Part A Probability

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Themes of the course

- Convergence of random variables
- Probabilistic limit laws:
  - Laws of large numbers
  - Central limit theorem
- Joint distributions
- Random *processes*:
  - Markov chains
  - Poisson processes

Review

Probability spaces and random variables

A probability space is a collection $(\Omega, \mathcal{F}, \mathbb{P})$ where:

- Ω is a set, called the sample space.
- $\mathcal{F}$ is a collection of subsets of Ω. An element of $\mathcal{F}$ is called an event.
- $\mathbb{P}$ is a function from $\mathcal{F}$ to $[0, 1]$, called the probability measure. It assigns a probability to each event in $\mathcal{F}$.

If we think of the probability space as modelling some "experiment", then Ω represents the "set of outcomes" of the experiment.

Events

The set of events $\mathcal{F}$ should satisfy the following natural conditions:

(1) $\Omega \in \mathcal{F}$

(2) If $\mathcal{F}$ contains some set A then $\mathcal{F}$ also contains its complement A^c (i.e. $\Omega \setminus A$).

(3) If $(A_i, i \in \mathcal{I})$ is a finite or countably infinite collection of events in $\mathcal{F}$, then their union $\bigcup_{i \in \mathcal{I}} A_i$ is also in $\mathcal{F}$.

By combining (2) and (3), we can also get finite or countable *intersections* as well as unions.

Probability axioms

The probability measure $\mathbb{P}$ should satsify the following conditions:

(1) $\mathbb{P}(\Omega) = 1$

(2) If $(A_i, i \in \mathcal{I})$ is a finite or countably infinite collection of **disjoint** events, then

$$\mathbb{P}\left(\bigcup_{i \in \mathcal{I}} A_i\right) = \sum_{i \in \mathcal{I}} \mathbb{P}(A_i).$$

The second condition is known as *countable additivity*.

Random variables

A random variable is a function from Ω, for example to $\mathbb{R}$.

A random variable represents an observable in our experiment; something we can measure.

Formally, for a function $X : \Omega \mapsto \mathbb{R}$ to be a random variable, we require that the events

$$\{\omega \in \Omega\colon X(\omega) \le x\}$$

are contained in $\mathcal{F}$, for every x. (Then by taking complements and unions, we will in fact have that the event $\{\omega \in \Omega\colon X(\omega) \in B\}$ is in $\mathcal{F}$ for a very large class of sets B).

We normally write just $\{X \in B\}$ for $\{\omega \in \Omega\colon X(\omega) \in B\}$. We write $\mathbb{P}(X \in B)$ for the probability of the event $\{X \in B\}$.

- Within one experiment, there will be many observables! That is, on the same probability space we can consider many different random variables.
- We generally do not work with the sample space Ω directly. Instead we work directly with the **events** and **random variables** (the “observables”) in the experiment.

Examples of systems (or "experiments") that we might model using a probability space.

- Throw two dice, one red, one blue. Random variables: the score on the red die; the score on the blue die; the sum of the two; the maximum of the two; the indicator function of the event that the blue score exceeds the red score....
- A Geiger counter detecting particles emitted by a radioactive source. Random variables: the time of the kth particle detected, for $k = 1, 2, \dots$; the number of particles detected in the time interval $[0, t]$ for $t \in \mathbb{R}_+$, ...
- A model for the evolution of a financial market. Random variables: the prices of various stocks at various times; interest rates at various times; exchange rates at various times....
- The growth of a colony of bacteria. Random variables: the number of bacteria present at a given time; the diameter of the colonised region at a given time....
- A call-centre. The time of arrival of the kth call; the length of service required by the kth caller; the wait-time of the kth caller in the queue before receiving service....

Distribution

The distribution of a random variable X is summarised by its (cumulative) distribution function:

$$F_X(x) = \mathbb{P}(X \leq x).$$

Once we know F we can obtain $\mathbb{P}(X \in B)$ for a large class of sets B by taking complements and unions.

F obeys the following properties:

(1) F is non-decreasing

(2) F is right-continuous

(3) $F(x) \to 0$ as $x \to -\infty$

(4) $F(x) \to 1$ as $x \to \infty$.

Note that two different random variables (two different "observables" within the same experiment) can have the same distribution. If X and Y have the same distribution we write $X \stackrel{d}{=} Y$.

Discrete random variables

A random variable X is discrete if there is a finite or countably infinite set B such that $\mathbb{P}(X \in B) = 1$.

We can represent its distribution by the probability mass function

$$p_X(x) = \mathbb{P}(X = x), \text{ for } x \in \mathbb{R}$$

We have

- $\sum_x p_X(x) = 1$
- $\mathbb{P}(X \in A) = \sum_{x \in A} p_X(x)$ for any set $A \subseteq \mathbb{R}$.

Continuous random variables

A random variable X is continuous if its distribution function F can be written as an integral; i.e. there is a function f such that

$$\mathbb{P}(X \leq x) = F(x) = \int_{-\infty}^{x} f(u)du.$$

f is the (probability) density function of X.

f is not unique; for example we can change the value at any single point without affecting the integral. At points where F is differentiable, it's natural to take $f(x) = F'(x)$.

For general (well-behaved) sets B,

$$\mathbb{P}(X \in B) = \int_{x \in B} f(x)dx.$$

Expectation

If X is discrete, its expectation (or mean) is given by

$$\mathbb{E}(X) = \sum_x x p_X(x).$$

For X continuous, instead

$$\mathbb{E}(X) = \int_{-\infty}^{\infty} x f(x) dx.$$

We could unify these definitions (and extend to random variables which are neither discrete nor continuous). For example, consider approximations of a general random variable by discrete random variables (analogous to the construction of an integral of a general function by defining the integral of a step function using sums, and then extending to general functions using approximation by step functions).

Properties of expectation

(1) $\mathbb{E}\, I_A = \mathbb{P}(A)$ for any event A.

(2) If $\mathbb{P}(X \geq 0) = 1$ then $\mathbb{E}\, X \geq 0$.

(3) **(Linearity 1)**: $\mathbb{E}\,(aX) = a\mathbb{E}\, X$ for any constant a.

(4) **(Linearity 2)**: $\mathbb{E}\,(X + Y) = \mathbb{E}\, X + \mathbb{E}\, Y$.

Expectation of a function of a random variable:

$$\mathbb{E}\, g(X) = \sum_x g(x) p_X(x) \text{ (discrete case)}$$

$$\mathbb{E}\, g(X) = \int_{-\infty}^{\infty} g(x) f(x) dx \text{ (continuous case)}$$

Variance and covariance

The variance of a random variable X is defined by

$$\begin{aligned}\mathrm{Var}(X) &= \mathbb{E}\left[(X-\mathbb{E}\,X)^2\right] \\ &= \mathbb{E}\,(X^2) - (\mathbb{E}\,X)^2.\end{aligned}$$

The covariance of two random variables X and Y is defined by

$$\begin{aligned}\mathrm{Cov}(X,Y) &= \mathbb{E}\left[(X-\mathbb{E}\,X)(Y-\mathbb{E}\,Y)\right] \\ &= \mathbb{E}\,(XY) - (\mathbb{E}\,X)(\mathbb{E}\,Y).\end{aligned}$$

Properties:

$$\begin{aligned}\mathrm{Var}(aX+b) &= a^2\,\mathrm{Var}\,X \\ \mathrm{Cov}(aX+b, cY+d) &= ac\,\mathrm{Cov}(X,Y) \\ \mathrm{Var}(X+Y) &= \mathrm{Var}\,X + \mathrm{Var}\,Y + 2\,\mathrm{Cov}(X,Y) \\ \mathrm{Var}(X_1+X_2+\cdots+X_n) &= \sum_{i=1}^{n}\mathrm{Var}(X_i) + 2\sum_{1\le i<j\le n}\mathrm{Cov}(X_i,X_j).\end{aligned}$$

Independence

Events A and B are independent if

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

More generally, a collection of events $\{A_i, i \in \mathcal{I}\}$ are independent if

$$\mathbb{P}\left(\bigcap_{i \in J} A_i\right) = \prod_{i \in J} \mathbb{P}(A_i)$$

for all finite subsets J of $\mathcal{I}$.

Random variables $X_1, \ldots, X_n$ are independent if for all $B_1, \ldots, B_n \subset \mathbb{R}$, the events $\{X_1 \in B_1\}, \ldots, \{X_n \in B_n\}$ are independent.

In fact, it's sufficient that for all $x_1, \ldots, x_n$,

$$\mathbb{P}(X_1 \leq x_1, \ldots, X_n \leq x_n) = \mathbb{P}(X_1 \leq x_1) \ldots \mathbb{P}(X_n \leq x_n).$$

If X and Y are independent, then $\mathbb{E}(XY) = \mathbb{E}(X)\mathbb{E}(Y)$, i.e. $\mathrm{Cov}(X, Y) = 0$. The converse is **not** true!

Examples of probability distributions

- Continuous:
  Uniform, exponential, normal, gamma...
- Discrete:
  Discrete uniform, Bernoulli, binomial, geometric, Poisson...