

Chapter 24

Probability

A **probability** is a real number between 0 and 1 that indicates how probable an event is. If an event is certain to happen, its probability is 1, and if an event is impossible, its probability is 0. The probability of an event is denoted $P(\dots)$ where the three dots describe the event.

For example, when throwing a dice, the outcome is an integer between 1 and 6, and the probability of each outcome is $1/6$. For example, we can calculate the following probabilities:

- $P(\text{"the outcome is 4"}) = 1/6$
- $P(\text{"the outcome is not 6"}) = 5/6$
- $P(\text{"the outcome is even"}) = 1/2$

24.1 Calculation

To calculate the probability of an event, we can either use combinatorics or simulate the process that generates the event. As an example, let us calculate the probability of drawing three cards with the same value from a shuffled deck of cards (for example, $\spadesuit 8$, $\clubsuit 8$ and $\diamondsuit 8$).

Method 1

We can calculate the probability using the formula

$$\frac{\text{number of desired outcomes}}{\text{total number of outcomes}}.$$

In this problem, the desired outcomes are those in which the value of each card is the same. There are $13 \binom{4}{3}$ such outcomes, because there are 13 possibilities for the value of the cards and $\binom{4}{3}$ ways to choose 3 suits from 4 possible suits.

There are a total of $\binom{52}{3}$ outcomes, because we choose 3 cards from 52 cards. Thus, the probability of the event is

$$\frac{13 \binom{4}{3}}{\binom{52}{3}} = \frac{1}{425}.$$

Method 2

Another way to calculate the probability is to simulate the process that generates the event. In this example, we draw three cards, so the process consists of three steps. We require that each step of the process is successful.

Drawing the first card certainly succeeds, because there are no restrictions. The second step succeeds with probability $3/51$, because there are 51 cards left and 3 of them have the same value as the first card. In a similar way, the third step succeeds with probability $2/50$.

The probability that the entire process succeeds is

$$1 \cdot \frac{3}{51} \cdot \frac{2}{50} = \frac{1}{425}.$$

24.2 Events

An event in probability theory can be represented as a set

$$A \subset X,$$

where X contains all possible outcomes and A is a subset of outcomes. For example, when drawing a dice, the outcomes are

$$X = \{1, 2, 3, 4, 5, 6\}.$$

Now, for example, the event "the outcome is even" corresponds to the set

$$A = \{2, 4, 6\}.$$

Each outcome x is assigned a probability $p(x)$. Then, the probability $P(A)$ of an event A can be calculated as a sum of probabilities of outcomes using the formula

$$P(A) = \sum_{x \in A} p(x).$$

For example, when throwing a dice, $p(x) = 1/6$ for each outcome x , so the probability of the event "the outcome is even" is

$$p(2) + p(4) + p(6) = 1/2.$$

The total probability of the outcomes in X must be 1, i.e., $P(X) = 1$.

Since the events in probability theory are sets, we can manipulate them using standard set operations:

- The **complement** \bar{A} means "A does not happen". For example, when throwing a dice, the complement of $A = \{2, 4, 6\}$ is $\bar{A} = \{1, 3, 5\}$.
- The **union** $A \cup B$ means "A or B happen". For example, the union of $A = \{2, 5\}$ and $B = \{4, 5, 6\}$ is $A \cup B = \{2, 4, 5, 6\}$.
- The **intersection** $A \cap B$ means "A and B happen". For example, the intersection of $A = \{2, 5\}$ and $B = \{4, 5, 6\}$ is $A \cap B = \{5\}$.

Complement

The probability of the complement \bar{A} is calculated using the formula

$$P(\bar{A}) = 1 - P(A).$$

Sometimes, we can solve a problem easily using complements by solving the opposite problem. For example, the probability of getting at least one six when throwing a dice ten times is

$$1 - (5/6)^{10}.$$

Here $5/6$ is the probability that the outcome of a single throw is not six, and $(5/6)^{10}$ is the probability that none of the ten throws is a six. The complement of this is the answer to the problem.

Union

The probability of the union $A \cup B$ is calculated using the formula

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

For example, when throwing a dice, the union of the events

$$A = \text{"the outcome is even"}$$

and

$$B = \text{"the outcome is less than 4"}$$

is

$$A \cup B = \text{"the outcome is even or less than 4"},$$

and its probability is

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) = 1/2 + 1/2 - 1/6 = 5/6.$$

If the events A and B are **disjoint**, i.e., $A \cap B$ is empty, the probability of the event $A \cup B$ is simply

$$P(A \cup B) = P(A) + P(B).$$

Conditional probability

The **conditional probability**

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

is the probability of A assuming that B happens. Hence, when calculating the probability of A , we only consider the outcomes that also belong to B .

Using the previous sets,

$$P(A|B) = 1/3,$$

because the outcomes of B are $\{1, 2, 3\}$, and one of them is even. This is the probability of an even outcome if we know that the outcome is between $1 \dots 3$.

Intersection

Using conditional probability, the probability of the intersection $A \cap B$ can be calculated using the formula

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

Events A and B are **independent** if

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

which means that the fact that B happens does not change the probability of A , and vice versa. In this case, the probability of the intersection is

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

For example, when drawing a card from a deck, the events

$$A = \text{"the suit is clubs"}$$

and

$$B = \text{"the value is four"}$$

are independent. Hence the event

$$A \cap B = \text{"the card is the four of clubs"}$$

happens with probability

$$P(A \cap B) = P(A)P(B) = 1/4 \cdot 1/13 = 1/52.$$

24.3 Random variables

A **random variable** is a value that is generated by a random process. For example, when throwing two dice, a possible random variable is

$$X = \text{"the sum of the outcomes"}.$$

For example, if the outcomes are $[4, 6]$ (meaning that we first throw a four and then a six), then the value of X is 10.

We denote $P(X = x)$ the probability that the value of a random variable X is x . For example, when throwing two dice, $P(X = 10) = 3/36$, because the total number of outcomes is 36 and there are three possible ways to obtain the sum 10: $[4, 6]$, $[5, 5]$ and $[6, 4]$.

Expected value

The **expected value** $E[X]$ indicates the average value of a random variable X . The expected value can be calculated as the sum

$$\sum_x P(X = x)x,$$

where x goes through all possible values of X .

For example, when throwing a dice, the expected outcome is

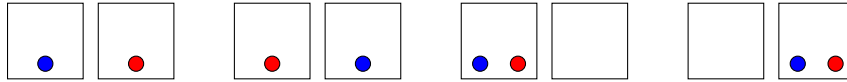
$$1/6 \cdot 1 + 1/6 \cdot 2 + 1/6 \cdot 3 + 1/6 \cdot 4 + 1/6 \cdot 5 + 1/6 \cdot 6 = 7/2.$$

A useful property of expected values is **linearity**. It means that the sum $E[X_1 + X_2 + \dots + X_n]$ always equals the sum $E[X_1] + E[X_2] + \dots + E[X_n]$. This formula holds even if random variables depend on each other.

For example, when throwing two dice, the expected sum is

$$E[X_1 + X_2] = E[X_1] + E[X_2] = 7/2 + 7/2 = 7.$$

Let us now consider a problem where n balls are randomly placed in n boxes, and our task is to calculate the expected number of empty boxes. Each ball has an equal probability to be placed in any of the boxes. For example, if $n = 2$, the possibilities are as follows:



In this case, the expected number of empty boxes is

$$\frac{0 + 0 + 1 + 1}{4} = \frac{1}{2}.$$

In the general case, the probability that a single box is empty is

$$\left(\frac{n-1}{n}\right)^n,$$

because no ball should be placed in it. Hence, using linearity, the expected number of empty boxes is

$$n \cdot \left(\frac{n-1}{n}\right)^n.$$

Distributions

The **distribution** of a random variable X shows the probability of each value that X may have. The distribution consists of values $P(X = x)$. For example, when throwing two dice, the distribution for their sum is:

x	2	3	4	5	6	7	8	9	10	11	12
$P(X = x)$	1/36	2/36	3/36	4/36	5/36	6/36	5/36	4/36	3/36	2/36	1/36

In a **uniform distribution**, the random variable X has n possible values $a, a+1, \dots, b$ and the probability of each value is $1/n$. For example, when throwing a dice, $a = 1$, $b = 6$ and $P(X = x) = 1/6$ for each value x .

The expected value of X in a uniform distribution is

$$E[X] = \frac{a+b}{2}.$$

In a **binomial distribution**, n attempts are made and the probability that a single attempt succeeds is p . The random variable X counts the number of successful attempts, and the probability of a value x is

$$P(X = x) = p^x(1-p)^{n-x} \binom{n}{x},$$

where p^x and $(1-p)^{n-x}$ correspond to successful and unsuccessful attempts, and $\binom{n}{x}$ is the number of ways we can choose the order of the attempts.

For example, when throwing a dice ten times, the probability of throwing a six exactly three times is $(1/6)^3(5/6)^7 \binom{10}{3}$.

The expected value of X in a binomial distribution is

$$E[X] = pn.$$

In a **geometric distribution**, the probability that an attempt succeeds is p , and we continue until the first success happens. The random variable X counts the number of attempts needed, and the probability of a value x is

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

where $(1-p)^{x-1}$ corresponds to the unsuccessful attempts and p corresponds to the first successful attempt.

For example, if we throw a dice until we throw a six, the probability that the number of throws is exactly 4 is $(5/6)^3 1/6$.

The expected value of X in a geometric distribution is

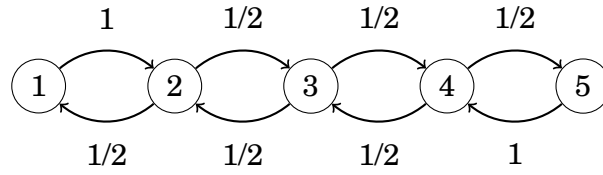
$$E[X] = \frac{1}{p}.$$

24.4 Markov chains

A **Markov chain** is a random process that consists of states and transitions between them. For each state, we know the probabilities for moving to other states. A Markov chain can be represented as a graph whose nodes are states and edges are transitions.

As an example, consider a problem where we are in floor 1 in an n floor building. At each step, we randomly walk either one floor up or one floor down, except that we always walk one floor up from floor 1 and one floor down from floor n . What is the probability of being in floor m after k steps?

In this problem, each floor of the building corresponds to a state in a Markov chain. For example, if $n = 5$, the graph is as follows:



The probability distribution of a Markov chain is a vector $[p_1, p_2, \dots, p_n]$, where p_k is the probability that the current state is k . The formula $p_1 + p_2 + \dots + p_n = 1$ always holds.

In the above scenario, the initial distribution is $[1, 0, 0, 0, 0]$, because we always begin in floor 1. The next distribution is $[0, 1, 0, 0, 0]$, because we can only move from floor 1 to floor 2. After this, we can either move one floor up or one floor down, so the next distribution is $[1/2, 0, 1/2, 0, 0]$, and so on.

An efficient way to simulate the walk in a Markov chain is to use dynamic programming. The idea is to maintain the probability distribution, and at each step go through all possibilities how we can move. Using this method, we can simulate a walk of m steps in $O(n^2m)$ time.

The transitions of a Markov chain can also be represented as a matrix that updates the probability distribution. In the above scenario, the matrix is

$$\begin{bmatrix} 0 & 1/2 & 0 & 0 & 0 \\ 1 & 0 & 1/2 & 0 & 0 \\ 0 & 1/2 & 0 & 1/2 & 0 \\ 0 & 0 & 1/2 & 0 & 1 \\ 0 & 0 & 0 & 1/2 & 0 \end{bmatrix}.$$

When we multiply a probability distribution by this matrix, we get the new distribution after moving one step. For example, we can move from the distribution $[1, 0, 0, 0, 0]$ to the distribution $[0, 1, 0, 0, 0]$ as follows:

$$\begin{bmatrix} 0 & 1/2 & 0 & 0 & 0 \\ 1 & 0 & 1/2 & 0 & 0 \\ 0 & 1/2 & 0 & 1/2 & 0 \\ 0 & 0 & 1/2 & 0 & 1 \\ 0 & 0 & 0 & 1/2 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}.$$

By calculating matrix powers efficiently, we can calculate the distribution after m steps in $O(n^3 \log m)$ time.

24.5 Randomized algorithms

Sometimes we can use randomness for solving a problem, even if the problem is not related to probabilities. A **randomized algorithm** is an algorithm that is based on randomness.

A **Monte Carlo algorithm** is a randomized algorithm that may sometimes give a wrong answer. For such an algorithm to be useful, the probability of a wrong answer should be small.

A **Las Vegas algorithm** is a randomized algorithm that always gives the correct answer, but its running time varies randomly. The goal is to design an algorithm that is efficient with high probability.

Next we will go through three example problems that can be solved using randomness.

Order statistics

The k th **order statistic** of an array is the element at position k after sorting the array in increasing order. It is easy to calculate any order statistic in $O(n \log n)$ time by first sorting the array, but is it really needed to sort the entire array just to find one element?

It turns out that we can find order statistics using a randomized algorithm without sorting the array. The algorithm, called **quickselect**¹, is a Las Vegas algorithm: its running time is usually $O(n)$ but $O(n^2)$ in the worst case.

The algorithm chooses a random element x of the array, and moves elements smaller than x to the left part of the array, and all other elements to the right part of the array. This takes $O(n)$ time when there are n elements. Assume that the left part contains a elements and the right part contains b elements. If $a = k$, element x is the k th order statistic. Otherwise, if $a > k$, we recursively find the k th order statistic for the left part, and if $a < k$, we recursively find the r th order statistic for the right part where $r = k - a$. The search continues in a similar way, until the element has been found.

When each element x is randomly chosen, the size of the array about halves at each step, so the time complexity for finding the k th order statistic is about

$$n + n/2 + n/4 + n/8 + \dots < 2n = O(n).$$

The worst case of the algorithm requires still $O(n^2)$ time, because it is possible that x is always chosen in such a way that it is one of the smallest or largest elements in the array and $O(n)$ steps are needed. However, the probability for this is so small that this never happens in practice.

Verifying matrix multiplication

Our next problem is to *verify* if $AB = C$ holds when A , B and C are matrices of size $n \times n$. Of course, we can solve the problem by calculating the product AB again (in $O(n^3)$ time using the basic algorithm), but one could hope that verifying the answer would be easier than to calculate it from scratch.

It turns out that we can solve the problem using a Monte Carlo algorithm² whose time complexity is only $O(n^2)$. The idea is simple: we choose a random vector X of n elements, and calculate the matrices ABX and CX . If $ABX = CX$, we report that $AB = C$, and otherwise we report that $AB \neq C$.

¹In 1961, C. A. R. Hoare published two algorithms that are efficient on average: **quicksort** [36] for sorting arrays and **quickselect** [37] for finding order statistics.

²R. M. Freivalds published this algorithm in 1977 [26], and it is sometimes called **Freivalds' algorithm**.

The time complexity of the algorithm is $O(n^2)$, because we can calculate the matrices ABX and CX in $O(n^2)$ time. We can calculate the matrix ABX efficiently by using the representation $A(BX)$, so only two multiplications of $n \times n$ and $n \times 1$ size matrices are needed.

The drawback of the algorithm is that there is a small chance that the algorithm makes a mistake when it reports that $AB = C$. For example,

$$\begin{bmatrix} 6 & 8 \\ 1 & 3 \end{bmatrix} \neq \begin{bmatrix} 8 & 7 \\ 3 & 2 \end{bmatrix},$$

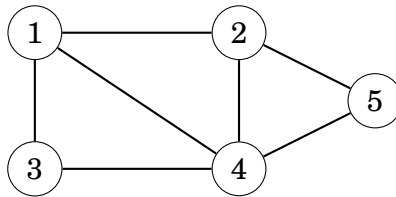
but

$$\begin{bmatrix} 6 & 8 \\ 1 & 3 \end{bmatrix} \begin{bmatrix} 3 \\ 6 \end{bmatrix} = \begin{bmatrix} 8 & 7 \\ 3 & 2 \end{bmatrix} \begin{bmatrix} 3 \\ 6 \end{bmatrix}.$$

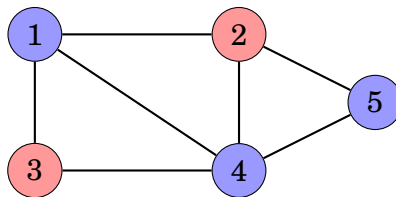
However, in practice, the probability that the algorithm makes a mistake is small, and we can decrease the probability by verifying the result using multiple random vectors X before reporting that $AB = C$.

Graph coloring

Given a graph that contains n nodes and m edges, our task is to find a way to color the nodes of the graph using two colors so that for at least $m/2$ edges, the endpoints have different colors. For example, in the graph



a valid coloring is as follows:



The above graph contains 7 edges, and for 5 of them, the endpoints have different colors, so the coloring is valid.

The problem can be solved using a Las Vegas algorithm that generates random colorings until a valid coloring has been found. In a random coloring, the color of each node is independently chosen so that the probability of both colors is $1/2$.

In a random coloring, the probability that the endpoints of a single edge have different colors is $1/2$. Hence, the expected number of edges whose endpoints have different colors is $m/2$. Since it is expected that a random coloring is valid, we will quickly find a valid coloring in practice.