

# Probability-I

Spring 2024



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**Literature used in the preparation of these notes:**

S. Bhattacharya, *The Probabilistic Pigeonhole Principle*, The American Mathematical Monthly, Vol. 130, No. 7, p. 678, 2023

G. H. Hardy and E. M. Wright, *An Introduction to the Theory of Numbers*, eds. D. R. Heath-Brown, J. H. Silverman, Oxford University Press, 2008

S. Ross, *A first course in Probability*, Pearson Education, 2002

<https://en.wikipedia.org/>

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*Life is either a daring [random experiment](#)\** or nothing at all.

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\*apologies to Helen Keller.

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# Probability Spaces

Probability is a measure of how likely an event is to occur. This subject has a wide range of applications in every aspect of human life. The first use of probabilistic notions occurred in Cardano's *Book on games of chance*\* (1663). Also, *The art of speculating*\*\* (1713) by Bernoulli and *The doctrine of chances*† (1718) by De Moivre had immense impacts on the development of the Theory of Probability. Initially, people studying probability were concerned about the actions which could result in only finitely many outcomes. So, the probability of obtaining a particular set of outcomes was defined as

(0.1) *the proportion of the required outcomes among all the possible outcomes*

of the action. The first attempt to extend probabilistic ideas beyond finite sets was in Laplace's *Analytical Theory of Probability*‡ (1812). Much later, the modern axioms of Probability were introduced by Kolmogorov in his book *Foundations of the Theory of Probability*§ (1933).

## 1 THE PROBABILISTIC PIGEONHOLE PRINCIPLE

The Pigeonhole principle asserts that if you put  $n$  pigeons into  $m < n$  pigeonholes, then at least two pigeons would be in the same hole.



You may wonder what happens if there are more pigeonholes than pigeons. In any case, if the pigeons are allocated to the pigeonholes indiscriminately, regardless of the number of occupants of any pigeonhole, then it is still a possibility that two or more pigeons end up in the same hole. The *Birthday problem* is only a special

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\*in Italian

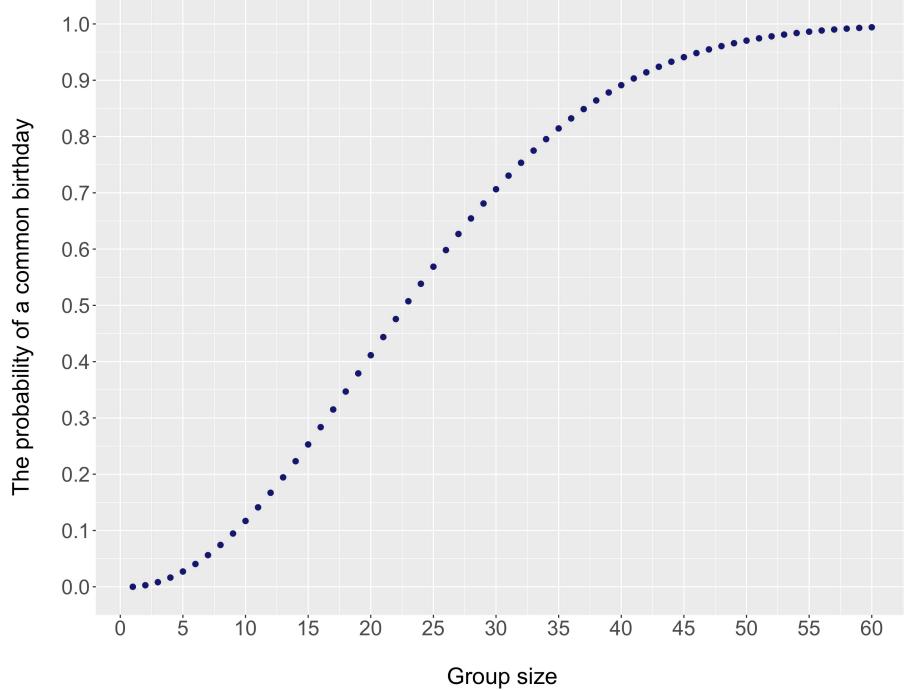
\*\*in Latin

†in English

‡in French

§in German

case of this which asks for the probability\* that in a group of  $n$  randomly chosen people, at least two shares a birthday. The apparent paradox is that the probability of two persons sharing a birthday exceeds 0.5 if the group size is at least 23. In fact, if a group has at least 57 members, the probability that at least two of the members have a common birthday is more than 0.99.



**THEOREM 1 (PROBABILISTIC PIGEONHOLE PRINCIPLE).** *Given  $m \in \mathbb{N}$  and  $p \in [0, 1)$ , let  $n \in \mathbb{N}$  be larger than or equal to*

$$(1.1) \quad \frac{1}{2} + \sqrt{2m \log\left(\frac{1}{1-p}\right)} + \frac{1}{4}.$$

*If  $n$  pigeons are placed in  $m$  pigeonholes randomly, then the probability that at least two pigeons would be in the same hole is greater than  $p$ .*

**PROOF.** We require to show that for an integer  $n$  which is larger than the quantity in (1.1), if  $n$  pigeons are placed in  $m$  pigeonholes randomly, then the probability of an overlap in the placement of the pigeons is greater than  $p$ . From (0.1), it follows that the probability of an overlap in the placement is greater than  $p$  if and only if the probability of no overlap in the placement of the pigeons is less than  $1 - p$ . Let us compute this probability: Since every pigeon could be placed in any of the  $m$  pigeonholes, the total number of ways in which  $n$  pigeons could be placed in  $m$  holes is  $m^n$ . Whereas, the number of ways in which  $n$  pigeons could be placed in  $m$  holes with no overlaps is  ${}^m P_n$ . Now, (0.1) implies that the required probability is the proportion of the placements of the pigeons in distinct pigeonholes among all possible placements of  $n$  pigeons in  $m$  pigeonholes. This

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\*For now, we take (0.1) as the definition of Probability.

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proportion is  ${}^mP_n/m^n$ . Hence, it suffices to show that if the integer  $n$  is greater than or equal to the quantity in (1.1), then  ${}^mP_n/m^n$  is less than  $1 - p$ .

Let  $n$  be greater than or equal to the quantity in (1.1). Then after subtracting  $1/2$  from both sides, squaring and dividing by  $2m$ , we obtain

$$\frac{n(n-1)}{2m} > \log\left(\frac{1}{1-p}\right),$$

which implies that

$$-\sum_{j=1}^{n-1} \log\left(1 - \frac{j}{m}\right) = \sum_{j=1}^{n-1} \sum_{\ell=1}^{\infty} \frac{j^\ell}{\ell m^\ell} > \sum_{j=1}^{n-1} \frac{j}{m} = \frac{n(n-1)}{2m} > \log\left(\frac{1}{1-p}\right).$$

After multiplying both sides by  $-1$  and exponentiating, we obtain

$$\prod_{j=1}^{n-1} \left(1 - \frac{j}{m}\right) < 1 - p.$$

Since the left hand side of the above inequality is  ${}^mP_n/m^n$ , the claim follows.  $\square$

Instead of using the logarithmic inequality as above, one may also use the fact that  $e^{-x} \geq 1 - x$  for all  $x \in \mathbb{R}$  to prove Theorem 1.

**COROLLARY 1.** *If  $3n + 1$  or more pigeons are placed in  $n^2$  pigeonholes randomly, then the probability that at least two pigeons would be in the same hole is greater than 0.98889.*

**PROOF.** Putting  $m = n^2$  and  $p = 0.98889$  in (0.1), we obtain a quantity that is smaller than

$$\frac{1}{2} + \sqrt{9n^2 + \frac{1}{4}},$$

which is less than  $3n + 1$ .  $\square$

## 2 THE LONGEST RUN IN A SEQUENCE OF TOSSES

During the last quarter of the twentieth century, it was a common practice\* among probability teachers around world to demonstrate a probabilistic method of lie detection: They used to give their students the homework of tossing a coin a hundred times\*\* and noting down the sequence of outcomes. Quite predictably, it was also a common practice among the students to evade this boring homework and make an attempt to dupe the teacher by writing down a sequence of heads and tails which they thought are sufficiently *random*. As in general, human intuition of *randomness* is rather poor, in almost all cases these made-up sequences did not contain any run of heads or tails of length larger than five or six. In the next class,

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\*See this article: [https://www.maa.org/sites/default/files/images/upload\\_library/22/Polya/07468342.di020742.02p0021g.pdf](https://www.maa.org/sites/default/files/images/upload_library/22/Polya/07468342.di020742.02p0021g.pdf)

\*\*Or even a thousand times, as recollected by Prof. Bimal Roy from the B. Stat.(Hons.) batch of 1978 of ISI Kolkata. Their teacher Prof. Jogabrata Roy gave them this homework in their first class of Probability.

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the teacher used to ask how many students obtained a run of eight\* or more heads, which was often answered in the negative. Then he used to tell the students to compute the probability of their claim to see how unlikely it is! Let's demonstrate how to compute such probabilities\*\* with a small example:

EXAMPLE 1. Find the probability of obtaining no two consecutive heads when a fair coin is tossed seven times.

ANSWER. For  $n \geq 1$ , let  $F_n$  denote the number of outcomes with no two consecutive heads when a fair coin is tossed  $n$  times. Then we have

$$F_1 = |\{T, H\}| = 2,$$

$$F_2 = |\{TT, HT, TH\}| = 3$$

and for  $n > 2$ ,

$$F_n = F_{n-1} + F_{n-2},$$

because, a sequence of  $n \geq 2$  tosses without two consecutive heads ends either in  $T$  or  $TH$ . It follows from above that  $F_7 = 34$ . Since the total number of possible outcomes in 7 tosses (assuming that the coin does not land on its side) is  $2^7$ . So, according to (0.1), the required probability is  $F_7/2^7 = 17/64$ .

### 3 THE RIEMANN HYPOTHESIS VIA PROBABILITY

As a brief motivation for the students of probability, below we describe the Riemann Hypothesis<sup>†</sup> (1859) in probabilistic terms.

DEFINITION 1 (PRIMORIAL). The  $k$ -th primorial is the product of the first  $k$  primes.

DEFINITION 2 (EULER–MASCHERONI CONSTANT). The limiting value  $\gamma$  of the difference between  $\sum_{k=1}^m \frac{1}{k}$  and  $\log m$  as  $m$  tends to infinity. Its first few digits are

$$0.5772156649015328606065120900824024310421593359399235988057672 \dots$$

The Riemann Hypothesis is equivalent to the claim that if an integer  $n$  is chosen at random from  $\{1, 2, \dots, N_k\}$ , where  $N_k$  denotes the  $k$ -th primorial, then the probability of  $n$  being coprime to  $N$  is less than

$$\frac{1}{e^\gamma \log \log N_k}$$

for all  $k \in \mathbb{N}$ .

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\*Of course, *eight* could be replaced by a larger number, depending on the class size.

\*\*Here we compute the probability only for one sequence of a given length. In a class, the same experiment is repeated as many times as the number of students in the class. So, the probability that nobody obtains a run of heads of length eight or more in hundred tosses reduces significantly when the class size is big.

<sup>†</sup>A 165 years old open conjecture which claims that the real part of any the nontivial zero of the Riemann Zeta function is  $1/2$ .

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## 4 THE AXIOMATIC DEFINITION OF PROBABILITY

**DEFINITION 3 (EXPERIMENT).** An experiment is an act that can be repeated under similar conditions.

**DEFINITION 4 (SAMPLE SPACE).** The set  $\Omega$  of all possible outcomes of an experiment is called its sample space.

**DEFINITION 5 (SET OF EVENTS AND THE AXIOMS OF PROBABILITY).** The set of events is a subset  $\mathcal{E}$  of the power set of the sample space  $\Omega$  such that

- (a)  $\Omega \in \mathcal{E}$ .
- (b) If  $A \in \mathcal{E}$ , then  $A^c \in \mathcal{E}$ .
- (c) The set  $\mathcal{E}$  is closed under countable unions.
- (d) There exists a function  $P : \mathcal{E} \rightarrow [0, 1]$  such that  $P(\Omega) = 1$ . and for pairwise disjoint events  $\{A_n\}_{n=1}^{\infty}$  with  $A = \bigcup_n A_n$ ,

$$P(A) = \sum_{n=1}^{\infty} P(A_n).$$

In particular, for a finite sample space, we may always assume the set of events to be identical with the power set of the sample space.

**DEFINITION 6 (PROBABILITY SPACE).** The sample space  $\Omega$  of an experiment together with the set of events  $\mathcal{E}$  and the probability function  $P : \mathcal{E} \rightarrow [0, 1]$ , is called a probability space and it is denoted by the triplet  $(\Omega, \mathcal{E}, P)$ .

**EXAMPLE 2 (GAMES OF CHANCES).**

- (i) Tossing a coin:  $\Omega = \{H, T\}$ .
- (ii) Rolling a die:  $\Omega = \{1, 2, 3, 4, 5, 6\}$ .
- (iii) Guessing the first letter of a stranger's name:  $\Omega = \{A, B, C, \dots, Z\}$ .
- (iv) Guessing someone's palm temperature in Fahrenheit:  $\Omega = [55, 115]$ .
- (v) Guessing the number of stars in the Milky Way:  $\Omega := \{1, 2, 3, \dots\}$ .

**DEFINITION 7 (MUTUALLY EXCLUSIVE EVENTS).** If two events  $A, B \in \mathcal{E}$  is such that  $A \cap B = \emptyset$ , then  $A$  and  $B$  are called mutually exclusive events.

Let  $(\Omega, \mathcal{E}, P)$  be a probability space. If  $A$  and  $B \in \mathcal{E}$  are mutually exclusive events, then Definition 5.(d) implies that  $P(A \cup B) = P(A) + P(B)$ .

However, if  $A \cap B \neq \emptyset$ , then we may write  $A = (A \cap B) \cup (A \cap B^c)$ , where  $B^c := \Omega \setminus B$ . Since  $A \cap B$  and  $A \cap B^c$  are mutually exclusive, it follows from Definition 5.(d) that

$$(4.1) \quad P(A) = P(A \cap B) + P(A \cap B^c).$$

Since  $A \cup B = (A \cap B^c) \cup B$  and since  $A \cap B^c$  and  $B$  are mutually exclusive,

$$(4.2) \quad P(A \cup B) = P(A \cap B^c) + P(B).$$

From (4.1) and (4.2), it follows that

$$(4.3) \quad P(A \cup B) = P(A) + P(B) - P(A \cap B).$$

By induction, the above equality can be generalized to any finite collection of events.

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**DEFINITION 8 (EXHAUSTIVE EVENTS).** The events in a set  $S \subseteq E$  are called exhaustive if  $\bigcup_{A \in S} A = \Omega$ , i.e. the entire sample space.

**EXAMPLE 3 (COUNTABLE SAMPLE SPACES).** Let  $\Omega = \{\omega_n\}_{n=1}^{\infty}$ . If  $\mathcal{E} = 2^{\Omega}$ , then in particular,  $\{\omega_n\} \subseteq \Omega$  for all  $n \in \mathbb{N}$ . Since for  $n \in \mathbb{N}$ , the events  $\{\omega_n\}$  are pairwise mutually exclusive and exhaustive, it follows from the axioms of probability that

$$\sum_{n=1}^{\infty} P(\omega_n) = P(\Omega) = 1.$$

**EXAMPLE 4.** Show that if you keep on tossing a coin where the probability of obtaining a head is  $p > 0$ , then the probability of eventual occurrence of at least one head is 1.

**PROOF.** Consider the random experiment, where you keep on tossing the coin till you get a head. The corresponding sample space is

$$\Omega := \{H, TH, TTH, TTTH, \dots\} \cup \{TTTTT \dots \infty\}$$

and the set of events is  $\mathcal{E} = 2^{\Omega}$ , where

$$P(H) = p, P(TH) = (1-p)p, P(TTH) = (1-p)^2p, \dots$$

Since probability of eventually obtaining a head is

$$\sum_{n=0}^{\infty} (1-p)^n p = \frac{p}{1-(1-p)} = 1,$$

the claim follows.  $\square$

Since the complement of the desired event (i.e. eventually obtaining a head) is  $\{TTTTT \dots \infty\}$ , showing that

$$P(TTTTT \dots \infty) = \lim_{n \rightarrow \infty} (1-p)^n = 0$$

would have also sufficed for Example 4 (see Exercise 10.i).

**DEFINITION 9 (EQUALLY LIKELY).** The events in a set  $S \subseteq E$  are called equally likely if  $P(A) = P(B)$  for all  $A, B \in S$ .

**THEOREM 2.** All the outcomes in a countably infinite sample space can not be equally likely.

**PROOF.** Let  $\Omega := \{\omega_n\}_{n=1}^{\infty}$ . Suppose, each of the outcomes  $\omega_n$  has an equal probability  $p$  of occurrence. Since the events  $\{\omega_n\}$  are mutually exclusive and exhaustive, it follows that

$$1 = P(\Omega) = \sum_{n=1}^{\infty} P(\omega_n) = \sum_{n=1}^{\infty} p,$$

which is absurd, since the right hand side does not converge if  $p > 0$ , whereas if  $p = 0$ , then the right hand side converges to zero!  $\square$

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## 5 EARLIER ATTEMPTS AT DEFINING PROBABILITY

**DEFINITION 10 (RANDOM EXPERIMENT).** If the sample space of an experiment is known but none of the outcomes of the experiment occurs with certainty, then we call the experiment a random experiment.

In particular, all the games of chances mentioned in Example 2 are random experiments.

**EXAMPLE 5 (EXAMPLES OF NON-RANDOM EXPERIMENTS).** All the experiments that verify certain physical/chemical/biological laws are not random experiments\*.

**DEFINITION 11 (CLASSICAL DEFINITION OF PROBABILITY).** If a random experiment results in  $m$  mutually exclusive, exhaustive and equally likely outcomes, of which exactly  $n(A)$  outcomes are favourable for an event  $A \in \mathcal{E}$ , then the probability of the event  $A$ , denoted by  $P(A)$  is given by

$$P(A) = \frac{n(A)}{m}.$$

Indeed, the last definition is meant only for finite sample spaces. However, an inherent flaw in the last definition of probability is that it is cyclic, since in order to define *equally likely* events, we have already used the notion of probability.

**DEFINITION 12 (FREQUENCY DEFINITION OF PROBABILITY).** Let a random experiment be repeated  $n$  times, in which the frequency of the event  $A$  was  $f_n(A)$ , i.e. the event  $A$  occurred exactly  $f_n(A)$  times. The ratio  $f_n(A)/n$  is called the relative frequency of the event  $A$  and the probability  $P(A)$  is defined by the limit

$$P(A) = \lim_{n \rightarrow \infty} \frac{f_n(A)}{n}.$$

An inherent drawback of the above definition of probability is that the existence of the above limit can not be proved in any case. However, later we shall see that the law of large numbers has its roots in this idea.

## 6 BOOLE'S AND BONFERONI'S INEQUALITIES

**THEOREM 3 (BOOLE'S INEQUALITY).** Let  $(\Omega, \mathcal{E}, P)$  be a probability space. Then for  $A_1, A_2, \dots, A_n \in \mathcal{E}$ , we have

$$P(A_1 \cup A_2 \cup \dots \cup A_n) \leq P(A_1) + P(A_2) + \dots + P(A_n).$$

**PROOF.** For  $i \in \{1, 2, \dots, n\}$ , define

$$B_i := \begin{cases} A_1 & \text{if } i = 1 \\ A_i \setminus \bigcup_{j=1}^{i-1} A_j & \text{if } i > 1. \end{cases}$$

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\*However, if the range of the possible errors in such an experiment is nonempty and is known a priori, then we may also view such an experiment as a random experiment, since no particular error occurs with certainty.

By construction, the events  $B_i$  for  $i \in \{1, 2, \dots, n\}$  are disjoint. Therefore,

$$P(A_1 \cup A_2 \cup \dots \cup A_n) = P(B_1 \cup B_2 \cup \dots \cup B_n) = \sum_{i=1}^n P(B_i) \leq \sum_{i=1}^n P(A_i),$$

where the second equality follows from Definition 5.(d) and the last inequality follows from Exercise 10.ii.  $\square$

**THEOREM 4 (BONFERRONI'S INEQUALITY).** *Let  $(\Omega, \mathcal{E}, P)$  be a probability space. Then for  $A_1, A_2, \dots, A_n \in \mathcal{E}$ , we have*

$$P(A_1 \cap A_2 \cap \dots \cap A_n) \geq P(A_1) + P(A_2) + \dots + P(A_n) - (n - 1).$$

**PROOF.** We proceed to prove the claim by induction. Note that since  $P(A_1 \cup A_2) \leq 1$ , for  $n = 2$  the claim follows trivially from (4.3). Suppose, the claim holds for an integer  $m \geq 2$ . Then

$$\begin{aligned} P(A_1 \cap A_2 \cap \dots \cap A_m \cap A_{m+1}) &\geq P(A_1 \cap A_2 \cap \dots \cap A_m) + P(A_{m+1}) - 1 \\ &\geq \sum_{i=1}^m P(A_i) - (m - 1) + P(A_{m+1}) - 1 \\ &= \sum_{i=1}^{m+1} P(A_i) - m, \end{aligned}$$

where the first inequality holds since the claim is true for two events, whereas the second inequality is implied by the induction hypothesis. Thus, the claim follows.  $\square$

### Exercises

1. Show that the probability of at least two persons sharing a birthday among a group of  $n$  persons is

$$1 - \frac{365!}{365^n} - \frac{97 \times 365!}{146097 \times 365^{n-1}}.$$

2. Show that for any sequence  $\{a_n\}$  of positive reals which diverges to infinity, if  $\lfloor a_n \sqrt{n} \rfloor$  pigeons are placed in  $n$  pigeonholes, then the probability that at least two pigeons are in the same hole tends to 1 as  $n \rightarrow \infty$ .
3. If you toss a fair coin 20 times, find the probability of obtaining 10 heads and 10 tails.
4. Compute the probability of obtaining a total of 10 points when two unbiased dice are rolled.
5. (i) Find the probability of obtaining no four consecutive heads when a fair coin is tossed ten times.  
(ii) Find the probability of obtaining neither four consecutive heads nor four consecutive tails when a fair coin is tossed ten times.

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6. Let  $x$  be a point inside a convex quadrilateral  $Q$ . Find the probability that  $x$  is neither on the boundary nor inside any of the circles drawn with the sides of the quadrilateral  $Q$  as their diameters.
7. (Bertrand's Paradox) Explain why there can't be a single answer to the question that asks for the probability of choosing a chord randomly of length less than  $r$  in a circle of radius  $r$ .
8. Let  $(\Omega, \mathcal{E}, P)$  be a probability space. Show that  $\mathcal{E}$  is closed under countable intersections.
9. Let  $(\Omega, \mathcal{E}, P)$  be a probability space. Let  $A, B \in \mathcal{E}$ . Show that

$$P(B \cap A^c) = P(B) - P(B \cap A).$$

10. Let Suppose  $(\Omega, \mathcal{E}, P)$  be a probability space and  $A, B \in \mathcal{E}$ . Using the axiomatic definition of probability, prove the following statements:
- $P(A^c) = 1 - P(A)$ .
  - If  $A \subseteq B$ , then  $P(A) \leq P(B)$ .

11. Let  $(\Omega, \mathcal{E}, P)$  be a probability space and  $A_1, A_2, \dots, A_n \in \mathcal{E}$ . Show that  $P(A_1 \cup A_2 \cup \dots \cup A_n)$  is equal to

$$\sum_{i=1}^n P(A_i) - \sum_{1 \leq i < j \leq n} P(A_i \cap A_j) + \sum_{1 \leq i < j < k \leq n} P(A_i \cap A_j \cap A_k) - \dots + (-1)^{n-1} P(A_1 \cap \dots \cap A_n).$$

12. Show that if you keep on throwing a fair die, the probability of eventual occurrence of the outcome 6 is 1.
13. Dropping two points uniformly at random on  $[0, 1]$ , the unit interval is divided into three segments. Find the probability that the three segments obtained in this way form a triangle.
14. Find the probability of obtaining no two consecutive heads when a fair coin is tossed  $n$  times.
15. Find the probability of obtaining a strictly increasing sequence of integers if you pick 3 integers (one at a time) (a) with replacement or (b) without replacement from  $\{1, 2, 3, \dots, 1000\}$ .
16. To the choice of each  $n \in \mathbb{N}$ , could you assign a probability  $P(n) > 0$  such that the following conditions hold?
- $P(m) \neq P(n)$  for all  $m, n \in \mathbb{N}, m \neq n$ .
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- (2) The probability of choosing an odd positive integer is the same as the probability of choosing an even positive integer.
17. Seven students of IISER Kolkata went to participate in an event at IISER Mohali. They booked AC 3-tier tickets from Howrah to Chandigarh in Netaji Express, which has three AC 3-tier coaches. Every such coach has eight coupes (i.e. compartments), each coupe containing eight berths. If the berths were allocated randomly, find the probability of at least two among the seven students being allocated berths in the same coupe.
18. A point is selected at random inside an equilateral triangle whose side length is 3. Find the probability that the distance of the chosen point from any vertex of the triangle is greater than 1.
19. On a rainy day, 4 students went for their coaching classes with nearly identical raincoats. They put their raincoats at the same place before going to the class. Find the probability that none of the students selects his/her own raincoat after the class.
20. Suppose, the planetary system of a star contains ten planets with coplanar orbits and suppose the distance from the star to the farthest point(s) on the orbit of the outermost planet is 1.5 astronomical units. Find the probability that at an arbitrary instant of time, at least two of these planets are less than or equal to  $\sqrt{2}$  astronomical units apart from each other.
21. Suppose, the planetary system of a star contains twenty-five planets with at least two planets having non-coplanar orbits and suppose the distance from the star to the farthest point(s) on the orbit of the outermost planet is 2 astronomical units. Show that the probability of at least two of these planets being less than or equal to  $\sqrt{3}$  astronomical units apart from each other at an arbitrary instant of time is greater than 0.99.
22. Carrom is played with a red, nine black and nine white coins (and a striker) on a square board with a pocket in each corner. Suppose, we have a 29 inch  $\times$  29 inch carrom board (excluding the raised borders) and suppose, the diameter of all the coins are  $3/5$  inches. If all these coins are scattered randomly (none of them being in any pocket) on it, show that the probability of at least two of the coins being less than two inches apart is greater than  $4/5$ .

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## Conditional Probability

There's a story of a statistician who told a friend that he never took an aeroplane. Because, he computed the probability that there will be a bomb on the plane. Although this probability was low, it was still too high for his comfort.



Two weeks later, to her amazement, the same friend discovered the statistician onboard in her aeroplane. “Well, well, well.. here I see a statistician who changes his theory every two weeks!”, She exclaimed. “No, no, I haven’t changed my theory at all!”, he replied in a rather serious voice.“Then how did you gather the courage to board this flight?”, she teased, without realizing that there’s little point in teasing a nerd. “Oh, I just computed the probability that there would simultaneously be two bombs on a plane. This Probability was low enough for my comfort. So, now I carry my own bomb.”, he grinned.

Was there any flaw in the statistician’s argument? We shall come back to this question after we learn some basic terminologies in conditional probability.

### 7 BAYES’ THEOREM

Given the occurrence of an event  $B$  in a random experiment, the occurrence of an event  $A$  is equivalent to the occurrence of the event  $A \cap B$ . However, since  $B$  has already occurred, none of the events which are disjoint from  $B$  can occur anymore. So, if the event  $B$  has already occurred, then the sample space is reduced to  $B$ . The probabilities of the sub-events of  $B$  are measured relative to

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the probability of  $B$ , which in particular ensures that given  $B$ , the probability of the occurrence of the event  $B$  is 1.

**DEFINITION 13 (CONDITIONAL PROBABILITY).** Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $A, B \in \mathcal{E}$  with  $P(B) > 0$ . Then the probability of  $A$  given  $B$  is defined by

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

**LEMMA 1 (TOTAL PROBABILITY).** Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $\{A_i\}_{i=0}^{\infty}$  be exhaustive and pairwise mutually exclusive events such that  $P(A_0) = 0$  and  $P(A_i)$  is nonzero for all  $i \geq 1$ . Then for all  $B \in \mathcal{E}$ , we have

$$P(B) = \sum_{i=1}^{\infty} P(A_i)P(B|A_i).$$

**PROOF.** Since  $\Omega$  is the disjoint union of the events  $\{A_i\}_{i=1}^{\infty}$ , we may write

$$\begin{aligned} P(B) &= P(B \cap \Omega) = P\left(B \cap \left(\bigcup_{i=0}^{\infty} A_i\right)\right) = P\left(\bigcup_{i=0}^{\infty} B \cap A_i\right) \\ &= \sum_{i=1}^{\infty} P(B \cap A_i) = \sum_{i=1}^{\infty} P(A_i)P(B|A_i), \end{aligned}$$

where the fourth equality follows from Definition 5.(d), since  $\{B \cap A_i\}_{i=0}^{\infty}$  are pairwise mutually exclusive events and since  $0 \leq P(B \cap A_0) \leq P(A_0) = 0$ .  $\square$

**THEOREM 5 (BAYES' THEOREM).** Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $\{A_i\}_{i=1}^{\infty}$  be exhaustive and pairwise mutually exclusive events such that  $P(A_i)$  is nonzero for all  $i$ . Then for all  $B \in \mathcal{E}$  with  $P(B) > 0$  and for all  $j \in \mathbb{N}$ ,

$$P(A_j|B) = \frac{P(A_j)P(B|A_j)}{\sum_{i=1}^{\infty} P(A_i)P(B|A_i)}.$$

**PROOF.** We have

$$P(A_j|B) = \frac{P(A_j \cap B)}{P(B)} = \frac{P(A_j)P(B|A_j)}{P(B)} = \frac{P(A_j)P(B|A_j)}{\sum_{i=1}^{\infty} P(A_i)P(B|A_i)},$$

where the last equality follows from Lemma 1.  $\square$

**EXAMPLE 6.** Consider the random experiment, where you keep on rolling a fair die till you get an outcome of 6 points. For  $n \in \mathbb{N}$ , let  $A_n$  denote the event that you stop rolling the die after the  $n$ -th roll, i.e. you obtain the outcome of 6 points for the first time on the  $n$ -th roll of the die. Let  $B$  denote the event that all the outcomes preceding the last one (which is necessarily 6) are odd. Determine  $P(A_m|B)$ .

---

**ANSWER.** From the definition of the events  $A_n$  and  $B$ , we obtain

$$P(A_n) = \frac{1}{6} \left(\frac{5}{6}\right)^{n-1} \text{ and } P(B|A_n) = \left(\frac{3}{5}\right)^{n-1}.$$

Therefore, Bayes' theorem implies that

$$P(A_m|B) = \frac{P(A_m)P(B|A_m)}{\sum_{n=1}^{\infty} P(A_n)P(B|A_n)} = \frac{\frac{1}{6} \cdot \frac{1}{2^{m-1}}}{\frac{1}{6} \sum_{n=1}^{\infty} \frac{1}{2^{n-1}}} = \frac{1}{2^m}.$$

## 8 ASKING SOMEONE OUT FOR COFFEE

**EXAMPLE 7.** Suppose, you find someone interesting and you'd like to ask that person out for a coffee. Let's assume that there are the following three pairwise mutually exclusive, exhaustive and equally likely cases:

- A. He/she finds you interesting too.
- B. He/she feels indifferent towards you.
- C. He/she feels repulsed by you.

In Case A, it is natural for him/her to accept your invitation with a rather high probability, say 0.9. In Case B, he/she accepts it with probability 0.5, whereas in Case C, there is still a little chance, say 0.1, that he/she accepts your invitation (in particular, if his/her affinity for coffee is more than the repulsion that he/she feels towards you).

- (i) Find the probability that he/she accepts your invitation.
- (ii) Given that he/she accepted your invitation, find the probability that he/she finds you interesting too.

**ANSWER.** (i) Since the cases A, B and C are pairwise mutually exclusive, exhaustive and equally likely, we have

$$P(A) = P(B) = P(C) = \frac{1}{3}.$$

Let  $Y$  denote the event that he/she accepts your invitation and  $N$  denote the event that he/she declines it. Then

$$\begin{aligned} P(Y) &= P(A)P(Y|A) + P(B)P(Y|B) + P(C)P(Y|C) \\ &= \frac{1}{3}(0.9 + 0.5 + 0.1) \\ &= 0.5. \end{aligned}$$

In other words, the events  $Y$  and  $N$  are equally likely.

(ii) We have

$$P(A|Y) = \frac{P(A)P(Y|A)}{P(Y)} = \frac{1}{3} \times \frac{0.9}{0.5} = 0.6.$$

In particular, given that he/she accepts your invitation, though the probability that he/she finds you interesting is greater than  $1/2$ , yet unfortunately, there's also much room for a mistaken conviction!

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## 9 GUESSING GAMES



**EXAMPLE 8.** (Monty Hall problem<sup>\*</sup>) Three paper cups are placed upside down on a table. There is a coin under one of these cups, whereas there are nothing under the other two. You don't know under which of the cups the coin lies but your friend does. She asks you to guess which cup hides the coin: You choose one of the cups randomly (but you do not lift it up). Then she lifts up another cup and shows that there's nothing under that. Now, except your initial choice, there still remains a cup which may or may not hide the coin. Given a chance to switch your choice to the remaining cup, would you switch your choice or would you stick to your initial guess? Please justify your answer!

**ANSWER.** Let  $A$  denote the event that the coin is under the cup which you have chosen initially and let  $L$  denote the event that your friend lifts another cup to show that there is nothing under it. Note that  $A^c$  is the event that the coin is not under the cup which you have chosen. Hence,  $A^c|L$  is the event that the coin is under the remaining cup. So, we only require to compare  $P(A|L)$  with  $P(A^c|L)$ . Since in any case, your friend always lifts up an empty cup and shows that there's nothing under that, the event  $L$  (and hence, also the event  $L|A$ ) is a sure event. In other words, we have  $P(L) = 1 = P(L|A)$ . Hence,

$$P(A|L) = \frac{P(A)P(L|A)}{P(L)} = P(A)P(L|A) = P(A) = \frac{1}{3}.$$

Therefore, we conclude that

$$P(A^c|L) = 1 - P(A|L) = \frac{2}{3}.$$

Since  $P(A^c|L) > P(A|L)$ , you should switch your choice.

If you are not convinced by the above reasoning, then look at the following table that lists all the possible scenarios:

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<sup>\*</sup>See [https://en.wikipedia.org/wiki/Monty\\_Hall\\_problem](https://en.wikipedia.org/wiki/Monty_Hall_problem).

Initial guess	Coin is under	Stick to the first guess	Switch to the remaining cup
Cup 1	Cup 1	Right	Wrong
Cup 1	Cup 2	Wrong	Right
Cup 1	Cup 3	Wrong	Right
Cup 2	Cup 1	Wrong	Right
Cup 2	Cup 2	Right	Wrong
Cup 2	Cup 3	Wrong	Right
Cup 3	Cup 1	Wrong	Right
Cup 3	Cup 2	Wrong	Right
Cup 3	Cup 3	Right	Wrong
Total right guesses		3	6

So, indeed your chance of guessing correctly doubles if you switch your choice.

**EXAMPLE 9 (RANDOM MONTY HALL).** Three paper cups are placed upside down on a table. There is a coin under one of these cups, whereas there are nothing under the other two. Neither you, nor your friend knows under which of the cups the coin lies. You are asked to guess which cup hides the coin: You choose one of the cups randomly (but you do not lift it up). Then your friend also chooses another cup randomly and lifts it up to find that there's nothing under that. Now, except your initial choice, there still remains a cup which may or may not hide the coin. Given a chance to switch your choice to the remaining cup, would you switch your choice or would you stick to your initial guess? Please justify your answer!

**ANSWER.** As before, let  $A$  denote the event that the coin is under the cup which you have chosen initially and let  $L$  denote the event that your friend lifts another cup randomly to find that there is nothing under it. Note that  $A^c$  is the event that the coin is not under the cup which you have chosen. Hence,  $A^c|L$  is the event that the coin is under the remaining cup. So, we only require to compare  $P(A|L)$  with  $P(A^c|L)$ . Given  $A$ , whichever cup your friend lifts, that will have no coin under it. So,  $P(L|A) = 1$ . However,  $P(L|A^c) = 1/2$ . Now, Bayes' theorem implies that

$$P(A|L) = \frac{P(A)P(L|A)}{P(A)P(L|A) + P(A^c)P(L|A^c)} = \frac{\frac{1}{3} \times 1}{\frac{1}{3} \times 1 + \frac{2}{3} \times \frac{1}{2}} = \frac{1}{2}.$$

Since  $P(A^c|L) = P(A|L)$ , you need not switch your choice in this case.

## 10 INDEPENDENCE

**DEFINITION 14 (INDEPENDENT EVENTS).** Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $A, B \in \mathcal{E}$ . If the occurrence of any of  $A$  and  $B$  does not affect the probability of occurrence of the other, i.e. if  $P(A|B) = P(A)$  and  $P(B|A) = P(B)$ , then we say that  $A$  and  $B$  are independent\*. In other words,  $A$  and  $B$  are independent if

$$P(A \cap B) = P(A)P(B).$$

---

\*If you wonder how independence looks like on a Venn diagram, then see this: <https://www.youtube.com/watch?v=pV3nZAsJxI0>

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The events in a set  $S \subseteq \mathcal{E}$  are said to be pairwise independent if the above equation is satisfied by all pairs  $A, B \in S$ , whereas all the events in  $S$  are said to be mutually independent if

$$P\left(\bigcap_{A \in T} A\right) = \prod_{A \in T} P(A)$$

for all countable sets  $T \subseteq S$ .

**EXAMPLE 10.** Consider the random experiment where a fair tetrahedral die (whose faces are marked with points from 1 to 4) is rolled. Let the events  $A, B$  and  $C$  be defined as follows:

$A$  : The die comes to rest on face 1 or face 2.

$B$  : The die comes to rest on face 2 or face 3.

$C$  : The die comes to rest on face 3 or face 1.

Note that

$$P(A \cap B) = P(\{2\}) = \frac{1}{4} = P(A)P(B), \quad P(B \cap C) = P(\{3\}) = \frac{1}{4} = P(B)P(C),$$

$$P(C \cap A) = P(\{4\}) = \frac{1}{4} = P(C)P(A).$$

However,

$$P(A \cap B \cap C) = P(\emptyset) = 0 \neq P(A)P(B)P(C).$$

In other words, pairwise independence doesn't ensure mutual independence.

**EXAMPLE 11.** Let's reconsider the story of the statistician from the beginning of this chapter. He computed the probability  $p$  that there will be a bomb on the aeroplane. Then he computed the probability of the event that there are two bombs  $B_1$  and  $B_2$  on the same aeroplane. Apparently, under the assumption of independence, he obtained

$$P(B_1 \cap B_2) = P(B_1)P(B_2) = p^2,$$

which according to him, was low enough compared to  $p$ . So, he carries his own bomb  $B_1$ ! That implies,  $B_1$  is given. Hence, he must instead consider

$$P(B_2|B_1) = \frac{P(B_1 \cap B_2)}{P(B_1)} = \frac{p^2}{p} = p.$$

In other words, to the utter discomfort of the statistician, the probability of there being another bomb on the plane is still  $p$ .

## 11 BASE RATE FALLACY

**EXAMPLE 12 (BASE RATE FALLACY / FALSE POSITIVE PARADOX).** Consider an extremely rare disease which affects only 0.1% of the population. Suppose, a test which checks whether the person has the disease, has 99% sensitivity\* (true positive rate) and 99% specificity (true negative rate). In other words, the test correctly identifies a positive in 99% of the cases and also correctly identifies a

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\*See [https://en.wikipedia.org/wiki/Sensitivity\\_and\\_specificity](https://en.wikipedia.org/wiki/Sensitivity_and_specificity).

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negative in 99% of the cases\*. Let's assume that the test always gives either a positive or a negative result.

- (i) Find the probability that a person has the disease given that he/she tests positive.
- (ii) Given that a person has tested positive once, find the probability that he/she has the disease if he/she tests positive again.
- (iii) Given that a person has tested positive twice, find the probability that he/she has the disease if he/she tests positive again.

**ANSWER.** (i) Let  $D$  denote the event that the person undergoing the test has the disease. Let  $P$  denote the event that the test shows a positive result and let  $N$  denote the event that the test shows a negative result. Since the test has 99% sensitivity, we have  $P(P|D) = 0.99$  and since the test has 99% specificity, we have  $P(N|D^c) = 0.99$ . Hence,  $P(P|D^c) = 1 - P(N|D^c) = 1 - 0.99 = 0.01$ .

$$\begin{aligned} P(D|P) &= \frac{P(D)P(P|D)}{P(D)P(P|D) + P(D^c)P(P|D^c)} \\ &= \frac{0.001 \times 0.99}{0.001 \times 0.99 + 0.999 \times 0.01} \approx 0.09. \end{aligned}$$

Despite the high base rates, viz.  $P(P|D)$  and  $P(N|D^c)$  apparently indicating a high degree of accuracy of the test, it is surprising that the probability  $P(D|P)$  is so low. This happens because the disease is very rare. More precisely, among 1000 persons, the disease affects only about  $1000 \times 0.001 = 1$  person. However, the specificity of the test is 99%, i.e. the test correctly identifies a negative in 99% of the cases. So, among 1000 persons, about  $1000(1-0.99) = 10$  persons get false positive results. Thus, even if the high sensitivity of the test guarantees that the test result is almost certainly positive for any person having the disease, there are also about 10 more persons in every 1000, who gets false positive results. So, even if a person gets a positive result, his/her chance of having the disease is only about  $1/11 \approx 0.09$ . The higher the prevalence of the disease, the greater would be the probability for a person who tested positive to actually have the disease.

(ii) Since the person has tested positive once, Part (i) implies that his/her probability of having the disease  $P(D)$  has now increased from 0.001 to 0.09. Hence, after the second test, we have

$$\begin{aligned} P(D|P) &= \frac{P(D)P(P|D)}{P(D)P(P|D) + P(D^c)P(P|D^c)} \\ &= \frac{0.09 \times 0.99}{0.09 \times 0.99 + 0.91 \times 0.01} \approx 0.9. \end{aligned}$$

(iii) Since the person has tested positive twice, Part (ii) implies that his/her probability of having the disease  $P(D)$  has now increased from 0.001 to 0.9.

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\*Such an ideal test does not exist in practice. See [www.statpearls.com/ArticleLibrary/viewarticle/96435#ref\\_18158403](http://www.statpearls.com/ArticleLibrary/viewarticle/96435#ref_18158403)

Hence, after the third test, we have

$$\begin{aligned} P(D|P) &= \frac{P(D)P(P|D)}{P(D)P(P|D) + P(D^c)P(P|D^c)} \\ &= \frac{0.9 \times 0.99}{0.9 \times 0.99 + 0.1 \times 0.01} \approx 0.999. \end{aligned}$$

In other words, the degree of accuracy of the test increases dramatically, if we repeat the test a few times.

## 12 RETURN OF THE COFFEE

**EXAMPLE 13.** In Example 7, check that  $P(Y|A) + P(N|A^c) > 1$  to conclude from Exercise 9 that\*

$$P(A|\underbrace{YY \dots Y}_n) \rightarrow 1 \text{ as } n \rightarrow \infty.$$



**ANSWER.** It is given in Exercise 7 that  $P(Y|A) = 0.9$ . Also, we have

$$\begin{aligned} P(N|A^c) &= 1 - P(Y|A^c) = 1 - \frac{P(Y)P(A^c|Y)}{P(A^c)} \\ &= 1 - \frac{P(Y)(1 - P(A|Y))}{1 - P(A)} = 1 - \frac{0.5 \times (1 - 0.6)}{0.67} \\ &\approx 0.7, \end{aligned}$$

where we have put the values of  $P(Y)$ ,  $P(A)$  and  $P(A|Y)$  from Example 7. In particular, we have  $P(Y|A) + P(N|A^c) > 1$ . So, under the suitable assumptions of independence, the last exercise implies that

$$P(A|\underbrace{YY \dots Y}_n) \rightarrow 1 \text{ as } n \rightarrow \infty.$$

In other words, if the person accepts your invitation as many times as you ask him or her out, then you could be almost sure that this person indeed finds you interesting.

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\*Of course, here we are making two contradicting assumptions about the person of your interest: (1) For him/her, the first impression is the last impression, i.e. his/her feelings of interest / indifference / repulsion towards you does not change over time.

(2) He/she lives in the moment: In particular, given that the person finds you interesting (or not), each time when you ask him/her out for a coffee, his/her spontaneous response is independent of all the past/future responses which you received/will receive from him/her.

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On the contrary, if you do not want to reveal your interest (in coffee or in the person), just occasionally decline invitations for coffee!

### Exercises

1. A hostel room is shared by two students, each of whom is equally likely to be either hard working or careless. Given that one of the roommates is hard working, what is the probability that the other one is careless?
2. Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $A_1, A_2, \dots, A_n \in \mathcal{E}$  with  $P(A_1 \cap \dots \cap A_n) \neq 0$ . Show that  $P(A_1 \cap \dots \cap A_n)$  is equal to
$$P(A_1) P(A_2 | A_1) P(A_3, | A_2 \cap A_1) \dots P(A_n | A_{n-1} \cap \dots \cap A_1).$$
3. Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $A_1, A_2, \dots, \in \mathcal{E}$  be pairwise mutually exclusive. Let  $A = \bigcup_{n=1}^{\infty} A_n$  and let  $B \in \mathcal{E}$  with  $P(B) \neq 0$ . Show that
$$P(A | B) = \sum_{n=1}^{\infty} P(A_n | B).$$
4. Find the probability that an analog watch shows a specified time if you look at the watch at a random instant\*.
5. Find the probability of obtaining  $n$  heads in  $m$  tosses of a fair coin, given that the  $m$ -th toss resulted in a head and no two of the  $n$  heads occurred in two consecutive tosses.
6. Let's consider a random experiment in which you keep on tossing a fair coin till you obtain either 4 heads or 4 tails in total. Find the probability that you stop tossing after 6 tosses, given that the first two tosses resulted in heads.
7. There are  $n$  boxes numbered  $1, 2, \dots, n$ , among which the  $r$ th box contains  $r - 1$  white cubes and  $n - r$  red cubes. Suppose, we choose a box at random and we remove two cubes from it, one after another, without replacement.
  - (a) Find the probability of the second cube being red.
  - (b) Find the probability of the second cube being red, given that the first cube is red.
8. We are familiar with the famous Monty Hall problem. Now suppose, instead of 3 doors, there are  $n$  doors, only one among which has a prize behind it.
  - (a) Find the probability of winning upon switching given that Monty opens  $k$  doors. Will switching benefit you?

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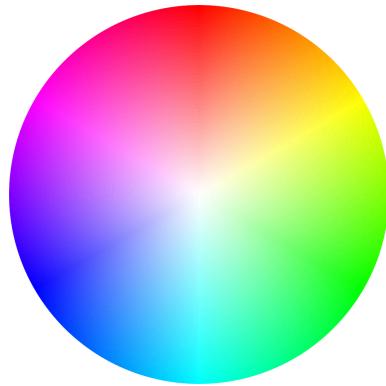
\*You may assume that the second-hand of the clock moves discretely.

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- (b) Find the probability of winning upon switching given that Monty opens maximum number of doors. Will switching benefit you?
  - (c) Find the probability of winning upon switching given that Monty opens no doors. Will switching benefit you?
9. In a similar situation as in Example 12, show that if
- $$\text{sensitivity} + \text{specificity} > 100\%,$$
- then
- $$P(D | \underbrace{PP \dots P}_n) \rightarrow 1 \text{ as } n \rightarrow \infty.$$
10. Suppose, you satisfy all the assumptions in Example 13. Figure out how often at least you need to decline someone's invitation for coffee if you do not want to reveal your interest in that person.

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## Random Variables

If you roll a die, you obtain an outcome between 1 to 6 points. When you ask a person for his/her phone number, you obtain\* a ten digit number. However in general, the outcomes of a random experiment need not be numbers. For example, consider random experiments like guessing the first letter of a stranger's name or guessing someone's favourite shade of colour.



Often it is useful to quantify the elements of the sample space. A random variable is just a tool for this quantification. For example, in the penultimate example, one may quantify the twenty-six roman alphabets by twenty-six real numbers, whereas in the last example, RGB coordinates may be used to quantify the shades of colours.

In complete generality, a *random variable* is a *measurable function*\*\* on the sample space. But here we restrict ourselves only to the real valued measurable functions:

**DEFINITION 15 (RANDOM VARIABLE).** A random variable is a real valued function on the sample space such that the preimage of every interval is an event.

**DEFINITION 16 (PROBABILITY DISTRIBUTION OF A RANDOM VARIABLE).** Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $X : \Omega \rightarrow \mathbb{R}$  be a random variable. Then for all  $a \in \mathbb{R}$ , the preimage of the interval  $(-\infty, a]$  under  $X$  is in  $\mathcal{E}$ . The random variable  $X$  translates the probability space  $(\Omega, \mathcal{E}, P)$  to the probability space  $(\mathbb{R}, \mathcal{E}_X, P_X)$ ,

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\*assuming that you get a precise numerical response.

\*\*In particular, if the range of the function is  $\mathbb{R}^3$  (resp.  $\mathbb{R}^2, \mathbb{R}$ ), then the preimage of every set having finite/ infinite volume (resp. area, length) is an event, i.e. a subset  $S$  of the sample space having *probability measure*  $P(S)$ .

where

$$(12.1) \quad \mathcal{E}_X := \{A \subseteq \mathbb{R} \mid X^{-1}(A) \in \mathcal{E}\}$$

and the function  $P_X : \mathcal{E}_X \rightarrow [0, 1]$  is defined by

$$(12.2) \quad P_X(A) := P(X^{-1}(A)) \text{ for all } A \in \mathcal{E}_X.$$

The function  $P_X$  is called the *probability distribution function* of  $X$ .

Henceforth, we use the notations  $P(X \in A)$  and  $P_X(A)$  interchangeably. In particular, we write  $P(X \leq a)$  for  $P_X((-\infty, a])$ .

**LEMMA 2.** *Let  $(\Omega, \mathcal{E}, P)$  be a probability space, let  $X : \Omega \rightarrow \mathbb{R}$  be a random variable and let the probability space  $(\mathbb{R}, \mathcal{E}_X, P_X)$  be defined as above. Then for all  $x \in \mathbb{R}$ , we have  $\{x\} \in \mathcal{E}_X$ .*

**PROOF.** Since  $\mathcal{E}$  is closed under complementation and countable unions, it follows from (12.1) that  $\mathcal{E}_X$  is also closed under complementation and countable unions. Since both  $(-\infty, x)$  and  $(x, \infty) \in \mathcal{E}_X$ , it follows that

$$\{x\} = [x, x] = ((-\infty, x) \cup (x, \infty))^c \in \mathcal{E}_X.$$

□

**COROLLARY 2.** *For a random variable  $X$  and for all  $x \in \mathbb{R}$ ,  $P(X = x)$  is well-defined.*

**DEFINITION 17 (PROBABILITY MASS FUNCTION).** Let  $X$  be a random variable. The function from  $\mathbb{R}$  to  $[0, 1]$  which maps

$$x \mapsto P(X = x)$$

is called the *probability mass function* (PMF) of  $X$ .

### 13 CUMULATIVE DISTRIBUTION FUNCTION

**DEFINITION 18 (CUMULATIVE DISTRIBUTION FUNCTION).** Let  $X$  be a random variable. We define the cumulative density function (CDF) of  $X$  by

$$F_X(a) := P(X \leq a)$$

for all  $a \in \mathbb{R}$ .

**LEMMA 3.** *The CDF of a random variable is a nondecreasing function.*

**PROOF.** For  $a \leq b$ , we have  $X^{-1}((-\infty, a]) \subseteq X^{-1}((-\infty, b])$ . Hence, from Exercise 10 in Chapter 1, we obtain

$$F_X(a) = P(X \leq a) \leq P(X \leq b) = F_X(b).$$

In other words,  $F_X : \mathbb{R} \rightarrow [0, 1]$  is a nondecreasing function. □

**EXAMPLE 14.** Let  $X$  denote the number of heads obtained in a toss of a fair coin. Write down the CDF of  $X$ .

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**ANSWER.** Here we have  $P(X < 0) = P(0 < X < 1) = P(X > 1) = 0$  and  $P(X = 0) = P(X = 1) = 1/2$ . Hence the CDF of  $X$  is given by

$$F_X(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1/2 & \text{if } 0 \leq x < 1 \\ 1 & \text{if } x \geq 1. \end{cases}$$

**THEOREM 6.** *The CDF of every random variable is right continuous.*

**PROOF.** Let  $X$  be a random variable with CDF  $F$ . We require to show that for every sequence  $\{x_n\}$  in  $(x, \infty)$  with  $x_n \rightarrow x$ , we have

$$(13.1) \quad \lim_{n \rightarrow \infty} F(x_n) = F(x)$$

Note that it suffices to prove the above equality for every *decreasing* sequence  $\{x_n\}$  with  $x_n \rightarrow x$ : Suppose,  $\{x_n\}$  be such a sequence which satisfies (13.1). In other words, for every  $\varepsilon > 0$ , there is an  $N \in \mathbb{N}$  such that for all  $n \geq N$ , we have  $F(x_n) \in B_\varepsilon(F(x))$ . Since  $F$  is a monotonic function, it follows that for all  $a \in (x, x_n]$ , we have  $F(a) \in B_\varepsilon(F(x))$ . Let  $\{y_n\}$  be an arbitrary sequence in  $(x, \infty)$  with  $y_n \rightarrow x$ . Then there exists an  $M \in \mathbb{N}$  such that for all  $m \geq M$ , we have  $y_m \in B_{|x_n-x|}(x) \cap (x, \infty) = (x, x_n)$ . Hence, for all  $m \geq M$ , we have  $F(y_m) \in B_\varepsilon(F(x))$ . That implies,  $\lim_{n \rightarrow \infty} F(y_n) = F(x)$ . So, if (13.1) is satisfied by a decreasing sequence which converges to  $x$ , then it is satisfied by every sequence which converges to  $x$  from above.

Therefore, we may assume that  $\{x_n\}$  is a decreasing sequence which converges to  $x$ . Let  $I := (x, \infty)$  and let  $I_n := (x_n, \infty)$  for all  $n \in \mathbb{N}$ . Then we have an ascending chain of intervals

$$I_1 \subseteq I_2 \subseteq \cdots \subseteq I_n \subset I_{n+1} \subseteq \cdots$$

and

$$\bigcup_{n \in \mathbb{N}} I_n = I.$$

Define the intervals  $I'_n$  by  $I'_1 = I_1$  and  $I'_n := I_n \setminus I_{n-1}$  for all integers  $n > 1$ . Then the intervals  $\{I'_n\}_{n \in \mathbb{N}}$  are disjoint with

$$\bigcup_{n \in \mathbb{N}} I'_n = I.$$

So, it follows from Definition 5 that

$$P_X(I) = \sum_{n=1}^{\infty} P_X(I'_n) = \lim_{m \rightarrow \infty} \sum_{n=1}^m P_X(I'_n) = \lim_{m \rightarrow \infty} P_X(I_m).$$

In other words,

$$P(X > x) = \lim_{n \rightarrow \infty} P(X > x_n).$$

i.e.

$$1 - F(x) = \lim_{n \rightarrow \infty} (1 - F(x_n)),$$

which implies the claim.  $\square$

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**COROLLARY 3.** *The CDF  $F_X$  of a random variable  $X$  is continuous if and only if  $F_X$  is left continuous.*

#### 14 CONTINUOUS RANDOM VARIABLES

**DEFINITION 19 (CONTINUOUS RANDOM VARIABLES).** A random variable with a continuous CDF\* is called a continuous random variable.

**THEOREM 7.** *Let  $X$  be a random variable. For  $x \in \mathbb{R}$ , we have*

$$P(X = x) > 0$$

*if and only if the cumulative distribution function  $F_X$  is discontinuous at  $x$ .*

**PROOF.** From Exercise 4, we know that  $F_X$  can have only a jump discontinuities. Since  $F_X$  is right continuous (see Theorem 6), a jump discontinuity of  $F_X$  at  $x$  occurs if and only if  $F_X(x-) < F_X(x)$ , i.e.

$$P(X < x) < P(X \leq x).$$

Since  $P(X \leq x) = P(X < x) + P(X = x)$ , it follows that  $F_X$  has a discontinuity at  $x$  if and only if

$$P(X = x) > 0.$$

□

**COROLLARY 4.** *Let  $X$  be a continuous random variable. Then*

$$P(X = x) = 0$$

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

**THEOREM 8.** *The CDF of a random variable has at most countably many discontinuities.*

**PROOF.** Follows immediately from Lemma 3 and Exercise 5. □

**THEOREM 9.** *For every random variable  $X$ , the sum*

$$\sum_{x : P(X=x)>0} P(X = x)$$

*is well-defined and converges in  $[0, 1]$ .*

**PROOF.** Let  $\mathcal{D}_X$  denote the set of discontinuities of the CDF of the random variable  $X$ . Theorem 7 implies that

$$\mathcal{D}_X = \{x : P(X = x) > 0\}$$

and Theorem 8 implies that  $\mathcal{D}_X$  is countable. Hence, the sum of  $P(X = x)$  over all  $x \in \mathcal{D}_X$  is well-defined and we have

$$0 \leq \sum_{x : P(X=x)>0} P(X = x) = P(X \in \mathcal{D}_X) \leq P(X \in \mathbb{R}) = 1,$$

where the sum is equal to 0 if and only if  $\mathcal{D}_X = \emptyset$ , i.e.  $X$  is a continuous random variable. Also, if  $\mathcal{D}_X$  is finite, the claim is trivial. Otherwise, the partial sums

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\*By Exercise 3, such a CDF is also uniformly continuous.

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of the above series of positive real numbers form a bounded increasing sequence in  $[0, 1]$ . So, the above series converges in  $[0, 1]$  by the Monotone Convergence Theorem.  $\square$

**DEFINITION 20 (CLASSIFICATION OF RANDOM VARIABLES).** Let  $X$  be a random variable. If

$$\sum_{x : P(X=x)>0} P(X = x) = \begin{cases} 0, & \text{then } X \text{ is a } \textit{continuous} \text{ random variable} \\ \mu & \text{for some } \mu \in (0, 1), X \text{ is a } \textit{mixed} \text{ random variable} \\ 1, & \text{then } X \text{ is called a } \textit{discrete} \text{ random variable.} \end{cases}$$

**DEFINITION 21 (PROBABILITY DENSITY FUNCTION).** For a continuous random variable  $X$ , if there exists a function  $f_X : \mathbb{R} \rightarrow \mathbb{R}_{\geq 0}$  such that

$$F_X(x) = \int_{-\infty}^x f_X(t) dt$$

for all  $x \in \mathbb{R}$ , then  $f_X$  is called a *probability density function* (PDF) of  $X$ . Here  $F_X$  denotes the CDF of  $X$ . In particular, we have

$$P(a < X \leq b) = F_X(b) - F_X(a).$$

and

$$\int_{-\infty}^{\infty} f_X(t) dt = 1.$$

In particular, if  $F_X$  is differentiable, then we may take  $f_X$  to be the derivative of  $F_X$ . Note that a PDF of a continuous random variable is not necessarily continuous. However, if  $f_X$  is continuous, then the Fundamental Theorem of Calculus implies that

$$f_X(t) = F'_X(t).$$

**EXAMPLE 15.** Define the CDF of a random variable  $X$  by

$$F(x) = \begin{cases} 0 & \text{if } x < 0 \\ \frac{x}{x+1} & \text{otherwise.} \end{cases}$$

Since  $F : \mathbb{R} \rightarrow [0, 1]$  is continuous,  $X$  is a continuous random variable. Moreover, since  $F$  is differentiable, we may take  $F'$  as a PDF of  $X$ . Thus, we may define  $f_X : \mathbb{R} \rightarrow [0, 1]$  by

$$f_X(t) = \begin{cases} 0 & \text{if } t < 0 \\ \frac{1}{(t+1)^2} & \text{otherwise.} \end{cases}$$

## 15 MIXED RANDOM VARIABLES

**THEOREM 10.** If the CDF  $F_X$  of a random variable  $X$

- (a) has a discontinuity in  $\mathbb{R}$  and

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(b) *is continuous and increasing\* in an interval of nonzero length\*\**,  
then  $X$  is a mixed random variable.

PROOF. Let  $I$  be an interval of nonzero length such that  $F_X$  is continuous on  $I$ . Let  $a, b \in I$  such that  $a < b$ . Then  $F_X$  is continuous and increasing on  $(a, b]$ . Hence, Theorem 7 implies that

$$P(X = x) = 0 \text{ for all } x \in (a, b].$$

However,

$$(15.1) \quad P(X \in (a, b]) = F_X(b) - F_X(a) > 0.$$

Let  $\mathcal{D}_X$  be the set of discontinuities of  $F_X$ . Since  $F_X$  is continuous on  $(a, b]$ , it follows that  $\mathcal{D}_X \cap (a, b] = \emptyset$ . Hence, from Definition 5, we obtain

$$P(X \in \mathcal{D}_X) + P(X \in (a, b]) = P(X \in \mathcal{D}_X \cup (a, b]) \leq P(R) = 1.$$

That implies,

$$(15.2) \quad P(X \in \mathcal{D}_X) \leq 1 - P(X \in (a, b]) < 1,$$

because  $P(X \in (a, b]) > 0$  (see (15.1)). Since  $F_X$  has a discontinuity in  $\mathbb{R}$ , it follows that  $\mathcal{D}_X \neq \emptyset$  and Theorem 7 implies that  $\mathcal{D}_X = \{x : P(X = x) > 0\}$ . Hence, from (15.2), it follows that

$$0 < \sum_{x : P(X=x)>0} P(X = x) < 1.$$

Therefore,  $X$  is a mixed random variable.  $\square$

EXAMPLE 16. Let the range of a random variable  $X$  be  $\{1, 4\} \cup [2, 3]$ , where  $[2, 3]$  denotes the closed interval with 2 and 3 at its extremities. Define the CDF of  $X$  by

$$F_X(x) = \begin{cases} 0 & \text{if } x < 1 \\ 1/4 & \text{if } 1 \leq x < 2 \\ x/4 & \text{if } 2 \leq x \leq 3 \\ 3/4 & \text{if } 3 \leq x < 4 \\ 1 & \text{if } x \geq 4. \end{cases}$$

Then  $F_X$  is continuous and increasing in the interval  $[2, 3]$  and it has discontinuities at 1, 2 and 4. Hence, Theorem 10 implies that  $X$  is a mixed random variable. We could have also checked this directly: Since there are only 3 values of  $x \in \mathbb{R}$  such that  $P(X = x)$  is nonzero, viz.

$$P(X = 1) = P(X = 2) = P(X = 4) = \frac{1}{4},$$

---

\*by *increasing*, we mean *strictly increasing*.

\*\*Note that, though the CDF of a random variable has countably many discontinuities, but in general, there may not be any interval of nonzero length on which the CDF is continuous. For example, consider a random variable which has nonzero probabilities only at the rational numbers.

it follows that

$$\sum_{x : P(X=x)>0} P(X = x) = \frac{3}{4} \in (0, 1).$$

Henceforth, we would restrict ourselves only to discussions about continuous and discrete random variables.

## 16 DISCRETE RANDOM VARIABLES

**THEOREM 11.** *If a random variable  $X$  assumes only countably many values, then  $X$  is a discrete random variable.*

**PROOF.** Let  $\mathcal{C}$  denote the set of values which  $X$  assumes, let

$$\mathcal{C}_+ = \{x \in \mathcal{C} : P(X = x) > 0\} \text{ and } \mathcal{C}_0 = \{x \in \mathcal{C} : P(X = x) = 0\}.$$

Then  $\mathcal{C}_+ \cup \mathcal{C}_0 = \mathcal{C}$  and  $\mathcal{C}_+ \cap \mathcal{C}_0 = \emptyset$ . Hence, from Definition 5, it follows that

$$\begin{aligned} \sum_{x \in \mathcal{C}_+} P(X = x) &= \sum_{x \in \mathcal{C}_+} P(X = x) + \sum_{x \in \mathcal{C}_0} P(X = x) \\ &= \sum_{x \in \mathcal{C}_+ \cup \mathcal{C}_0} P(X = x) = \sum_{x \in \mathcal{C}} P(X = x) \\ &= P(X \in \mathcal{C}). \end{aligned}$$

Since  $X$  does not assume any value in  $\mathbb{R} \setminus \mathcal{C}$ , we have

$$P(X \in \mathbb{R} \setminus \mathcal{C}) = 0.$$

In particular, it follows from the above equation and Exercise 10 that

$$P(X = x) = 0 \text{ for all } x \in \mathbb{R} \setminus \mathcal{C}.$$

Hence, the set of all the real numbers  $x$  such that  $P(X = x) > 0$  is  $\mathcal{C}_+$ , i.e.

$$\{x : P(X = x) > 0\} = \mathcal{C}_+.$$

Thus, we obtain

$$\begin{aligned} \sum_{x : P(X=x)>0} P(X = x) &= \sum_{x \in \mathcal{C}_+} P(X = x) \\ &= P(X \in \mathcal{C}) \\ &= P(X \in \mathcal{C}) + P(X \in \mathbb{R} \setminus \mathcal{C}) \\ &= P(X \in \mathbb{R}) \\ &= 1. \end{aligned}$$

So,  $X$  is indeed a discrete random variable according to Definition 20.  $\square$

Since every set of isolated points in  $\mathbb{R}$  is countable, we conclude:

**COROLLARY 5.** *If a random variable  $X$  takes values only in a discrete set\*, then  $X$  is a discrete random variable.*

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\*A set of isolated points.

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**DEFINITION 22 (BERNOULLI/BINARY RANDOM VARIABLE).** If a random variable  $X$  assumes only a pair of distinct values, we call  $X$  a Bernoulli/Binary random variable.

In particular, if a random experiment has only two possible outcomes, e.g.

- (a) tossing a coin:  $\Omega = \{H, T\}$
- (b) writing an exam:  $\Omega = \{\text{pass, fail}\}$
- (c) undertaking a mission:  $\Omega = \{\text{success, failure}\}$
- (d) asking someone out for coffee:  $\Omega = \{\text{positive reply, negative reply}\}$ ,

then any random variable  $X : \Omega \rightarrow \mathbb{R}$  which is not a constant function, is a Bernoulli random variable. However, having exactly two element is not at all a necessary condition on the sample space  $\Omega$  for  $X : \Omega \rightarrow \mathbb{R}$  to be a Bernoulli random variable. For example, the range of human body temperature is uncountable, whereas a person is said to have a fever if his/her temperature is higher than  $98.6^\circ$  Fahrenheit. So, for a randomly chosen person, we may define a Bernoulli random variable  $X$  on the range of human body temperature, say  $[55, 115]$  in Fahrenheit such that  $X = 1$  if the temperature of the person is higher than  $98.6^\circ$  F and  $X = 0$  otherwise.

**NOTATION 1.** Let  $X$  be a Bernoulli random variable taking values in  $\{0, 1\}$  such that  $P(X = 1) = p$ . Then we write

$$X \sim \text{Bernoulli}(p).$$

The probability  $p$  is called the *parameter* of Bernoulli distribution.

**DEFINITION 23 (DISCRETE UNIFORM RANDOM VARIABLE).** If a random variable  $X$  assumes only  $n$  equally probable distinct values, then we call  $X$  a Discrete Uniform random variable and we write

$$X \sim \text{Uniform}(n).$$

## 17 INDEPENDENCE OF RANDOM VARIABLES

**DEFINITION 24.** Let  $X$  and  $Y$  be two random variables defined on the same sample space and let  $A \in \mathcal{E}_X$  and  $B \in \mathcal{E}_Y$ . If  $P(Y \in B) > 0$ , we define the conditional probability

$$P(X \in A | Y \in B) := \frac{P(X \in A, Y \in B)}{P(Y \in B)},$$

where

$$P(X \in A, Y \in B) := P(\{X \in A\} \cap \{Y \in B\}).$$

Two random variables are *independent* if prior knowledge about the value assumed by any one of them does not alter the probability of occurrence of the other in any given subset of  $\mathbb{R}$ , i.e. the random variables  $X$  and  $Y$  are independent if and only if

$$P(X \in A | Y \in B) = P(X \in A) \text{ and } P(Y \in B | X \in A) = P(Y \in B),$$

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provided  $P(Y \in B) > 0$  and  $P(X \in A) > 0$ , respectively. In other words, two random variables  $X$  and  $Y$  are independent if and only if

$$(17.1) \quad P(X \in A, Y \in B) = P(X \in A)P(Y \in B).$$

for all  $A \in \mathcal{E}_X$  and  $B \in \mathcal{E}_Y$ . Let  $\{X_i\}_{i \in S}$  be a set of random variables. The random variables  $X_i$  are said to be *pairwise independent* if the above equation is satisfied by all pairs  $\{X_i, X_j\}$  for distinct  $i, j \in S$ , whereas all the random variables  $X_i$  are said to be *mutually independent* if

$$(17.2) \quad P\left(\bigcap_{i \in T} \{X_i \in A_i\}\right) = \prod_{i \in T} P(X_i \in A_i).$$

for all  $A_i \in \mathcal{E}_{X_i}$  and for all countable sets  $T \subseteq S$ .

**DEFINITION 25 (IID RANDOM VARIABLES).** Let  $\{X_i\}_{i \in S}$  be a set of random variables. The random variables  $X_i$  are said to be *independent and identically distributed* (iid) if they satisfy both of the following conditions:

- (a) The random variables  $X_i$  are mutually independent.
- (b)  $F_{X_i}(x) = F_{X_j}(x)$  for all  $i, j \in S$  and for all  $x \in \mathbb{R}$ .

## 18 EXPECTATION, MOMENTS AND VARIANCE

We define expectation and variance for only discrete random variables or continuous random variables having a PDF.

**DEFINITION 26 (EXPECTATION OF A FUNCTION OF A DISCRETE RANDOM VARIABLE).** Let  $X$  be a discrete random variable and let  $g : \mathbb{R} \rightarrow \mathbb{R}$  be a function. If the series

$$\sum_{x : P(X=x)>0} g(x)P(X=x)$$

converges absolutely, then we define the *expectation* of  $g(X)$  by

$$E(g) := \sum_{x : P(X=x)>0} g(x)P(X=x).$$

**DEFINITION 27 (EXPECTATION OF A FUNCTION OF A CONTINUOUS RANDOM VARIABLE).** Let  $X$  be a continuous random variable with PDF  $f_X$  and let  $g : \mathbb{R} \rightarrow \mathbb{R}$  be a function. If the integral

$$\int_{-\infty}^{\infty} g(x)f_X(x)dx$$

converges absolutely, then we define the *expectation* of  $g$  by

$$E(g) := \int_{-\infty}^{\infty} g(x)f_X(x)dx.$$

**DEFINITION 28 ( $n$ -TH MOMENT AND EXPECTATION).** Let  $X$  be a random variable. We call  $E(X^n)$  the  $n$ -th moment of  $X$ . In particular, the first moment  $E(X)$  is called the *expectation* of  $X$  and it is often denoted by  $\mu_X$ .

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EXAMPLE 17. Let  $X \sim \text{Bernoulli}(p)$ . Then

$$E(X) = 1 \cdot P(X = 1) + 0 \cdot P(X = 0) = p.$$

DEFINITION 29 (VARIANCE). Let  $X$  be a random variable with expectation  $\mu = E(X)$ . We define the variance of  $X$  by

$$\begin{aligned} \text{Var}(X) &:= E((X - \mu)^2) \\ &= E(X^2 - 2\mu X + \mu^2) \\ &= E(X^2) - 2\mu E(X) + \mu^2 \\ &= E(X^2) - 2\mu^2 + \mu^2 \\ &= E(X^2) - \mu^2 \\ &= E(X^2) - E(X)^2, \end{aligned}$$

where the third equality follows from Exercise 16, assuming the existence of the second moment of  $X$ .

Note that variance of a random variable is a nonnegative quantity by definition.

### Exercises

1. Let  $(\Omega, \mathcal{E}, P)$  be a probability space and let  $A \subset \Omega$ . Define  $X : \Omega \rightarrow \mathbb{R}$  by

$$X(\omega) = \begin{cases} 1 & \text{if } \omega \in A \\ 0 & \text{otherwise.} \end{cases}$$

In which of the following cases is  $X$  a random variable?

- (i)  $A \in \mathcal{E}$       (ii)  $A \notin \mathcal{E}$ .

2. Let  $(\Omega, \mathcal{E}, P)$  be a probability space with  $\Omega = \{1, 2, 3, 4, 5\}$  and  $\mathcal{E} = \{\emptyset, \Omega, \{1\}, \{2, 3, 4, 5\}\}$ . Define  $X : \Omega \rightarrow \mathbb{R}$  by

$$X(\omega) = \omega + 1$$

for all  $\omega \in \Omega$ . Is  $X$  a random variable? Justify your answer!

3. Show that a bounded monotone continuous function is uniformly continuous.
4. Show that no monotone function has a discontinuity of the second kind.
5. Show that a monotone function has at most countably many discontinuities.
6. Let  $X$  be a random variable taking values in  $\{1, 2, \dots, 10\}$  with PMF  $f(x) = ax + b$  and expectation 7. Find  $a$  and  $b$ .

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7. For what value of the constant  $c$ , the real valued function  $f : \mathbb{R} \rightarrow \mathbb{R}$  given by

$$f(x) = \frac{c}{1 + (x - \theta)^2},$$

where  $\theta$  is a real parameter, is a PDF of random variable  $X$ .

8. Let  $p \in [0, 1]$ ,  $a, b \in \mathbb{R}$  with  $a > b$  and let  $X$  be a random variable such that

$$P(X = a) = p \text{ and } P(X = b) = 1 - p.$$

Find the expectation and variance of  $\frac{X-b}{b-a}$ .

9. A bag contains five coins, two of which are made of gold and the rest are made of silver. Consider the random experiment in which the coins are drawn out of the bag randomly, one after another, without replacement. Let  $X$  denote the number of draws until the last gold coin is drawn. Find the PMF, the CDF and the expectation of the random variable  $X$ .

10. Given a sequence  $\{a_n\}$  of positive real numbers such that  $\sum_{n=1}^{\infty} a_n = 1$  and a sequence  $\{x_n\}_{n=1}^{\infty}$  of distinct real numbers, define

$$F(x) := \sum_{n \in \mathbb{N} : x_n \leq x} a_n.$$

Show that  $F$  is nondecreasing, the discontinuities of  $F$  is given by  $\{x_n\}_{n=1}^{\infty}$  and  $\lim_{x \rightarrow \infty} F(x) = 1$ . Conclude that  $F$  is the CDF of a discrete probability distribution.

11. Explain why the proof of the right continuity of the cumulative density function can not be adopted to prove also left continuity of the same function.

12. Show that if the cumulative distribution function  $F_X$  of a random variable  $X$  is a step function, then  $X$  is a discrete random variable.

13. Provide an example of a continuous random variable without a PDF.

14. Provide an example of a continuous random variable with infinitely many PDFs.

15. Let  $X \sim \text{Uniform}(n)$ . Find  $E(X)$  and  $\text{Var}(X)$ .

16. Let  $f(t) = a_n t^n + \cdots + a_1 t + a_0$  be a polynomial with real coefficients and let  $X$  be a random variable such that its  $j$ -th moment exists for all  $j \in \{1, 2, \dots, n\}$ . Show that

$$E(f(X)) = a_n E(X^n) + \cdots + a_1 E(X) + a_0.$$