



A minimal introduction to probability theory,
statistical inference & hypothesis testing

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Contents

Preface	iii
The purpose of these notes	iii
Introduction	v
A bit of history	v
1 Descriptive statistics	1
1.1 Sampling and data types	2
1.2 Central tendency and variation	4
1.3 Data visualization	7
2 Foundations of Probability	11
2.1 What is probability?	11
2.2 Discrete events	12
2.2.1 Bernoulli trials	12
2.2.2 Binomial distribution	12
2.2.3 Poisson distribution	12
2.2.4 Discrete uniform distribution	12
2.3 Continuous events	12
2.3.1 Gaussian distribution	12
2.3.2 Exponential distribution	12
2.3.3 Continuous uniform distribution	12
2.4 Expected values	12
3 Estimation, prediction and inference	13
3.1 Prediction vs inference	13
3.2 The Law of Large Numbers	13
3.3 The Central Limit Theorem	13
3.4 Application to Generalized Linear Models	13
4 Introduction to hypothesis testing	16
4.1 Prediction vs inference revisited	16
4.2 General approach to hypothesis testing	17
4.3 Statistical tests: some examples	18
4.3.1 Compare sample mean with hypothesized value - One sample t-test	18
4.3.2 Compare sample means of two independent groups - Two sample t-test	19
4.3.3 Compare variation on two groups - Fisher's exact test	19
4.3.4 Compare variation o multiple groups - Fisher's ANOVA	20
4.3.5 Compare distributions and testing for normality - χ^2 test	20
4.4 Parametric and non-parametric tests	20
4.5 Error types in hypothesis testing	20

5	Modelling, dependency and correlation	26
5.1	Introduction and Philosophy	26
5.2	Estimation and Inference	26
6	Introduction to conditional probability	29
6.1	Motivation and philosophy	29
6.2	Dependent and independent events	29
6.3	Some examples of conditional probability	29
7	Stochasticity and Markov Processes	32
7.1	Motivation and philosophy	32
7.2	Mathematical definition	32
7.3	Some examples of conditional probability	32
7.4	Stochasticity and Markov processes	32
A	Appendix 1	35
B	Appendix 2	36
C	Appendix 3	37

Preface

The purpose of these notes

In the following pages one will find an introductory course to the theory of probability and statistical inference, aiming to cover both foundations and basic mathematical concepts, but also practical tools to deal with real data science problems, such as bayesian probability and hypothesis testing. The text is composed by five chapters, together with some appendix sections reviewing basic mathematical notions, and a bibliographic note. The purpose of these lecture notes is to make both probability and statistical analysis an easy, engaging and exciting topic for anyone interested, without the need for prior experience.

Both, predictive probability and descriptive statistics have deep historical roots, from ancient works on chance and divination to modern scientific topics oriented towards information theory, modelling and data analysis. As one could guess, rivers of ink have been written about such topics, and endless literature sources are available. However, after following many different courses at both bachelor and postgraduate levels, and teaching such topics myself during the last three years, I have found that most resources belong, almost certainly, to one of the next three classes. Either (i) deeply mathematical, and hence out of reach for most experimental or clinically oriented scientists, (ii) laboratory oriented, focusing on inference and experimental design, and hence missing most of the mathematical background, or (iii) with a direct focus towards programming and computation, relying on domain specific notebooks (Python, R, Matlab, SPSS, etc), and online resources with precompiled libraries for simulation, which again miss most of the mathematical and formal intuitions. Indeed, the misuse of statistics in experimental sciences is a critical topic in modern times, as mathematicians have extensively discussed during the last decades. The well-known article by John P. A. Ioannidis, "*Why most published research findings are false*" [17], serves as a prominent example, and it may serve as motivation for a rigorous study.

As a matter of fact, when it comes to modern statistics, data analysis or experimental design, concepts like *stochasticity*, *randomness*, *sampling*, *hypothesis*, *significance*, *statistic test*, *p-value*—just to mention some of them—are frequently used, but for most bachelor and even master's level degrees they are rarely introduced or properly defined. Indeed, for most experimental and clinically oriented degrees, they are not introduced at all, leaving the student with just a superficial knowledge relying on intuition about some particular cases. Hence, developing high-quality, simple, and accessible open source material for present and future generations, covering both probability and statistical inference from both a fundamental *and* applied level, remains an urgent task for scientists and educators.

This is intended to be a complete introductory course, and no previous mathematical background is required. By keeping the theory simple and always followed by examples, we will build the definitions and quantities from simple to more complex. All mathematical formulas will be introduced with rigorous notation, but keeping in mind that it is not the symbols or the numbers, but the intuitions and the general understanding, what we are after. Additionally, all topics will be introduced alongside with some short historical discussion and context, as we believe that a purely technical knowledge just grasps the complexity—and beauty—of scientific

topics. As one could anticipate already, a proper understanding of ideas such as uncertainty, variation, chance, probability, inference, etc, can be applied to describing a vast amount of real-world phenomena, ranging from gambling and to games of chance to data analysis and modelling in physics, biology, machine learning and quantum mechanics, among many others.

As mentioned, the course is organised in five chapters.

Chapter 1 [...] Chapter 2 [...] Chapter 3 [...] Chapter 4 [...] Chapter 5 [...]

At the end of each chapter there will be a series of exercises and coding examples to illustrate and demonstrate the concepts discussed. To avoid misconceptions, let us emphasize here that both, probability and statistics are just branches of mathematics dealing chance and information in random events, *much earlier* than computers, coding languages, Python, R or P-values were even conceived. The data-oriented, practical ways in which probability and statistics are usually taught, relying heavily on computation, is just a consequence of the fact that automatized measurements are nowadays available and trendy in modern times [...].

Example textbooks covering introduction to probability and statistical inference, for further reading:

- A simple, intuitive introduction to statistics with few mathematical concepts is provided in Spiegelhalter's *"The Art of Statistics: How to Learn from Data"* [27].
- A more foundational textbook, with more advanced mathematical approach, can be found at DeGroot and Schervish's *"Probability and Statistics"* [9].
- For a philosophical and historical perspective on probability and statistics, please find Forster and Bandyopadhyay's handbook *"Philosophy of Statistics"* [1].
- A comprehensive introduction with focus on practical applications and modern data analysis tools is can be found at Diez, Barr & Mine *"OpenIntro Statistics"* [11].
- For fundamental concepts in probability and statistics, including random variables, distributions and statistical inference, with practical examples and exercises follow Hossein Pishro-Nik's *"Probability, Statistics & Random Processes"* [23].

Introduction

Even fire obeys the laws of numbers.

— J.B. Joseph Fourier

A bit of history

As one might expect, the origins of probability and related concepts can be traced back to very ancient times. Civilizations such as the Babylonians, Egyptians, and Greeks already encountered uncertainty in various aspects of life, including commerce, games of chance, and divination. Consequently, notions of randomness and stochasticity have deep historical roots. For instance, archaeological findings suggest that the earliest known dice date back over 5,000 years, reflecting humanity's early fascination with chance and unpredictability [12]. Although these cultures had not yet developed a formal mathematical theory of probability, they recognized recurring patterns in random events and attempted to anticipate outcomes through either empirical observation or superstition. For a detailed historical overview, see Florence Nightingale's 1962 manuscript *"Games, Gods and Gambling"* [7].

While classical Greek and Roman philosophers frequently discussed the nature of chance, necessity, and determinism, their inquiries remained primarily philosophical rather than mathematical. Thinkers such as Cicero distinguished between events occurring by chance and those determined by fate, foreshadowing later developments in probability theory [5]. These early ideas, though lacking quantitative formalism, provided the intellectual foundation for later scientific inquiry into randomness and causality.

A significant shift occurred during the late medieval and early Renaissance periods, when more rigorous mathematical ideas began to shape. Italian mathematician and gambler Gerolamo Cardano (1501–1576) made substantial contributions to the mathematical analysis of chance. His work *"Liber de Ludo Aleae"* (*"Book on Games of Chance"*) [4], posthumously published in 1663, is one of the earliest known texts to explore probability through the analysis of gambling problems. However, Cardano's reasoning, while insightful, lacked the symbolic clarity and mathematical rigour of modern probability theory. Readers consulting the original manuscript will notice an ambiguous and sometimes inconsistent symbolic system, quite unlike the formal structures we use nowadays.

The formalization of probability as a mathematical discipline did not occur until the 17th century, most notably through the seminal correspondence between Blaise Pascal and Pierre de Fermat. Their work, motivated by problems such as finding a fair division of stakes in interrupted games of chance, introduced foundational concepts such as combinatorics, expected values, and variance [10]. These developments paved the way for later contributions by Christiaan Huygens, who in 1657 wrote the first published textbook on probability *"De Ratiociniis in Ludo Aleae"* [16], and Jacob Bernoulli, whose 1713 *"Ars Conjectandi"* remains among the most influential early texts in the field. Their works, along with many others, collectively laid the groundwork for the probabilistic and statistical methods that foreshadow modern scientific reasoning [3, 15].

It is from the 19th century onwards, that probability theory began to intertwine with statistics and inference, building the modern mathematical frameworks that we use nowadays to analyze and model physical phenomena. Florence Nightingale, best known for her pioneering role in modern nursing, made significant contributions to statistical methodology and graphical representation of data. Her advocacy for statistical reasoning in public health policy helped popularize quantitative approaches to uncertainty and variation. Around the same period, Joseph Fourier's work on heat conduction introduced Fourier series and integral transforms, tools that would later become indispensable for studying random processes, including the analysis of signals, noise, and diffusion phenomena. Although Nightingale and Fourier approached problems of uncertainty from very different perspectives—one through empirical data on human wellbeing, the other through mathematical physics—their contributions expanded the reach of probabilistic thinking and prepared the ground for future developments in stochastic analysis. [...]

A further conceptual leap, worth mentioning, occurred in the early 20th century with the work of Andrey Markov. Motivated partly by a desire to extend the law of large numbers beyond the assumption of independent trials, Markov developed what are now known as Markov chains, thereby inaugurating the study of dependence structures in stochastic processes. His investigations demonstrated that long-run statistical regularities could emerge even when successive events were not independent, a discovery that profoundly influenced both theoretical probability and its applications in fields as diverse as statistical mechanics, linguistics, quantum mechanics, and modern machine learning. We shall cover some basic notations of Markovian probability in Chapter 7 [...]

The modern axiomatic formulation of probability was introduced in the early 20th century by the Russian mathematician Andrey Kolmogorov. In his 1933 monograph *"Grundbegriffe der Wahrscheinlichkeitsrechnung"* (*"Foundations of the Theory of Probability"*) [18], Kolmogorov synthesized classical and frequentist ideas into a rigorous mathematical framework based on measure theory. His axioms remain the standard foundation for probability theory to this day. It may seem surprising that a concept with such ancient origins was not formally axiomatized until relatively recent times, and we will return to Kolmogorov's formulation and its implications in greater detail in Chapter 5. Nevertheless, philosophical discussions about the interpretation of probability and its relation to the physical sciences—especially in the context of determinism, epistemology, and modern topics such as quantum mechanics—predate Kolmogorov's formulation and continue to evolve to this day.

Chapter 1

Descriptive statistics

Statistics is the grammar of science.

— Karl Pearson

As a first approach to probability and statistics, we should properly define both topics and their main fields of study. Even deeply related, and both rooted in *combinatorics*—the study of uncertainty and things that change—they constitute well differentiated fields of mathematical analysis. A clear distinction often made is that probability is a *predictive* branch of mathematics, dealing with random events, also referred to as *stochastic*, aiming to compute expected values for such unknown outcomes. On the other hand, statistics would be a *descriptive* way of dealing with uncertainty, by sampling finite sets of observations from a given population, and building informative quantities, called statistical *estimators* to explore central tendency and variation. Such distinction has been extensively debated and discussed by mathematicians, experimental scientists, and philosophers of science.

As a rule of thumb, probability provides a formal language for modelling uncertainty, whereas statistics concerns the epistemic problem of learning from data. Through this chapter we will introduce basic ideas on statistical inference such as population, sampling, and estimators of central tendency and variation, together with some notions of representation and visualization. The foundations of probability theory, rooted in the works of Bernoulli, Laplace, and Gauss, among others, will be covered in Chapter 2. Hence, a philosophical position often adopted is that statistics is essentially the study of uncertainty, and that the statistician's role is to assist other fields who encounter uncertainty in their work. In practice, there is a restriction in that statistics is ordinarily associated with data; and it is the link between the uncertainty, or variability, in the data and that in the topic itself that has occupied statisticians. Statistics does not have a monopoly of studies of uncertainty. Probability discusses how randomness in one part of a system affects other parts.

As a note, let us emphasize how these two approaches can and do coexist in science. We have many times heard that science works by making hypothesis and then predictions, that are compared and benchmarked with an experiment. This is a simplification, and it is not always true. Some sciences, like Newtonian mechanics, most of physics, chemistry, and certainly parts of biology, do rely on building accurate models and predictions, that are later compared with an experimental result. A clear example would be to use Newtonian mechanics as our theory, or model, to compute a prediction on where and when would a stone fall if I throw it. Then the experiment would be simply to measure, when and where. On the other hand, the archetypical example of an inference problem, which does not aim to build a prediction, but to give—or *reconstruct* or *infer*—an explanation given a set of observations, would be Darwinian evolution. This distinction is worth mentioning, since the usual definitions of sciences tend to rely heavily on the predictive power, which can be inaccurate and misleading [...]. Different

sciences may strongly differ on methods, instrumentation, or conceptual tools, but they are all equally legitimate, regardless of how they are defined.

1.1 Sampling and data types

A large part of history of science could be summarized as a continuous effort to translate observations of reality into precise, mathematical terms. To such endeavour, of describing the vast phenomena we find in the natural world with numerical language, it is necessary to develop tools that relate the one or more relevant quantities—sometimes called *variables*—and how they relate or change depending on one another. The purpose of modelling might be, for instance, to determine the distance from the earth to the sun, estimate the number of stars in the observable universe, or relate the number of lung cancer patients to pollution levels around smoking areas.

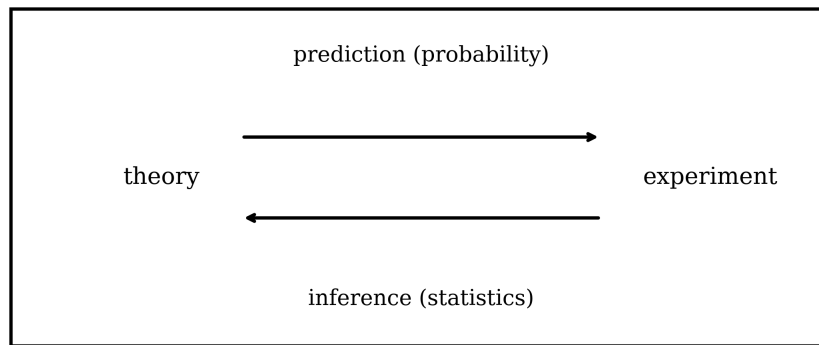


Figure 1.1: Representation of the predictive (from theory, or model, to experimental verification) and inferential (from data, measurement, observation to underlying truth) approaches to natural phenomena. As an example of the predictive branch of mathematics dealing with uncertainty we would find the theory of probability, while the descriptive way of addressing the same problem is normally regarded as statistical inference.

In the same way mathematics as a whole has been summarized as three simple tasks—*count*, *measure*, and *sort*—we could group statistical problems in three main groups. The problem of *sampling*—selecting a finite group of observations from a larger, unknown population—the *estimation*—build some mathematical quantity that represents how the measurements of my sample are distributed, and finally *visualization*—how my observations look like, and how that changes if I represent them in one way or another. Again, all of these problems are related to the phenomenon of *uncertainty*, or *variation* among measurements.

Hence, all statistical inquiries begin with observations and measurements, which we normally refer to as *data*. And data begins with the act of selection, or *sampling*. The natural world overflows with phenomena, offering endless opportunities for observation, but only a finite subset can ever be recorded. This distinction gives rise to two central notions: the *population*, which we denote by \mathcal{P} , represents the complete set of all possible observations under study. We will write it as

$$\mathcal{P} = \{x_1, x_2, \dots, x_N\}. \quad (1.1)$$

The *sample* \mathcal{S} , on the other hand, is the finite subset actually collected. For a series of N observations x_1, x_2, \dots, x_N , a sample of just n elements—less than the total, which is denoted by the upper case N —is defined as

$$\mathcal{S} = \{x_1, x_2, \dots, x_n\}, \quad n < N, \quad (1.2)$$

where the elements the sample x_i consist of just a selected group of observations from the population, not necessarily consecutive or in the same order. The population represents the

ideal object of inference, while the sample is the concrete, finite evidence available to us. As an example, if I want to study some disease and its relation smokers in a given country, I will never have access to the *complete population*, but only the amount of them that I am able to question, measure, or survey. This distinction is far from trivial. A poorly chosen sample often misrepresents the population and may induce bias, whereas a carefully constructed one mirrors its essential features, and can be used to describe the underlying nature.

Equally important is the recognition that not all data is equal, neither behaves in the same way. A common distinction is to consider *categorical* and *numerical* data. Categorical—or *qualitative*—data describes qualities or labels such as the eye colour of students in a classroom (blue, brown, green), the brand of a purchased smartphone, etc. Sometimes they are further divided into *nominal* categories, with no natural order, like the eye colour or the smartphone brand, and *ordinal* categories with a meaningful order. Examples of these would be the finishing places in a race (first, second, third), survey responses ranging from *strongly disagree* to *strongly agree*, etc.

The other big family is normally referred to as numerical—or *quantitative*—data. It represents numerical quantities and is often subdivided into *discrete*, countable numbers, such as the number of books on a shelf (4, 5, 6) or the number of goals scored in a match, and *continuous* values that can take any number within a range, such as the time a sprinter takes to run 100 meters, or the height of a person measured with some arbitrary precision.

Distinguishing between these types is no mere slang; different types of observations require different mathematical tools, and will be described in different ways. For example, it would not make sense to compute a mean out of smartphone brands, but to compute the mean of their prices is informative. Similarly, the distribution of finishing places after a race might be summarized by a median position, whereas heights of athletes could be studied with averages and measures of spread. A correct classification of data is thus a safeguard against misuse and a guide toward insight.

As a summary, sampling and proper description of data establish the ground upon which statistics is built. Before calculating, summarizing, or diving into inference, one must ensure that the information collected is both *representative and properly understood*. Without these foundations, descriptive measures risk floating unmoored, detached from the reality they claim to represent. Accurate sampling and rigorous description will lead to a faithful representation of the phenomena under study and their relationships, detecting anomalies, and even building accurate predictions.

Let's end this section with a historical note. As we have mentioned, uncertainty has been associated with games of chance and gambling from quite old times, but it was not addressed as a statistics problem until much later. The Royal Statistical Society, founded in 1834, together with many other statistical groups, was originally set up to just gather and publish data, as an attempt to reduce such uncertainty. It did not take long before statisticians wondered how the data might best be used and modern *statistical inference* was born. Charles Babbage, Adolphe Quetelet [...]. Among its famous members was Florence Nightingale, the society's first female member in 1858, whose work was shaped by this same intellectual climate. [...] Other notable RSS presidents have included William Beveridge, Ronald Fisher, which we will discuss in Chapter 4.

Andrew Lang's famous quote "*most people use statistics as a drunken man uses lamp-posts—for support rather than illumination*", highlights the tendency to use statistics as a crutch, relying on them for validation rather than seeking genuine understanding. Lang's observation serves as a cautionary reminder to approach statistical data with critical thinking and not merely as a tool to bolster preconceived notions.

1.2 Central tendency and variation

Once we have a clear distinction between the population under study and the selected sample, we face a problem. Neither the population—referred as the *true*—mean value, sometimes written as μ , nor its variance—referred as the *true* variance, and written as σ^2 are available to us. As we just saw, the *only thing we have is the finite set of observations in our sample*, hence we could try to build some "informative quantities" out of our data that would give us a hint of the central value, a measure of spread, etc. Such quantities are called *statistical estimators*. Common examples of such estimators are the *sample mean*, the *median*, and the *variance*, among others.

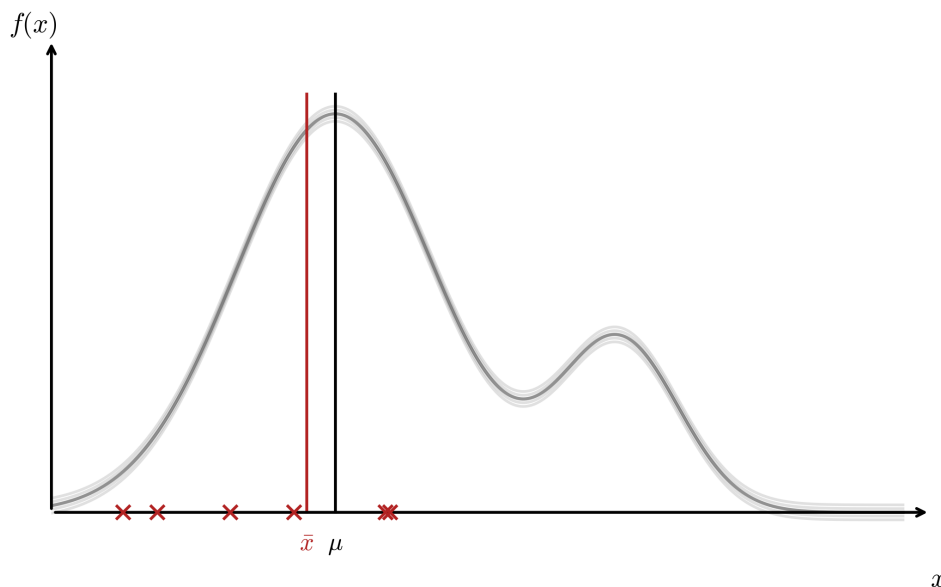


Figure 1.2: Representation of the *true* population mean μ , in black, and the observed *sample* mean \bar{x} . The true mean is an ideal and unaccessible quantity, while the sample mean can be computed as an estimator of the finite sample.

Once observations have been collected, a natural question arises: what is the *center*, or *typical* value of this data set? Mathematical quantities that measure the central tendency will be useful to summarize our data with a single representative number, providing an immediate sense of location within the distribution.

The *sample mean*, or *average* is perhaps the most familiar measure of central tendency. Imagine we are doing an experiment where we measure some variable, and let's call it x for simplicity. x can be anything we could measure, like position at a given time, energy of some system, concentration of a specific substance, etc. Let's imagine we repeat the measurement n times, and we obtain the values x_1, x_2, \dots, x_n . That will be our set of observations—our *sample*— \mathcal{S} . We could simply write it as a list—or a *vector*—in the following way:

$$\mathcal{S} = \{x_1, x_2, \dots, x_n\}.$$

Keep in mind that from the mathematics perspective the word *vector* has a slightly different meaning, with subtleties related to algebraic operations and relations they should satisfy, but for the purpose of this course, where we prioritize above all simplicity, a vector and a list of numbers will be essentially the same thing.

We can define the sample mean of an arbitrary large sample of n observations, as the sum of all elements divided by the total. We will write it as \bar{x} , and define it as follows:

$$\bar{x} = \frac{1}{n}(x_1 + x_2 + \dots + x_n). \quad (1.3)$$

We can write this in a slightly more compact way as a *summation*, as follows:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i . \quad (1.4)$$

Here we denote the sum of all elements x_i with the greek letter \sum , starting with the first one (x_1 , for $i = 1$) and until the last one (x_n , for $i = n$). The expressions (1.3) and (1.4) mean *exactly* the same thing, just written in different ways.

Let's illustrate with an example. Suppose we repeat a measurement three times, obtaining the results $x_1 = 1$, $x_2 = 2$, and $x_3 = 3$. Our sample is then $\mathcal{S} = \{1, 2, 3\}$, and the sample mean is

$$\bar{x} = \frac{1}{3} \sum_{i=1}^3 x_i = \frac{1}{3}(1 + 2 + 3) = 2 .$$

As a warm-up exercise, try computing the same mean value for a second sample, let's say $\mathcal{S} = \{4, 5, 6\}$. Substituting into the general expression (1.4) gives

$$\bar{x} = \frac{1}{3} \sum_{i=1}^3 x_i = \frac{1}{3}(4 + 5 + 6) = 5 .$$

As we see, the sample mean captures information about the "central" value, where most events cluster. Although useful, it is sensitive to extreme values—often called *outliers*—which motivates the definition additional, more robust measures of central tendency.

The *median* represents similar information, as the value that splits the ordered data set in half. For an ordered sample $x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(n)}$, the median M is defined as

$$M = \begin{cases} x_{(k+1)} , & \text{if } n = 2k + 1 \text{ (odd) ,} \\ \frac{x_{(k)} + x_{(k+1)}}{2} , & \text{if } n = 2k \text{ (even) .} \end{cases} \quad (1.5)$$

Note that here k is just an integer that helps locate the middle position of an ordered data set of size n . If the sample size n is even, we write $n = 2k$, while for n odd, we write $n = 2k + 1$. In the case of an odd-sized sample, the median is just the middle-point, while for an even size, it is computed as the average of the two middle points.

The mathematical definition (1.5) may seem a bit unnatural at first, so let's navigate it with a couple of examples. Consider the sample $\mathcal{S} = \{1, 2, 3, 5, 3, 2, 7\}$. First, we order the data:

$$\mathcal{S}_{\text{ordered}} = \{1, 2, 2, 3, 3, 5, 7\} .$$

Since the sample has an odd number of elements ($n = 7$), the median is just the middle value:

$$M = x_{(4)} = 3 .$$

Now consider an even-sized sample $\mathcal{S} = \{1, 2, 3, 5, 4, 3, 2, 7\}$. Ordering the data gives

$$\mathcal{S}_{\text{ordered}} = \{1, 2, 2, 3, 3, 4, 5, 7\} .$$

Which has now an even number of elements ($n = 8$). Hence, applying such case in (1.5), the median is the average of the two middle values

$$M = \frac{x_{(4)} + x_{(5)}}{2} = \frac{3 + 3}{2} = 3 .$$

Unlike the mean, the median is robust to outliers and skewed data, capturing the central position of the dataset even with repeated values. To illustrate that, let's have a look at the following sample $\mathcal{S} = \{1, 2, 3, 3, 4, 4, 200\}$, which contains the value 200 as a huge outlier. The sample mean would be

$$\bar{x} = \frac{1}{7}(1 + 2 + 3 + 3 + 4 + 4 + 200) = \frac{217}{7} = 31 .$$

While the median, given a size $n = 7$ would just be the middle (4th) value

$$M = 3 .$$

For instance, the data represented in LHS of Figure [...] will be accurately described by computing the mean, given its symmetric behaviour, while the one in the RHS will be better addressed with a median, accounting for the skewness and the presence of outliers.

A straightforward measure often used is the *mode*, the value—or values—that appear most frequently in the observation set. For the first sample $\mathcal{S} = \{1, 2, 3, 5, 3, 2, 7\}$ we just count the frequency of each value, and conclude that since both 2 and 3 occur most frequently, the dataset is *bimodal*, with modes 2 and 3. In the case of categorical data, such as eye colour or smartphone brands, the mode corresponds to the most common category.

Beyond central location, it is important to understand the *spread* of the data. We can define the *sample variance* s^2 of a set as a quantity that captures how far are the elements from the mean value,

$$s^2 = \frac{1}{n-1} \sum_{i=1}^N (x_i - \bar{x})^2 , . \quad (1.6)$$

The $n-1$ in the denominator of (1.6) is called the Bessel correction factor, which ensures that only out of at least $n = 2$ elements we can compute a finite variance. A more technical explanation is that it ensures that s^2 is an *unbiased estimator*, which we will discuss in Chapter 3

Note that the variance is just a sum of differences, and squared just so that we obtain a positive value. It is a measure starting with the first element (x_1 , for $i = 1$) and until the last one (x_N , for $i = N$), of how far is each element from the mean value. If all elements in our sample are very close to the mean, then the sum of differences will be a small number, and we would get a variance s^2 close to zero. Meanwhile, if the elements are very different, we would obtain a larger variance.

Again, let's illustrate with an example. If we compute the variance of our very first example set $\mathcal{S} = \{1, 2, 3\}$, which has just $n = 3$ observations, we get

$$s^2 = \frac{1}{3-1} \sum_{i=1}^3 (x_i - \bar{x})^2 = \frac{1}{2}((1-2)^2 + (2-2)^2 + (3-2)^2) = \frac{1}{2}(1 + 0 + 1) = 1 ,$$

which we could interpret as, on average, the elements of the list being *one unit* away from the mean.

As a warm up exercise, try to compute the variance for a second sample, let's say $\mathcal{S} = \{4, 5, 6\}$. By substituting in the general expression (1.6) you should get the result

$$s^2 = \frac{1}{3-1} \sum_{i=1}^3 (x_i - \bar{x})^2 = \frac{1}{2}((4-5)^2 + (5-5)^2 + (6-5)^2) = \frac{1}{2}(1 + 0 + 1) = 1 .$$

We obtain again a variance $s^2 = 1$, indicating as in the previous example, that the elements of this sample \mathcal{S} are also *one unit* away from the mean.

Another useful quantity used to characterize variability is the so called *standard deviation*, which is just the square root of the variance,

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (1.7)$$

At a glance, variance and standard deviation quantify how much the elements of a dataset deviate from the mean, capturing the notion of *spread*.

Finally, *quantiles* divide the ordered data into equal proportions. The p -th quantile Q_p is the value below which a fraction p of the data lies. Special cases include the *first quartile* (Q_1 , 25th percentile), the *median* (Q_2 , 50th percentile), and the *third quartile* (Q_3 , 75th percentile). A rigorous definition of quantiles requires the idea of distribution and cumulative probability, so we will discuss them in next chapter. As a note, for a continuous cumulative distribution function (CDF) F , the p -th quantile satisfies

$$Q_p = \inf\{x : F(x) \geq p\}. \quad (1.8)$$

In summary, mean, median, mode, variance, standard deviation, and quantiles provide a rich, complementary view of the dataset's central tendency and variability, allowing for both numerical and graphical summaries that capture the essence of the data.

Variation is not merely a technicality; it is the very essence of uncertainty. Without spread, probability would be trivial, for every outcome would be the same. It is in the differences among observations that statistical inquiry finds its substance. Hence, central tendency and variation together provide the complementary lenses through which data becomes intelligible. They allow us to say whether two groups are alike or unlike, whether a new result is ordinary or surprising, whether the observed variation is too great to be dismissed as chance. In this sense, descriptive statistics foreshadows the inferential methods to come, hinting at deeper laws beneath the numbers.

1.3 Data visualization

While numerical summaries are useful, the human mind often understands patterns much faster through vision than calculation. By *data visualization* we mean a series of techniques used to transform numbers and sequences into shapes, colours and structures that are easier to interpret, and that can be grasped at a glance. It turns abstraction into perception and often reveals regularities invisible to formulas alone. Nowadays, a broad series of fields falling under the name of data visualization - or data *representation* - have become among the pillars of any scientific or data related topic.

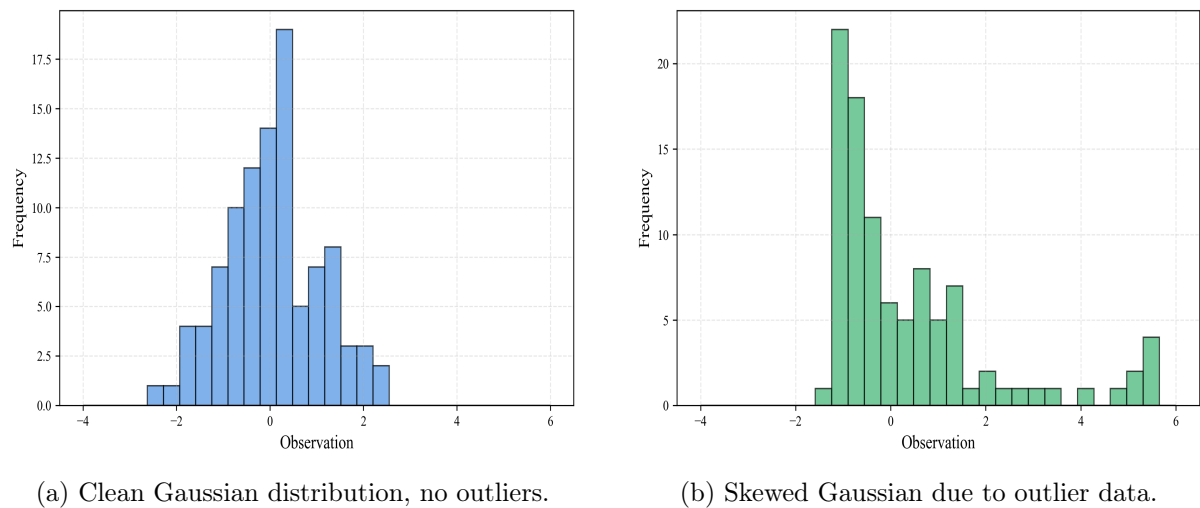


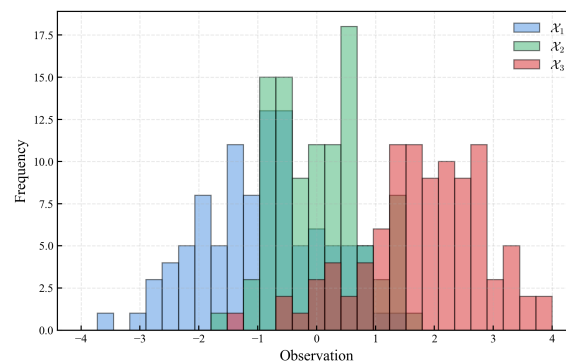
Figure 1.3: Box plots representing $n = 100$ observations drawn from a Gaussian distribution. The central black line shows the mean value, representing the central tendency where the bulk of events lie. The shadowed area highlights the standard deviation, as measure of the variability and spread the observations with respect to the mean

Exercises

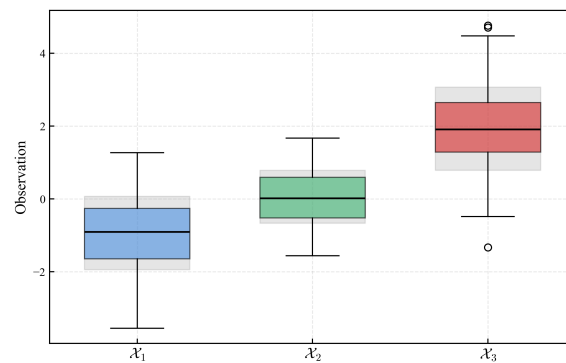
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Solutions

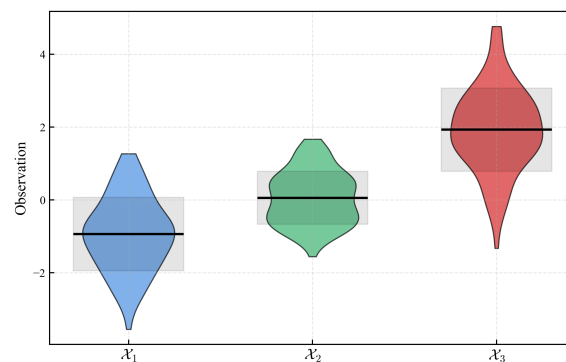
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(a) Three sets of observations, with the mean value and standard deviation represented as a histogram-based plot [...].



(b) Three sets of observations, with the mean value and standard deviation represented as a box plot [...].



(c) Three sets of observations, with the mean value and standard deviation represented as a violin plot [...].

Figure 1.4: Comparison of three visualization methods—histogram, box plot, and violin plot—showing the mean and variability of three samples of size $n = 100$.

Chapter 2

Foundations of Probability

It is through the calculation of probabilities that the divine order becomes visible.

— Jacob Bernoulli

The study of probability, though having very ancient roots, began its modern development in the seventeenth century through the famous correspondence between Blaise Pascal and Pierre de Fermat. Their discussion on games of chance, and in particular the “problem of the division of stakes,” laid the groundwork for the systematic analysis of uncertain events. Years later, Jacob Bernoulli’s *Ars Conjectandi* established the first classical definition of probability, providing the study of random events with mathematical clarity. Refinements by De Moivre and Laplace transformed it into a powerful analytical theory, while its true axiomatic structure only crystallised in the twentieth century with Kolmogorov’s *Grundbegriffe der Wahrscheinlichkeitsrechnung* in 1933 [18].

The mathematical formalization of decision-making is actually quite a recent development. It is usually attributed to British mathematician Frank P. Ramsey (1903–1930), who in his 1926 paper *Truth and Probability* [25] introduced a formal, subjective interpretation of probability, laying the groundwork for what later became expected utility theory in decision-making under uncertainty. In short, Ramsey formalized how rational agents should assign probabilities and make decisions based on personal beliefs and preferences. All starting from the apparently-simple question ‘*how should we make decisions in the face of uncertainty?*’. to the twentieth-century developments of Pearson, Fisher, and Neyman addressed the latter rather than establishing the former distinction.

At its heart, probability is nothing more - and nothing less - a branch of mathematics developed to describe random events, also referred to as *stochastic*. Indeed, the word “stochastic” comes from the Greek word *στοχαστικός*, which literally means “to guess” or “to aim.” The way we describe such events, characterized by the uncertainty of their outcome, is by defining a quantity we will call \mathbb{P} , of probability. That quantity \mathbb{P} will denote a number between 0 and 1, which reflects the degree of uncertainty, or *surprise*, with which the random event produces a specific outcome. For an event A , such as observing a heads when tossing a coin, or a given face when rolling dice, the numerical convention is written as follows,

2.1 What is probability?

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quantity we will call \mathbb{P} , of probability. That quantity \mathbb{P} will denote a number between 0 and 1, which reflects the degree of uncertainty, or *surprise*, with which the random event produces a specific outcome. For an event A , such as observing a heads when tossing a coin, or a given face when rolling dice, the numerical convention is written as follows,

- If I am sure A will never occur, $\mathbb{P}(A) = 0$.
- If I am sure A will always occur, $\mathbb{P}(A) = 1$.
- For anything in between, if A is *uncertain*, then $\mathbb{P}(A) \in (0, 1)$,

where the \in symbol just means "belongs to". Thus, probability measures the whole span between impossibility and absolute certainty.

2.2 Discrete events

By *discrete* we mean that the number of possible outcomes is a finite or countable number [...]. In such cases, distributions will exactly represent a probability, and they are referred to as *mass* distributions [...]

2.2.1 Bernoulli trials

2.2.2 Binomial distribution

2.2.3 Poisson distribution

2.2.4 Discrete uniform distribution

2.3 Continuous events

By *continuous* we mean that the number of possible outcomes is an infinite, uncountable number, in a continuous range [...]. In such cases, we will need to build a new mathematical object, referred as a probability *density* [...]

2.3.1 Gaussian distribution

2.3.2 Exponential distribution

2.3.3 Continuous uniform distribution

2.4 Expected values

Chapter 3

Estimation, prediction and inference

Numbers have an important story to tell, if given a voice.

— Florence Nightingale

Let's revisit again the difference between prediction and inference, as is through estimation that both, probability and inference become part of a two-folded problem.

3.1 Prediction vs inference

3.2 The Law of Large Numbers

3.3 The Central Limit Theorem

3.4 Application to Generalized Linear Models

Exercises

1. Exercise [...].
2. Exercise [...].
3. Exercise [...].

Solutions

1. Solution [...].
2. Solution [...].
3. Solution [...].

Chapter 4

Introduction to hypothesis testing

The object of statistical science is the reduction of data to relevant information.

— Ronald A. Fisher

The term *hypothesis testing* lies on top of the two pillars we have mentioned in previous chapters. On the one hand, we will use probability theory to predict expected values about the true population parameters, assuming certain distributions, etc. Then, applying the tools of descriptive statistics we discussed in Chapter 1 and Chapter 3, we will compute estimators that reliably represent our samples, quantifying their central tendency and variations. Out of these, we will define a new type of *informative quantity* normally referred to as *statistic*, or *statistic test*, that quantifies how much our expectation match—or differ from—our data, obtained through measure and observation. Finally, following the so-called modern approach, or Pearson-Neyman, we will learn how to compute significance through the computation of the Pearson value—or P-value, for short.

Fisher (1922, 1925) connected least squares, likelihood, and sampling distributions, establishing the foundations of modern inference. Neyman (1937) formalized confidence intervals as frequentist procedures, contributing to philosophical debates on inference that continue today.

4.1 Prediction vs inference revisited

Here we shall review, one last time, the main difference between predictive—or modelling—statements, and inferential—also referred to as reconstructive. When formulating hypothesis about natural phenomena, there is normally a bit of both. The very idea of *hypothesis* in the modern sense is a recent one [...] and it is normally explained in terms of a mathematical prediction. If I believe in Newtonian mechanics, a hypothesis could be to write down Newton's second law and use it to predict where and when a stone would fall when dropped from a certain height. If my hypothesis is that a gene has a certain impact in a known disease, or in response to stress, . Or, if I am studying the relation between smokers in the UK and their probability to develop lung cancer [...]. In any of these cases, upon hypothesis, I would need samples, or groups, of measurements, normally referred to simply as *data*.

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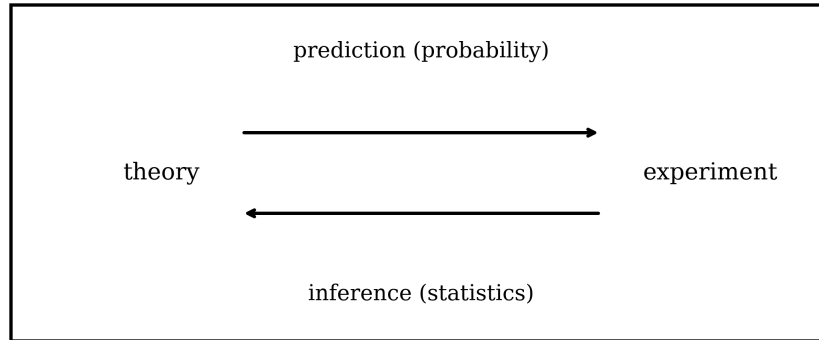


Figure 4.1: Representation of the predictive (from theory, or model, to experimental verification) and inferential (from data, measurement, observation to underlying truth) approaches to natural phenomena. As an example of the predictive branch of mathematics dealing with uncertainty we would find the theory of probability, while the descriptive way of addressing the same problem is normally regarded as statistical inference.

4.2 General approach to hypothesis testing

When dealing with hypothesis, predictions, experiments and data, there is plenty of approaches and formulations, as many as instruments, scales and fields of study. These do change from one field to another, and they do change in time. Our very idea of hypothesis, prediction, measurement, and law [...]. Nowadays, when people refer to *hypothesis testing* they mean very specific approach, almost and algorithmic-wise set of rules, that is applied in general to inference and data science problems. We will define such approach as the "modern", or "general" approach to hypothesis testing, that assumes some basic notions of probability theory, distributions and randomness, with some of statistics, estimators and sample description [...]. The whole idea of statistic test, P-value and significance, that we will discuss now, ranges indeed from quite recent times, back to Pearson, Fisher, and Neyman in the early 1900s.

- Formulate hypothesis. Normally referred to as *null* hypothesis H_0 , as the expectation that our prediction or expectation will follow, and *alternative* hypothesis H_1 , representing the case of finding a surprising observation, that deviates from H_0 . These hypothesis will *always* be made about the *true population parameters*, and commonly formulated as the computation of an expected value, that we discussed in Chapter 2.
- Experiment, measurement, observation. Any process, regardless of instrumentation and object of study, that involves a measurement, an observation, or data collection of any kind from one or more samples.
- Compute statistic, or statistic test. Out of our random data we can compute any *informative quantity*, which can be an estimator like the sample mean, the variance, etc, or a more abstract quantity that represents how close are these mean and variance from their expected values, given H_0
- Compute P-value: the probability that, given a certain assumption for our true population parameters and our random data, we obtained a value at least as extreme as the one we got for our statistic.

- interpretation of the result, normally accept / reject the null hypothesis based on the P-value and some significance threshold.

A couple of notes about this general roadmap. A statistic can be just an estimator, like the sample mean [...]. Fisher's definition of P-value as extrem [...]. The approach is a mixed of Fisher and Pearson-Neyman [...].

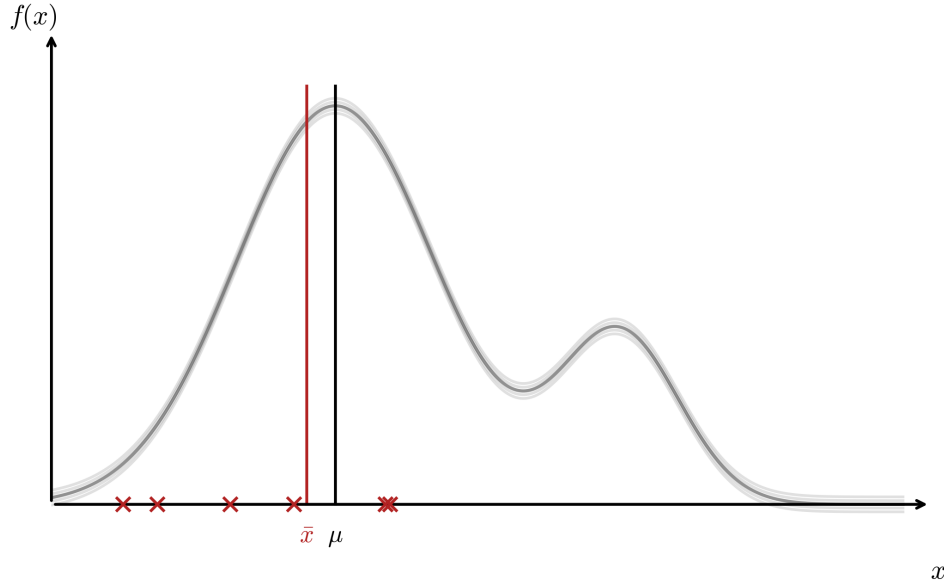


Figure 4.2: Representation of the *true* population mean μ , in black, and the observed *sample* mean \bar{x} . The true mean is an ideal and unaccessible quantity, while the sample mean can be computed as an estimator of the finite sample.

4.3 Statistical tests: some examples

4.3.1 Compare sample mean with hypothesized value - One sample t-test

The *t*-test is arguably the simplest example of statistic test we will discuss. It was introduced by W.S. Gosset, a statistician working at the Guinness factory in Dublin, trying to accurately describe error of the mean when the population variance is unknown, as part of the brewing process. Due to his affiliation to the Guinness company we have not allowed to share his work and hence we submitted to the *Biometrika* statistics journal under the pseudonym *Student*. This is why it remains nowadays known as the Student's *t*-test.

We start by formulating some hypothesis about the true population parameters, *prior to collect data from any sample*. It is important here to stop and think carefully about *what is the physical quantity that we are eventually going to measure*. Normally, the null hypothesis is simply written as "the true population mean is given by μ ". Remember that such quantity can be computed as an expected value of a random variable.

$$\mu = \mathbb{E}[x] = \frac{1}{N} \sum_{i=1}^{\infty} x_i \mathbb{P}(x_i) \quad (4.1)$$

If x is a discrete random variable, or

$$\mu = \mathbb{E}[x] = \int_{-\infty}^{\infty} x_i * f(x) dx \quad (4.2)$$

if x is a continuous random variable.

We will now take a series of observations, or measurements, from a given sample $x = \{x_1, x_2, \dots, x_n\}$. Out of them, we can compute the sample mean \bar{x} , as an estimator of the true population mean.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{\infty} x_i \quad (4.3)$$

and the observed sample variance

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{\infty} (x_i - \bar{x})^2} \quad (4.4)$$

Now, given these two elements, the expected true mean μ and the observed sample mean \bar{x} and standard deviation S ,

$$T = \frac{\bar{X} - \mu_0}{S/\sqrt{n}}, \quad T \sim t_{\nu}, \quad \nu = n - 1 \quad \text{under } H_0 : \mu = \mu_0.$$

p-values.

$$\text{One-sided: } p = \mathbb{P}(T \geq t_{\text{obs}}) = \int_{t_{\text{obs}}}^{\infty} f_{t_{\nu}}(t) dt,$$

$$\text{Two-sided: } p = \mathbb{P}(|T| \geq |t_{\text{obs}}|) = 2 \int_{|t_{\text{obs}}|}^{\infty} f_{t_{\nu}}(t) dt.$$

Example. If $n = 10$, $\bar{X} = 5.2$, $S = 1.0$, $\mu_0 = 5$, then

$$t_{\text{obs}} = \frac{5.2 - 5}{1/\sqrt{10}} \approx 0.63,$$

with $\nu = 9$, giving a two-sided p-value $p \approx 0.54$. As $\nu \rightarrow \infty$, $t_{\nu} \rightarrow \mathcal{N}(0, 1)$.

4.3.2 Compare sample means of two independent groups - Two sample t-test

4.3.3 Compare variation on two groups - Fisher's exact test

Fisher's variance-ratio test and the F distribution. Fisher introduced the variance-ratio test in the 1920s in the context of ANOVA. For two independent normal samples,

$$F = \frac{S_1^2}{S_2^2}, \quad F \sim F_{\nu_1, \nu_2}, \quad \nu_1 = n_1 - 1, \quad \nu_2 = n_2 - 1,$$

under $H_0 : \sigma_1^2 = \sigma_2^2$.

p-values.

$$\text{One-sided: } p = \mathbb{P}(F \geq f_{\text{obs}}) = \int_{f_{\text{obs}}}^{\infty} f_{F_{\nu_1, \nu_2}}(f) df,$$

$$\text{Two-sided: } p = 2 \min \left\{ \int_0^{f_{\text{obs}}} f_{F_{\nu_1, \nu_2}}(f) df, \int_{f_{\text{obs}}}^{\infty} f_{F_{\nu_1, \nu_2}}(f) df \right\}.$$

Example. If $n_1 = n_2 = 10$, $S_1^2 = 4$, $S_2^2 = 2$, then

$$f_{\text{obs}} = 2, \quad \nu_1 = \nu_2 = 9,$$

yielding a one-sided p-value $p \approx 0.12$. As $\nu_1, \nu_2 \rightarrow \infty$, F_{ν_1, ν_2} concentrates at 1 and $\log F$ becomes approximately Gaussian.

4.3.4 Compare variation o multiple groups - Fisher's ANOVA

4.3.5 Compare distributions and testing for normality - χ^2 test

Pearson's χ^2 test and the chi-square distribution. Pearson's χ^2 test (1900) assesses agreement between observed and expected frequencies. With observed counts O_i and expected counts E_i ,

$$X^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i}, \quad X^2 \sim \chi_\nu^2,$$

where $\nu = k - 1 - p$ and p is the number of estimated parameters.

p-values.

$$\text{One-sided (standard): } p = \mathbb{P}(X \geq x_{\text{obs}}) = \int_{x_{\text{obs}}}^{\infty} f_{\chi_\nu^2}(x) dx,$$

$$\text{Two-sided: } p = 2 \min \left\{ \int_0^{x_{\text{obs}}} f_{\chi_\nu^2}(x) dx, \int_{x_{\text{obs}}}^{\infty} f_{\chi_\nu^2}(x) dx \right\}.$$

Example. For $k = 4$ categories with $\nu = 3$ and observed statistic $x_{\text{obs}} = 6$, the right-tailed p-value is $p \approx 0.11$. As $\nu \rightarrow \infty$,

$$\frac{X^2 - \nu}{\sqrt{2\nu}} \xrightarrow{d} \mathcal{N}(0, 1),$$

so the chi-square becomes approximately Gaussian after centering and scaling.

4.4 Parametric and non-parametric tests

4.5 Error types in hypothesis testing

Modern hypothesis testing emerged in the early twentieth century as an attempt to formalize uncertainty, error, and decision making in empirical science. Three major approaches—Fisherian significance testing, Neyman–Pearson hypothesis testing, and Bayesian inference—address these issues in fundamentally different ways, while later philosophical analyses by Reichenbach and Popper clarified their distinct aims. Subsequent commentators such as Cox, Mayo, and Lehmann have emphasized both the strengths of each framework and the conceptual tensions created by their later amalgamation in textbook practice.

Ronald A. Fisher introduced significance tests in the 1920s as tools for assessing the *strength of evidence* against a null hypothesis [13, 14]. In Fisher's view, a null hypothesis H_0 is a reference model, and the p-value is defined as the probability, under H_0 , of observing data at least as extreme as those obtained. Small p-values indicate discordance between data and model, but Fisher rejected fixed decision thresholds and did not formalize Type II errors or power. Type I error appears implicitly as the tail probability under H_0 , not as a long-run operating characteristic. Hypothesis testing, for Fisher, is evidential rather than decisional: it informs scientific judgment but does not prescribe action.

Jerzy Neyman and Egon Pearson developed a sharply different framework in the 1930s, motivated by repeated decision making [22]. Here, hypotheses H_0 and H_1 are competing models, and tests are designed to control error rates in the long run. Type I error (α) and Type II error (β) are central primitives, and optimal tests maximize power subject to a fixed α . P-values play no essential role; instead, decisions are based on pre-specified critical regions. This approach interprets hypothesis testing as a rule for action under uncertainty rather than as a measure of evidential support.

Bayesian inference, originating in Bayes's posthumous essay [2] and developed by Laplace and later subjectivists such as de Finetti [8], rejects Type I and Type II errors as fundamental

concepts. Probability is interpreted as rational degree of belief, and hypotheses themselves are assigned probabilities. Inference proceeds by updating prior beliefs via Bayes' theorem to obtain posterior probabilities or Bayes factors. Hypothesis testing becomes model comparison, and decisions—if required—are made by minimizing expected loss. The Bayesian framework thus dissolves the classical error dichotomy by reframing uncertainty epistemically rather than behaviorally.

Hans Reichenbach provided the clearest philosophical articulation of the frequentist stance underlying Neyman–Pearson theory [26]. He distinguished *prediction*—statements about long-run frequencies—from *inference*—claims about truth or belief. Statistical tests, on this view, justify actions and predictions through their error properties, not through probabilistic assertions about hypotheses. This position sharply contrasts with Bayesian epistemology and clarifies why frequentist testing can function without assigning probabilities to hypotheses.

Karl Popper rejected probabilistic confirmation altogether, arguing that science advances through bold conjectures and severe attempts at falsification [24]. Statistical tests, in his view, contribute by formulating risky predictions whose failure can refute theories, not by accumulating evidence or controlling long-run errors. Popper's philosophy is incompatible with Bayesian confirmation and only partially aligned with frequentist testing, insofar as both emphasize error and refutation rather than belief.

Erich Lehmann, in his definitive treatment of hypothesis testing [19], emphasized the formal coherence and optimality of Neyman–Pearson theory while explicitly distinguishing it from Fisher's evidential approach. D. R. Cox later argued that the routine combination of p-values with fixed significance thresholds conflates logically distinct inferential goals [6]. Deborah Mayo further developed an error-statistical philosophy in which evidential interpretation is grounded in the severity with which hypotheses are tested [20, 21]. Together, these authors converge on a common diagnosis: the modern textbook procedure of hypothesis testing is a pragmatic but conceptually hybrid construct, blending incompatible foundations.

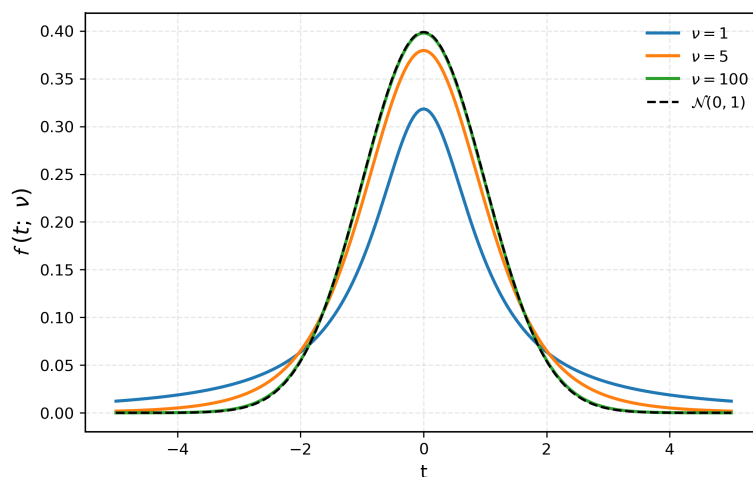
The coexistence of Fisherian evidence, Neyman–Pearson decision rules, Bayesian belief updating, Popperian falsification, and Reichenbach's predictive frequentism reflects not confusion but plurality. Each framework answers a different question—about evidence, action, belief, or prediction—and Type I and Type II errors acquire meaning only within the Neyman–Pearson decision-theoretic context. Understanding these distinctions is essential for the principled use and interpretation of hypothesis tests in modern statistics.

Exercises

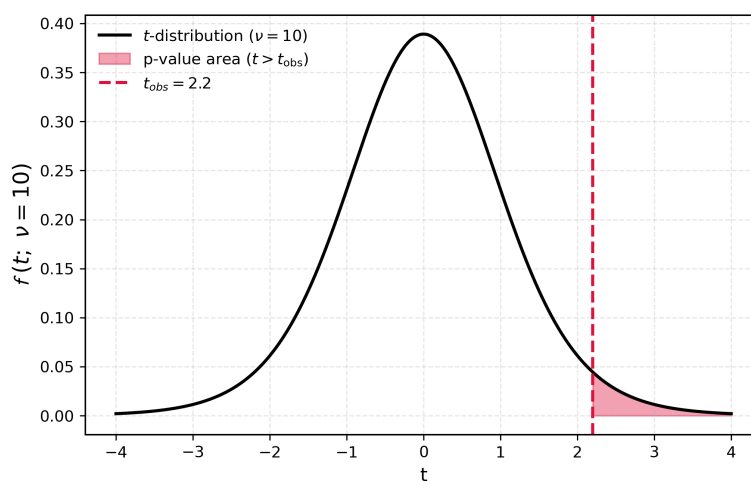
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Solutions

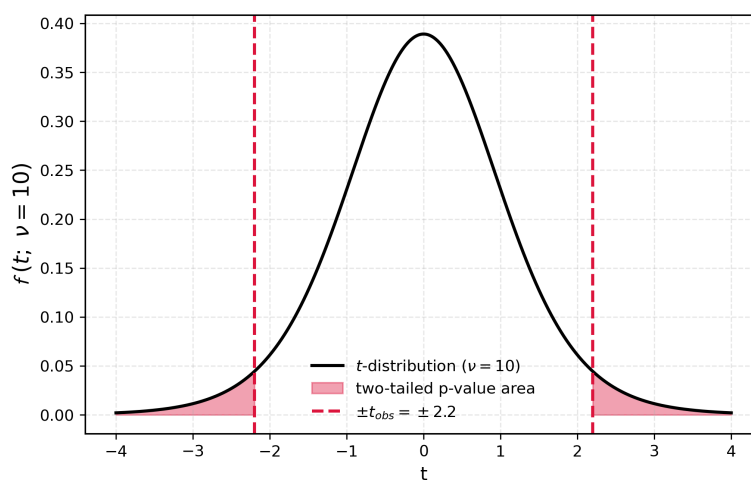
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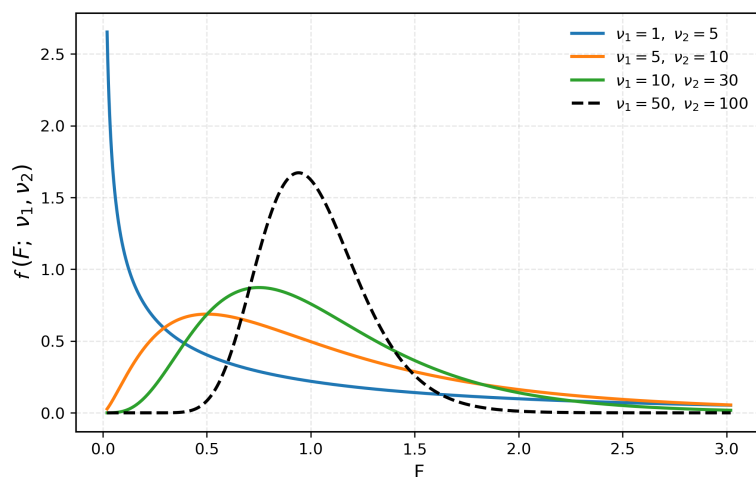
(a) The Student's t distribution of the t -statistic, given different values of the degrees of freedom ν .



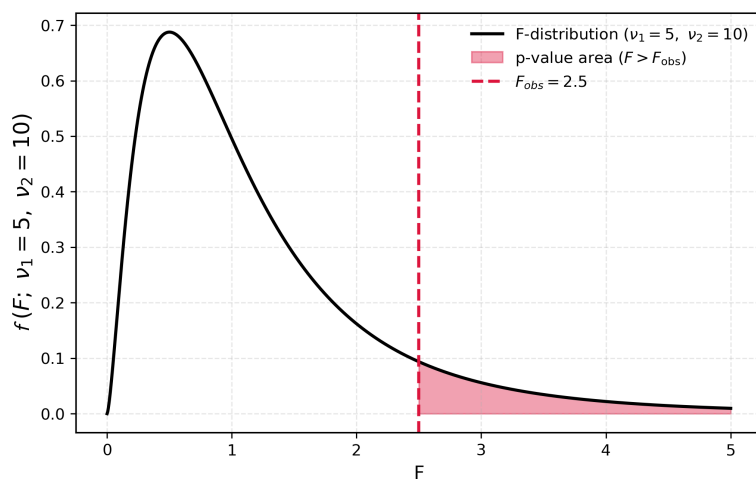
(b) Representation of the 1-sided P-value, computed as the integral of the right tail of the t distribution.



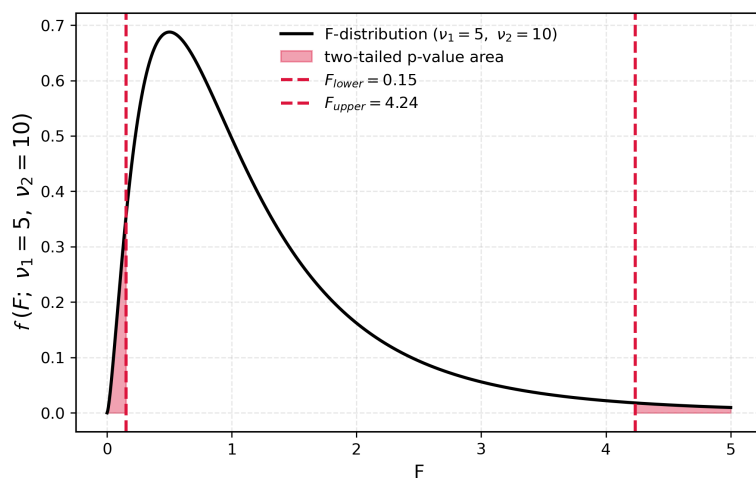
(c) Representation of the 2-sided P-value. Given the symmetry of the t -distribution, it can be obtained as double in size of the 1-sided integral.



(a) The Student's t distribution of the t -statistic, given different values of the degrees of freedom ν .



(b) Representation of the 1-sided P-value, computed as the integral of the right tail of the t distribution.



(c) Representation of the 2-sided P-value. Given the symmetry of the t -distribution, it can be obtained as double in size of the 1-sided integral.

Chapter 5

Modelling, dependency and correlation

The theory of probabilities is at bottom nothing but common sense reduced to calculation.

— Pierre-Simon Laplace

5.1 Introduction and Philosophy

Matrix-based linear modelling was systematized in the mid-20th century, notably in the work of C. R. Rao (1945, *Bulletin of the Calcutta Mathematical Society*), who developed the Cramér–Rao bound and unified estimation in linear models.

5.2 Estimation and Inference

Model estimation chooses parameter values that best describe the data; inference quantifies uncertainty around these estimates.

Mathematical Formulation

The ordinary least squares estimator is

$$\hat{\beta} = (X^\top X)^{-1} X^\top \mathbf{Y},$$

with residuals $\hat{\varepsilon} = \mathbf{Y} - X\hat{\beta}$. Under the normal-error model,

$$\hat{\beta} \sim \mathcal{N}(\beta, \sigma^2 (X^\top X)^{-1}).$$

Numerical Example

For

$$X = \begin{pmatrix} 1 & 1 \\ 1 & 2 \\ 1 & 3 \end{pmatrix}, \quad Y = \begin{pmatrix} 2 \\ 3 \\ 5 \end{pmatrix},$$

one obtains

$$\hat{\beta} = \begin{pmatrix} 0.333 \\ 1.5 \end{pmatrix},$$

so $\hat{Y} = 0.333 + 1.5X$.

Exercises

1. Exercise [...].
2. Exercise [...].
3. Exercise [...].

Solutions

1. Solution [...].
2. Solution [...].
3. Solution [...].

Chapter 6

Introduction to conditional probability

*Probability statements are just summaries of
repeated observations.*

— W. V. Quine

The topic of conditional—sometimes referred as *bayesian*—probability has its roots in one most fundamental principles know by human nature. That is, the idea that we all have bias, and that purely objective knowledge is beyond our reach.

6.1 Motivation and philosophy

6.2 Dependent and independent events

6.3 Some examples of conditional probability

Exercises

1. Exercise [...].
2. Exercise [...].
3. Exercise [...].

Solutions

1. Solution [...].
2. Solution [...].
3. Solution [...].

Chapter 7

Stochasticity and Markov Processes

The development of mathematics is a continuous process of abstraction.

— Emmy Noether

To end this manuscript, we—plural de cortesía—would like to introduce a topic of growing interest in the present years, because of its deep implication—among many others, much less known—than LLMs or AI-related applications.

7.1 Motivation and philosophy

7.2 Mathematical definition

7.3 Some examples of conditional probability

7.4 Stochasticity and Markov processes

Exercises

1. Exercise [...].
2. Exercise [...].
3. Exercise [...].

Solutions

1. Solution [...].
2. Solution [...].
3. Solution [...].

Appendix A

Appendix 1

The integral

$$\int_a^b f(x) \, dx = \lim_{n \rightarrow \infty} \sum_{i=0}^n f(x_i) \, \Delta x \quad (\text{A.1})$$

Equivalently

$$\int_a^b f(x) \, dx = \lim_{n \rightarrow \infty} \sum_{i=0}^n f(x_i) \, \Delta x \quad (\text{A.2})$$

Appendix B

Appendix 2

Additional examples and computations may be placed here.

Appendix C

Appendix 3

Additional examples and computations may be placed here.

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