

**Example.** The sample space  $\Omega$  for a coin flip is  $\{H, T\}$ .

Note that **events** are just subsets of the sample space, and **elementary events** are just elements of the sample space.

**Example.** For a dice roll:  $\Omega = \{1, 2, 3, 4, 5, 6\}$ , some events could be  $\{1, 2\}$ ,  $\{3, 6\}$ ,  $\{3\}$ . There are a total of  $2^6$  events.

**Definition 9.** If  $\Omega$  is a finite set, a probability  $P$  on  $\Omega$  is a function:  $P: 2^\Omega \rightarrow [0, 1]$  such that  $P(\emptyset) = 0$  and  $P(\Omega) = 1$ .

**Lemma 1.** If  $A_1, \dots, A_\alpha \subset \Omega$  are disjoint,  $P(\bigcup_i A_i) = \sum_i P(A_i)$ .

**Proposition 1.** Let  $A = \{a_1, a_2, \dots, a_I\}$  such that  $a_i$  are elementary events. Then,

$$P(A) = \sum_{i=1}^I P(\{a_i\}).$$

**Example.** For the dice roll, if  $A = \{1, 3, 5\}$ , then  $P(A) = 3 \cdot \frac{1}{6} = \frac{1}{2}$ .

**Definition 10. Equiprobable outcomes:** Let's say we have the set  $\Omega = \{\omega_1, \dots, \omega_N\}$  and  $P(\omega_i) = P(\omega_j)$  for all  $i$  and  $j$ . Then,  $P(\omega) = \frac{1}{N}$  for all  $\omega \in \Omega$  and  $P(A) = \frac{|A|}{N}$ . In other words, when outcomes are probable,

$$P(\text{event}) = \frac{\text{number of outcomes for that event}}{\text{number of possible outcomes}}.$$

### 1.3 Counting

Suppose 2 experiments are being performed. Let's say that experiment 1 has  $m$  possible outcomes, and experiment 2 has  $n$  possible outcomes. Then together, there are total of  $n \cdot m$  total outcomes.

**Example.** Rolling a dice and then flipping a coin, how many possible outcomes are there?

**Proof.** You have  $6 \cdot 2 = 12$  outcomes.

**Example.** Let's say you have a college planning committee that consists of 3 freshman, 4 sophomores, 5 juniors, and 2 seniors. How many ways are there to select a subcommittee of 4 with one person from each grade?

**Proof.** There are 4 events with 3, 4, 5, and 2 possible outcomes for each. Therefore, there are  $3 \cdot 4 \cdot 5 \cdot 2 = 120$  total subcommittees.

**Example.** How many 7-place license plates are there if the first 3 are letters and the last 4 are numbers?

**Proof.** There are  $26^3 \cdot 10^4$  license plates.

**Definition 11.** A **permutation** is an ordering of elements in a set. The number of ways to order  $n$  elements is given by  $n!$ .

**Example.** Alex has a bunny ranch with 10 bunnies. They are going to run an obstacle course and ranked 1-10 based on completion time. How many possible rankings are there (no ties)?

**Proof.** There are  $10!$  possible rankings.

**Example.** Assume 6 bunnies have straight ears and 4 have floppy ears. We rank the bunnies separately. How many possible rankings are there?

**Proof.** There are  $6! \cdot 4!$  possible outcomes.

**Definition 12.** A **combination** denotes the number of ways to choose  $k$  elements from  $n$  total elements (counting subsets).

**Example.** How many ways are there to pick a 2 person team from a set of 5 people?

**Proof.** There are  $C(5, 2) = \binom{5}{2} = \frac{5!}{2! \cdot 3!} = 10$  ways.

**Example.** How many committees consisting of 2 women and 3 men can be formed from a group of 5 women and 7 men?

**Proof.** We have  $C(5, 2) \cdot C(7, 3)$  possible committees.

**Example.** What if two of the men do not want to serve on the committee together?

**Proof.** The number of ways to choose the women stays the same. However, for the men we must subtract the number of committees that have both men. Therefore, we have  $C(5, 2) \cdot (C(7, 3) - C(5, 1))$  possible committees.

**Example.** How many ways can we divide a 10 person class into 3 groups, sizes 3, 3, and 4?

**Proof.** We just have 3 events, multiplying:  $C(10, 3) \cdot C(7, 3) \cdot C(4, 4)$ .

**Definition 13.** This is known as a **multinomial**, and is given by

$$\binom{n}{n_1, n_2, \dots, n_r} = \frac{n!}{n_1! \cdot n_2! \cdot \dots \cdot n_r!}.$$

It counts the number of ways to partition a set of size  $n$  into sets of sizes  $n_1, n_2, \dots, n_r$ .

### 1.4 Back to Probability Again

**Example.** Flip 10 fair coins. What is the likelihood of flipping 3 heads?

**Proof.** Number of events of 3 heads is  $C(10, 3)$ . Total number of events is  $2^{10}$ . Therefore,

$$P(10 \text{ heads}) = \frac{C(10, 3)}{2^{10}}.$$

In general, we have  $\sum_{k=0}^n P(k \text{ heads}) = 1$ . In other words,

$$\frac{1}{2^{10}} \cdot \sum_{k=0}^{10} \binom{10}{k} = 1.$$

such that

$$\sum_{k=0}^{10} \binom{10}{k} = 2^{10}.$$

More generally,

**Definition 14.** The **binomial theorem** states that for all  $x, y \in \mathbb{R}$ ,  $n \geq 1$ ,  $n \in \mathbb{N}$ ,

$$(x + y)^n = \sum_{k=0}^n \binom{n}{k} x^k y^{n-k}.$$

**Example.** Rolling 10 dice, what is the likelihood of exactly 2 outcomes each of 1,2,3,4, 1 outcome of 6, and 1 outcome of 5.

**Proof.** There are total  $6^{10}$  outcomes, and there are  $\binom{10}{2,2,2,2,1,1}$  desired outcomes. Therefore, the probability of this event is  $\frac{\binom{10}{2,2,2,2,1,1}}{6^{10}}$ .

**Definition 15.** The **multinomial theorem** states that  $(x_1 + \dots + x_r)^n =$

$$\sum_{n_1 + \dots + n_r = n} \binom{n}{n_1, \dots, n_r} x_1^{n_1} x_2^{n_2} \dots x_r^{n_r}.$$

## 1.5 Measure Theory

This is just a generalization of what we have seen before.

**Definition 16.** Let  $\mathcal{F} \subset 2^\Omega$  be an “event space”. A mapping  $P : \mathcal{F} \rightarrow \mathbb{R}$  is a **probability measure** on  $(\Omega, \mathcal{F})$  if

- $P(A) \geq 0 \quad \forall A \in \mathcal{F}$
- $P(\emptyset) = 0, P(\Omega) = 1$

- If  $A_1, A_2, \dots$  are disjoint,

$$P\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} P(A_i).$$

## Lecture 2

### 1.6 Properties of Event Spaces

**Definition 17.** A collection  $\mathcal{F}$  of subsets of the sample space  $\Omega$  is called an **event space** if

- $\mathcal{F}$  is non-empty.
- if  $A \in \mathcal{F}$  then  $\Omega \setminus A \in \mathcal{F}$ .
- if  $A_1, A_2, \dots \in \mathcal{F}$  then  $\bigcup_{i=1}^{\infty} A_i \in \mathcal{F}$ .

**Theorem 1.** If  $A \in \mathcal{F}$ , then  $P(A) + P(\Omega \setminus A) = 1$

**Proof.** Notice that  $A$  and  $\Omega \setminus A$  are disjoint. And, that  $A \cup (\Omega \setminus A) = \Omega$ . Then,

$$P(A \cup (\Omega \setminus A)) = P(\Omega) = 1.$$

□

**Theorem 2.** If  $A, B \in \mathcal{F}$  then  $P(A \cup B) + P(A \cap B) = P(A) + P(B)$ .

**Proof.** Note that  $A \cup B = (A \setminus B) \cup (A \cap B) \cup (B \setminus A)$ . This is a union of disjoint sets, such that  $P(A \cup B) = P(A \setminus B) + P(A \cap B) + P(B \setminus A)$ . Then, we have  $P(A \cup B) + P(A \cap B) = P(A \setminus B) + P(A \cap B) + P(B \setminus A) + P(A \cap B)$ , of which the RHS simplifies to  $P(A) + P(B)$ . □

**Theorem 3.** If  $A, B \in \mathcal{F}$ , and  $A \subseteq B$ , then  $P(A) \leq P(B)$ .

**Proof.** We wish to show  $A \subseteq B \Rightarrow P(A) \leq P(B)$ . Then,  $B = (B \setminus A) \cup (B \cap A) = (B \setminus A) \cup A$ , such that  $P(B) = P(B \setminus A) + P(A) \geq P(A)$  because  $P(B \setminus A) \geq 0$ . □

### 1.7 Examples

**Example.** What is the probability that one is dealt a full house?

**Proof.** This is the number of ways one can get a full house, divided by the total number of poker hands (5 card). The total number of poker

hands is  $\binom{52}{5}$ . The number of full houses is  $\frac{52 \cdot \binom{3}{2} \cdot 48 \cdot 3}{2!3!}$ . Another way we can count the number of full houses is  $\binom{13}{1} \cdot \binom{4}{3} \cdot \binom{12}{1} \cdot \binom{4}{2}$ . The result of the division is our answer.

**Example.** A box contains 3 marbles, 1 red 1 green and 1 blue. Consider an experiment that consists of us taking 1 marble, replacing it, and drawing another marble. What is the sample space?

**Proof.**

$$\Omega = \{(r, r), (r, b), (r, g), (b, r), (b, g), (b, b), (g, r), (g, g), (g, b)\}.$$

**Example.** What about if we don't replace the first marble?

**Proof.** Everything without  $(r, r), (b, b), (g, g)$ .

**Example.** What is the probability of being dealt a flush?

**Proof.** This is just number of flushes divided by number of poker hands. The number of flushes is  $\binom{4}{1} \cdot \binom{13}{5}$ .

**Example.** What is the probability of being dealt a straight?

**Proof.** We can do the probability of any straight, minus probability of straight flush. The number of straights is 10 number-wise. Therefore, the number of straights is  $10 \cdot (4^5 - 4)$ . The probability can be then calculated.

**Example.** An urn contains  $n$  balls. If  $k$  balls are withdrawn one at a time, what is the probability that a special ball is chosen?

**Proof.**  $P(\text{special}) = 1 - P(\text{special}^c)$ . If the special ball is not chosen, it would be  $\frac{(n-1)!}{(n-k-1)!}$ . The total number of withdrawals is  $\frac{n!}{k!}$ . Then, the total probability is  $1 - \frac{n-k}{n}$ .

**Example.** If  $n$  people are present in a room, what is the prob that no two celebrate their birthday on the same date? How large must  $n$  be such that this probability is  $< \frac{1}{2}$ .

**Proof.**  $P(\text{no people with same birthday})$  is the number of no same birthday situations divided by the number of possibilities. Total possibilities is  $365^n$ . No same birthday situations is  $P(365, n) = \frac{365!}{(365-n)!}$ . For the second question,  $n = 23$ .

## 1.8 Conditional Probability

**Definition 18.** If  $A, B \in \mathcal{F}$  and  $P(B) > 0$  then the **conditional probability** if  $A$  given  $B$  is denoted by  $P(A | B)$  and defined by

$$P(A | B) = \frac{P(A \cap B)}{P(B)}.$$

**Theorem 4.** If  $B \in \mathcal{F}$  and  $P(B) > 0$  then  $(\Omega, \mathcal{F}, \mathbb{Q})$  is a probability space where  $\mathbb{Q} : \mathcal{F} \rightarrow \mathbb{R}$  is defined by  $\mathbb{Q}(A) = P(A | B)$

**Example.** Let's say a coin is flipped twice. What is the conditional probability that both flips land on heads, given that the first flip lands on heads?

**Proof.**  $\frac{P(\text{two heads} \cap \text{first heads})}{P(\text{first heads})} = \frac{P(\text{two heads})}{P(\text{first heads})}$ . This is just  $\frac{1}{2}$ .

**Example.** What if given at least one lands on heads?

**Proof.**  $\frac{P(\text{two heads} \cap \text{at least one head})}{P(\text{at least one head})} = \frac{P(\text{two heads})}{P(\text{at least one head})} = \frac{2}{3}$ .

**Example.** In the card game bridge, the 52 cards are dealt equally. If North and South have a total of 8 spades among them, what is the probability that East has 3 of the 5 remaining spades?

**Proof.** No rule:  $P(\text{E has 3 spades}) = \frac{\binom{5}{3} \cdot \binom{21}{10}}{\binom{26}{13}}$ .

**Theorem 5.** Probability of intersection of three sets (insert here).

**Definition 19.** We call two events  $A, B$  **independent** if the occurrence of one does not affect the other. Formally,

$$P(A | B) = P(A) \text{ and } P(B | A) = P(B).$$

We can also check that  $P(A \cap B) = P(A) \cdot P(B)$ .

**Example.** Flip three fair coins. What is likelihood that all three come up heads?

**Proof.** With the sample space approach:  $\Omega = \{H, T\}^3$ . Of 8 total elementary events, 1 has three heads, so the probability is  $\frac{1}{8}$ .

With independence: we know that each event is independent, and all events are  $\frac{1}{2}$ , so the probability is  $(\frac{1}{2})^3 = \frac{1}{8}$ .

**Definition 20.** Independence can be expanded to more than just two events (insert from canvas). However, note that events can be pairwise independent, but may not be all together independent.