

Essential Probability

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Objectives

Today's objectives:

- Review probability definitions and concepts
- Review combinatorics definitions and concepts
- Review properties of distributions
- Understand which distributions to use to model which types of processes

Agenda

Today's plan:

- 1 Combinatorics
- 2 Probability
- 3 Random variables and probability distributions

References

A couple helpful references:

- [Mathematical Statistics: A Unified Introduction](#) provides an accessible introduction with many examples
- [Statistical Inference](#) provides a graduate level introduction
- [All of Statistics: A Concise Course in Statistical Inference](#)
- [Probability and Measure](#) provides a rigorous mathematical foundation for those with 'extreme math' skills

Review: sets

Some definitions:

- A set S consists of all possible outcomes or events and is called the *sample space*
- *Union*: $A \cup B = \{x : x \in A \text{ or } x \in B\}$
- *Intersection*: $A \cap B = \{x : x \in A \text{ and } x \in B\}$
- *Complement*: $A^c = \{x : x \notin A\}$
- *Disjoint*: $A \cap B = \emptyset$
- *Partition*: a set of pairwise disjoint sets, $\{A_j\}$, such that $\bigcup_{j=1}^{\infty} A_j = S$
- Plus the commutative, associative, distributive, and DeMorgan's laws

Combinatorics

Example: tea

R. A. Fischer is invited to tea with a lady who claims she can tell whether tea or milk is added to the cup first. Fisher is incredulous and proposes the following experiment:

- He will prepare three cups with tea added first and milk second and three cups prepared in the opposite order
- He will order the cups randomly
- The lady will guess which are which
- What is the probability she guesses all three correctly by chance?

Factorial

Factorial counts the number of ways of ordering or picking something when order matters:

- We write $n! = n \times (n - 1) \times \dots \times 1$
- $0! = 1$ by convention
- Example: how many ways can we shuffle a deck of cards?

Combination

Combination counts the number of ways of picking something when order doesn't matter:

- $\binom{n}{k} = \frac{n!}{(n-k)!k!}$
- We say '*n choose k*'
- This is the number of ways of choosing k items from n total items
- Typically, the items are identical
- Urns and balls are the classic example:
 - ▶ If I draw k balls from an urn with n balls, how many different sets are possible?
 - ▶ If I draw W white balls and B black balls from an urn, how many different orderings are possible?

Example: tea revisited

What if we prepare eight cups with four cups tea first and four milk first:

- What is the probability she can guess at least three out of four cups correctly?
- Will R. A. Fisher be impressed?

The number of ways of assigning (n_1, n_2, \dots, n_k) objects to k different categories:

- $$\binom{n}{n_1 n_2 \cdots n_k} = \frac{n!}{n_1! n_2! \cdots n_k!}$$
- Example: an urn contains red, white, and blue balls. . .

Probability

Introduction

Probability provides the mathematical tools we use to model randomness:

- Probability tells us how likely an event (Frequentist) is or how likely our beliefs are to be correct (Bayesian)
- Provides the foundation for statistics and machine learning
- Often our intuitions about randomness are incorrect because we live only one realization
- Enumerating all possible outcomes (using combinatorics) can help us compute the probability of an event

Definition of probability

Given a sample space, S , a *probability function*, P , has three properties:

- $P(A) \geq 0, \forall A \subset S$
- $P(S) = 1$
- For a set of pairwise disjoint sets $\{A_j\}$, $P(\cup_j A_j) = \sum_j P(A_j)$

Note: for those who really care about the details, you need to use measure theory and sigma algebras

Example: tossing a coin

Consider a coin toss:

- $S = \{H, T\}$
- $P(H) = P(T) = \frac{1}{2} > 0$
- $P(S) = 1$

Note: this means $P(A) = 1 - P(A^c)$

Independence

Two events A and B are said to be *independent* if

$$\Pr[A \cap B] = \Pr[A] \cdot \Pr[B]$$

or, equivalently, if

$$\Pr[B|A] = \Pr[B],$$

i.e., knowledge of A provides no information about B

- $A \perp B$ means A and B are independent
- To compute the probability that any one of a set of independent events, $\{A_n\}$, occurs:

$$\Pr[\cup_k A_k] = \sum \Pr[A_k],$$

where $A_i \perp A_j, \forall i \neq j$

Multiplication rule

To compute the probability that two independent events occur, multiply their probabilities:

$$\Pr[A \cap B] = \Pr[A] \cdot \Pr[B]$$

Example:

- What is the probability that A and B happen?

Example: coin tosses

Take a moment to solve this question:

- Three types of fair coins are in an urn: HH, HT, and TT
- You pull a coin out of the urn, flip it, and it comes up H
- **Q:** what is the probability it comes up H if you flip it a second time?

Conditional probability

We often care about whether one event provides information about another event. The *conditional probability* of B given A is:

$$\Pr[B|A] = \frac{\Pr[A \cap B]}{\Pr[A]}$$

- We say this is the '*probability of B conditional on A* '
- I.e., if A has occurred, what is the probability B will occur?
- For a pdf of two random variables,

$$f(y|x) = \frac{f(x, y)}{f(x)}$$

Probability chain rule

Can condition on an arbitrary number of variables:

- Simple example:

$$\Pr[A_3, A_2, A_1] = \Pr[A_3|A_2, A_1] \cdot \Pr[A_2|A_1] \cdot \Pr[A_1]$$

- General case:

$$\Pr[A_n, \dots, A_1] = \prod_j \Pr[A_j|A_{j-1}, \dots, A_1]$$

or

$$\Pr[\bigcap_j^n A_j] = \prod_j^n \Pr[A_j | \bigcap_k^{j-1} A_k]$$

Law of total probability

If $\{B_n\}$ is a partition of the sample space, the *Law of total probability* states:

$$\Pr[A] = \sum_j \Pr[A \cap B_j]$$

or

$$\Pr[A] = \sum_j \Pr[A|B_j] \cdot \Pr[B_j]$$

$\Pr[A]$ is said to be a *marginal distribution* of $\Pr[A, B]$

Bayes's Rule

Use Bayes's Rule when you need to compute conditional probability for $B|A$ but only have probability for $A|B$:

$$\Pr[B|A] = \frac{\Pr[A|B] \cdot \Pr[B]}{\Pr[A]}$$

- Proof: use the definition of conditional probability
- For an arbitrary partition of event space, $\{A_j\}$, use the general form of Bayes's rule:

$$\Pr[A_k|B] = \frac{\Pr[B|A_k] \cdot \Pr[A_k]}{\sum_j \Pr[B|A_j] \cdot \Pr[A_j]}$$

Example: drug testing

A test for EPO has the following properties:

Variable	Value
$\Pr[+ doped]$	0.99
$\Pr[+ clean]$	0.05
$\Pr[doped]$	0.005

Q: What is the probability the cyclist is using EPO if the test is positive?
I.e., what is $\Pr[doped|+]$?

Solution: drug testing

- 1 Compute probability of being clean:

$$\Pr[\text{clean}] = 1 - \Pr[\text{doped}]$$

- 2 Use Bayes's Rule:

$$\begin{aligned}\Pr[\text{doped}|+] &= \frac{\Pr[+|\text{doped}] \cdot \Pr[\text{doped}]}{\Pr[+|\text{doped}] \cdot \Pr[\text{doped}] + \Pr[+|\text{clean}] \cdot \Pr[\text{clean}]} \\ &= \frac{0.99 \cdot 0.005}{0.99 \cdot 0.005 + 0.05 \cdot (1 - 0.005)} \\ &= 0.090\end{aligned}$$

Based on **this** example

Random variables and probability distributions

Definition: random variable

Given a sample space S , a *random variable*, X , is a function such that $X(s) : S \mapsto \mathbb{R}$:

- Use capital letters to refer to a random variable, e.g., X
- Use lower case to refer to a specific realization, x , or $X = x$
- Consequently, $\Pr[X = x] = \Pr[\{s \in S : X(s) = x\}]$
- We write $X \sim \text{XYZ}(\alpha, \beta, \dots)$ to mean X is distributed like the XYZ distribution with parameters α, β, \dots
- We say a series of random variables are *i.i.d.* if they are '*independent and identically distributed*'
- Example: $X \sim \mathcal{N}(\mu, \sigma^2)$ or $X \sim \mathcal{U}(0, 1)$

Cumulative distribution function (CDF)

Definition: the cumulative distribution function $F_X(x) = \Pr[X \leq x]$:

- Properties:

- ▶ $0 \leq F_X(x) \leq 1$
- ▶ $\lim_{x \rightarrow -\infty} F_X(x) = 0$
- ▶ $\lim_{x \rightarrow \infty} F_X(x) = 1$
- ▶ $F_X(x)$ is monotonically increasing

- Applies to discrete and continuous random variables
- Note: $\Pr[a < X \leq b] = F_X(b) - F_X(a)$

Discrete: probability mass function (PMF)

For a random variable, X , which takes discrete values $\{x_i\}$, use a PMF to determine the probability of an individual event:

- $f_X(x) = P(X = x), \forall x$
- We say there is *probability mass* p_i on x_i , where $p_i = \Pr[X = x_i]$
- Example: tossing coins
 - ▶ $X \in \{H, T\}$
 - ▶ $p_H = p_T = \frac{1}{2}$

Continuous probability density function (PDF)

For a continuous random variable, X , use a PDF:

- $f_X(x)dx = \Pr[x < X < x + dx]$
- $f_X(x) = \frac{dF_X(x)}{dx}$, assuming some regularity conditions
- $F_X(x) = \int_{-\infty}^x f_X(s)ds$
- Example: survival time, T , of uranium before decay
 - ▶ $T \sim \text{Exp}(\lambda)$
 - ▶ PDF: $f_T(t) = \lambda \cdot \exp(-\lambda \cdot t)$
 - ▶ CDF: $F_T(t) = 1 - \exp(-\lambda \cdot t)$ if $t \geq 0$
 - ▶ What fraction survives longer than t ?

Properties of distributions

Use these properties to characterize a distribution:

- Expectation/mean
- Variance/standard deviation
- Skew
- Kurtosis
- Correlation

We often compute sample analogs of these properties to compare the empirical distribution of our data to standard distributions

Expectation/mean

The *expectation*, *mean*, or *expected value* is a measure of what is a likely value of a random variable:

- $\mu_{g(X)} = \mathbb{E}_X[g(x)]$:
 - ▶ Continuous: $\mathbb{E}_X[g(x)] = \int_{-\infty}^{\infty} g(s)f_X(s)ds$
 - ▶ Discrete: $\mathbb{E}_X[g(x)] = \sum_{s \in \{x_i\}} g(s)f_X(s)$
- Expectation is a linear operator
- The mean is $\mathbb{E}_X[x] = \int_{-\infty}^{\infty} sf(s)ds$
- The sample mean is $\bar{x} = \frac{1}{n} \sum_{j=1}^n x_j$

Variance

Variance measures the spread of a distribution:

- $\text{Var}[x] = \mathbb{E}_X[(x - \mu_x)^2]$
- Sometimes variance is written as $\sigma^2(x) = \text{Var}(x)$
- Often, we use *standard deviation*, $\sigma(X) = \sqrt{\text{Var}[X]}$ which has the same dimensions as X
- Note: the sample variance is $s^2 = \frac{1}{n-1} \sum_{j=1}^n (x_j - \bar{x})^2$

Warning: ddof

Many Numpy functions compute population values by default:

- Example: `np.var(..., ddof=0, ...)` computes

$$s^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$$

- Must set `ddof=1` to get sample variance!

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

- `ddof` means 'delta degrees of freedom'

Skew and kurtosis

Skew and kurtosis are higher order moments:

- Skewness:

- ▶ $\gamma_1 = \mathbb{E}\left[\left(\frac{X - \mu}{\sigma}\right)^3\right]$
- ▶ Measures asymmetry of a distribution
- ▶ Sign of skewness tells whether distribution is left or right skewed

- Kurtosis:

- ▶ $\kappa = \mathbb{E}\left[\left(\frac{X - \mu}{\sigma}\right)^4\right]$
- ▶ Measures the 'fatness' of the tails of the distribution

Variance of the mean

Statistics like the sample mean are random variables:

- Thus, they have a distribution
- Can compute their variance:

$$\text{Var}(\bar{x}) = \frac{\text{Var}(x)}{N}$$

- Hence, the standard deviation is:

$$\sigma(\bar{x}) = \sqrt{\frac{\text{Var}(x)}{N}}$$

or

$$\sigma(\bar{x}) = \frac{\sigma(x)}{\sqrt{N}}$$

Quantiles (percentiles)

Quantiles are another way to characterize the distribution of data:

- The *quantile function* of X is

$$Q_\alpha(x) = \min_x \{x : \Pr(X \leq x) \geq \alpha\}$$

$$Q_\alpha(x) = \min_x \{x : F(x) \geq \alpha\},$$

where $\alpha \in (0, 1)$

- Given regularity conditions, $Q_\alpha[x] = F^{-1}(\alpha)$
- If $u = F_X(x)$ then $U \sim U(0, 1)$
- *percentiles* are just the quantile $\times 100$

Common quantiles

During EDA, it is often helpful to examine:

- Median: $Q_{0.5}[x]$
- Upper quartile: $Q_{0.75}[x]$
- Lower quartile: $Q_{0.25}[x]$
- Note: the median usually does not equal the mean, especially for data with a long tail

Pro tip: compute a box plot

Multivariate distributions

Model relationships between multiple random variables with a multivariate (joint) distribution:

- Let $X(s) : S \mapsto \mathbb{R}^k$, i.e., X is a vector of random variables,
 $X(s) = (x_1(s), x_2(s), \dots, x_k(s))^T$
- CDF:

$$F(x_1, x_2, \dots, x_k) = \Pr[X_1 \leq x_1, X_2 \leq x_2, \dots, X_k \leq x_k]$$

- PDF:

$$F(x_1, x_2, \dots, x_k) = \int_{-\infty \dots -\infty}^{x_1 x_2 \dots x_k} f(s_1, s_2, \dots, s_k) ds_1 ds_2 \cdots ds_k$$

Multivariate moments

Can compute vector analogs of all moments we have discussed:

- Mean: $\mu_x = \mathbb{E}[x]$
- Variance: $\text{Var}[x] = \mathbb{E}[(x - \mu_x) \cdot (x - \mu_x)^T]$
- Covariance: $\text{Cov}[x, y] = \mathbb{E}[(x - \mu_x) \cdot (y - \mu_y)^T]$
- Correlation: $\rho_{XY}(x, y) = \frac{\text{Cov}[x, y]}{\sigma(x) \cdot \sigma(y)}$

Marginal and conditional distributions

To compute the marginal distribution from the joint (multivariate) distribution, just integrate (sum) over the other variable(s):

$$f_X(x) = \int_{-\infty}^{\infty} f_{XY}(x, s) ds$$

For a bivariate distribution, conditional pdf is:

$$f(y|x) = \frac{f_{XY}(x, y)}{f_X(x)}$$

Covariance and correlation

To explore the relationship between variables compute:

- *Covariance*:

- ▶ $\text{Cov}(x, y) = \mathbb{E}[(x - \mu_x) \cdot (y - \mu_y)]$
- ▶ Size changes with scaling of variables
- ▶ For random variables which are vectors, use $\text{Cov}[x, y] = \mathbb{E}[(x - \mu_x) \cdot (y - \mu_y)^T]$

- *Correlation (Pearson)*:

- ▶ Dimensionless measure relationship
- ▶ $\rho_{XY}(x, y) = \frac{\text{Cov}(x, y)}{\sigma(x) \cdot \sigma(y)}$
- ▶ Thus, $\rho_{XY} \in [-1, 1]$
- ▶ Other correlation coefficients, such as Spearman, use rank and are more robust

- Correlation is not causation!

Correlation and linearity

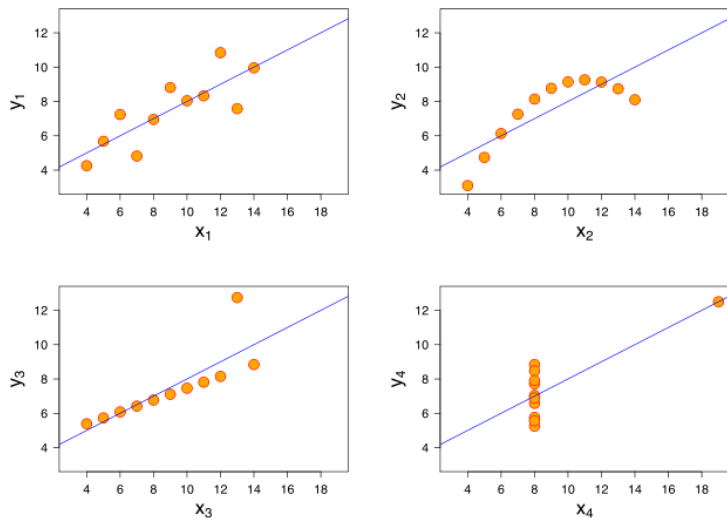


Figure 1: Correlation and linearity: $r = 0.816$ From Wikipedia

Correlation captures noisiness and direction

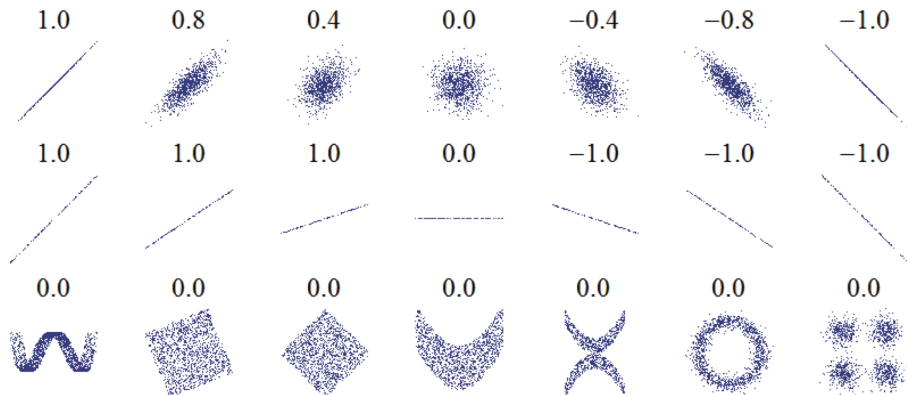


Figure 2: Correlation and non-linearity. From [Wikipedia](#).

The weak law of large numbers and the analog principle

The *weak law of large numbers* states that, given some regularity conditions,

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n x_i = \mathbb{E}[x]$$

This motivates the *analog principle*: when creating sample estimators, replace expectations, \mathbb{E} , with sums, $\frac{1}{n} \sum_{i=1}^n$

Common distributions

Overview

We now review the properties of some common distributions:

- Discrete

- ▶ Bernoulli
- ▶ Binomial
- ▶ Geometric
- ▶ Poisson

- Continuous

- ▶ Uniform
- ▶ Exponential
- ▶ Gaussian a.k.a. Normal
- ▶ χ^2
- ▶ Student's t
- ▶ F distribution

Models a toss of an unfair coin or clicking on a website:

- $X \sim \text{Bernoulli}(p)$
- PMF: $\Pr[H] = p$ and $\Pr[T] = 1 - p$
- Mean: $\mathbb{E}[x] = p$
- Variance: $\text{Var}[x] = p \cdot (1 - p)$

Example: click through rate

Given N visitors of whom n click on the 'Buy' button:

- What is click through rate (CTR)?
- What is the variance of the click through rate?

Models repeated tosses of a coin:

- $X \sim \text{Binomial}(n, p)$ for n tosses of a coin where $\Pr[H] = p$
- PMF: $\Pr[X = k] = \binom{n}{k} p^k \cdot (1 - p)^{(n-k)}, \forall 0 \leq k \leq n$
- Mean: $n \cdot p$
- Variance: $n \cdot p \cdot (1 - p)$
- Approaches Gaussian for limit of large n

Models probability succeeding on the k -th try:

- $X \sim \text{Geometric}(p, k)$
- PMF: $\Pr[X = k] = p \cdot (1 - p)^{(k-1)}$
- Mean: $\frac{1}{p}$
- Variance: $\frac{1 - p}{p^2}$

Models number of events in a period of time, such as number of visitors to website:

- $X \sim \text{Poisson}(\lambda)$
- PMF: $\Pr[X = k] = \exp(-\lambda) \cdot \frac{\lambda^k}{k!}, \forall k = 0, 1, 2, \dots$
- Mean = variance = λ
- λ is the number of events during the interval of interest
- Note: $\Pr[X = k]$ is just one term in the Taylor's series expansion of $\exp(x)$ when suitably normalized

Remark: the assumption that mean = variance is very strong. In practice, better to fit a model with *overdispersion* such as the negative binomial distribution, and test whether the assumption holds

Models a process where all values in an interval are equally likely:

- $X \sim U(a, b)$
- PDF: $f(x) = \frac{1}{b-a}, \forall x \in [a, b]$ and 0 otherwise
- Mean: $\frac{a+b}{2}$
- Variance: $\frac{(b-a)^2}{12}$
- Note: any continuous random variable can be transformed into a uniformly distributed variable by letting $u = F_X(x)$

Exponential

Models survival, such as the fraction of uranium which has not decayed by time t or time until a bus arrives:

- $T \sim \text{Exp}(\lambda)$
- $1/\lambda$ is the half-life
- CDF: $\Pr[T \leq t] = 1 - \exp(-\lambda \cdot t), x \geq 0, \lambda \geq 0$
- Mean: $1/\lambda$
- Variance: $1/\lambda^2$
- 'Memory-less'

Gaussian a.k.a. Normal

A benchmark distribution:

- $X \sim N(\mu, \sigma^2)$
- PDF: $f(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{(x - \mu)^2}{\sigma^2}\right)$
- Often, compute the 'z-statistic':
 - ▶ $z = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}}$
 - ▶ Perform a 'z-test' to check probability of observed value
- 'Standard normal' is $N(0, 1)$:
 - ▶ PDF is $\phi(x)$
 - ▶ CDF is $\Phi(x)$
- Will discuss Central Limit Theorem tomorrow

This is the famous 'Bell-curve' distribution and is associated with many processes, such as white noise, Brownian motion, etc.

Other distributions

Some other distributions:

- χ^2 :
 - ▶ Models sum of k squared, independent, normally-distributed random variables
 - ▶ Use for goodness of fit tests
- Student's t : distribution of the t -statistic:
 - ▶ t -statistic: $t = \frac{\bar{x} - \mu}{s/\sqrt{n}}$, where s is the standard error
 - ▶ Perform a 't-test' to check probability of observed value
 - ▶ Has fatter tails than normal distribution
- F-distribution:
 - ▶ Distribution of the ratio of two χ^2 random variables
 - ▶ Use to test restrictions and ANOVA

Digression: random numbers

Bad news: the computer generates *pseudo*-random numbers:

- Not truly random
- Generated using a variety of algorithms so that they satisfy statistical tests
- Most proofs use true random numbers ... so be careful they may not hold with pseudo-random numbers

Summary

Summary

Q: When do you use factorial vs. combination?

Q: What is independence?

Q: What is conditional probability? How do I use Bayes's rule?

Q: What are the PDF and CDF?

Q: What are moments should you use to characterize a distribution? How do you calculate them?

Q: What is a quantile?

Q: What are some common distributions? What type of processes do they model?