



工程概率统计

Probability and Statistics for Engineering

第二章 随机变量与分布

Chapter 2 Random Variables and Distributions

Chapter 2 Random Variables and Distributions

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2.1 Introduction

- In Chapter 1, we learned the basic concepts like random experiment, sample space, random event, classical model of probability, geometric model of probability, etc.
- Dealing with complex problems, we need a tool that allows for a unified study of random events.
- The goal is to simplify problems into functional operations, enabling the use of mathematical tools such as calculus.
- A random variable is such a tool: **it connects the real world with the mathematical world.**
 - Simply put, a random variable converts each possible outcome of a random experiment into a number.
 - For example, suppose an organization wants to survey public opinion on a proposal, asking whether people support or oppose it, by randomly sampling 50 individuals.
 - According to classical probability, there are 2^{50} possible outcomes.
 - However, if we use X to represent the number of people who support the proposal, then X is a random variable, and its range of values is limited to $\{0, 1, 2, \dots, 50\}$.
 - Thus, random variables helps us to describe the problem in a precise and concise manner.

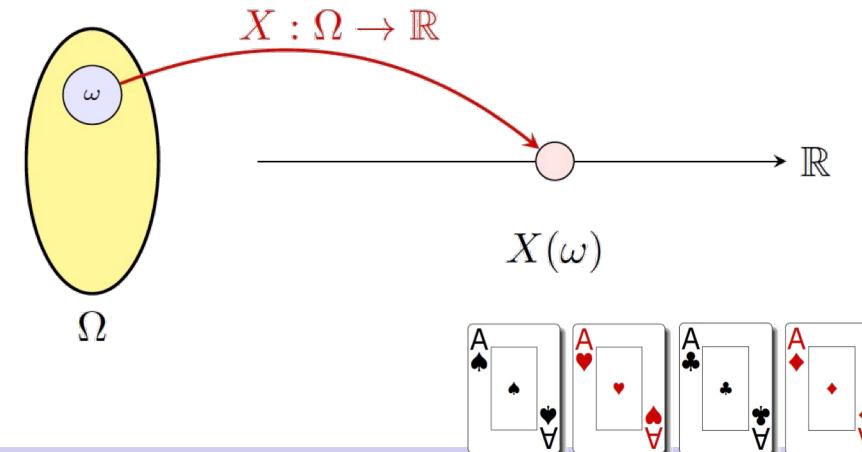


2.1.1 Definition of Random Variable

- Here we provide the mathematical definition of a **random variable** (随机变量).

Random Variable

A random variable (or r.v. for short) is a **real-valued function** defined on the sample space, typically denoted by capital letters like X, Y, Z .



Example 3.1

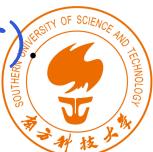
- On Valentine's Day a restaurant offers a Lucky Lovers discount that could save couples money on their romantic dinners. How to define the Lucky Lovers discount as a random variable:
- When the waiter brings the check, he'll also bring the four aces from a deck of cards. He'll shuffle them and lay them out face down on the table. The couple will then get to turn one card over.
- If it's a black ace, they'll owe the full amount, but if it's the ace of hearts, the waiter will give them a \$20 Lucky Lovers discount.
- If they first turn over the ace of diamonds (hey—at least it's red!), they'll then get to turn over one of the remaining cards, earning a \$10 discount for finding the ace of hearts this time.



2.1.1 Definition of Random Variable

Solution

- With random variables defined, the study of random events can be simplified to the study of random variables.
- The study of r.v.s essentially involves examining all possible values that the r.v. can take and the probability associated with each value, which is known as the **probability distribution (概率分布)**.



2.1.1 Definition of Random Variable

- With the probability distribution, we can grasp the overall certainty of the random event, providing a foundation for further exploration of its underlying regularity.
- Based on the possible values a random variable can take, they can be classified into:
 - **Discrete random variable** (离散型随机变量): take a finite or countable number of values, e.g., the number of customers that visit a restaurant.
 - **Continuous random variable** (连续型随机变量): take continuous values (an uncountable number of values), e.g., the waiting time for a bus.
- The differences and similarities in how the probability distributions of these two types of r.v.s are described:
 - Discrete r.v. can be described using a **probability mass function** (PMF, 概率质量函数).
 - Continuous r.v. can be described using a **probability density function** (PDF, 概率密度函数).
 - Both types of r.v.s can be described using a **cumulative distribution function** (CDF, 累积分布函数).



2.1.2 Description of Probability Distribution

Probability Mass Function

Let X be a discrete random variable, $S = \{a_1, a_2, \dots\}$ be the **support** (支撑集) of X , i.e., the set of values that X can take. Then the **probability mass function** (PMF, 概率质量函数) of X is $p: S \rightarrow [0, 1]$ defined as

$$p(a_i) = p_i = P(X = a_i), i = 1, 2, \dots,$$

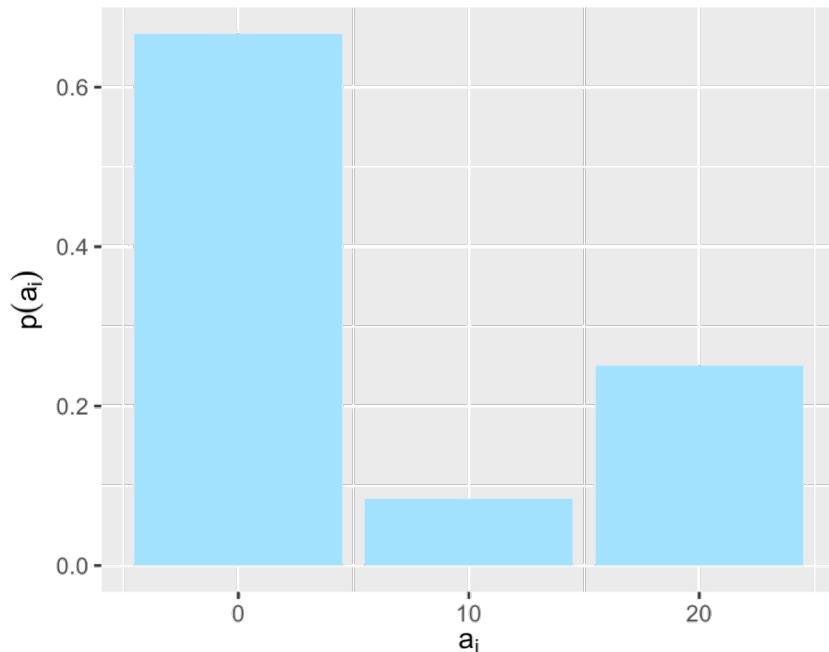
which satisfies:

- **Non-negativity** (非负性): $p(a_i) \geq 0, i = 1, 2, \dots$;
- **Normalization** (规范性): $\sum_i p(a_i) = 1$.

- The PMF can also be displayed in a tabular format

Value	a_1	a_2	\dots	a_i	\dots
Probability	p_1	p_2	\dots	p_i	\dots

- The PMF can be displayed in a graphical format by plotting $p(a_i)$ on the y -axis against a_i on the x -axis.



2.1.2 Description of Probability Distribution

Example 3.1 (Continued)

Obtain the PMF of the Lucky Lovers discount.

Solution



2.1.2 Description of Probability Distribution

Example 3.2

Suppose that the support of a r.v. X is $\{0, 1, 2, \dots\}$ and the PMF of X is given by $P(X = k) = c\lambda^k/k!$, where λ is some positive constant. Please express the value of c in terms of λ .

Solution



2.1.2 Description of Probability Distribution

Continuous Random Variable and Probability Density Function

X is called a continuous random variable if there exists a non-negative function f , defined for all $x \in \mathbb{R}$, satisfies that

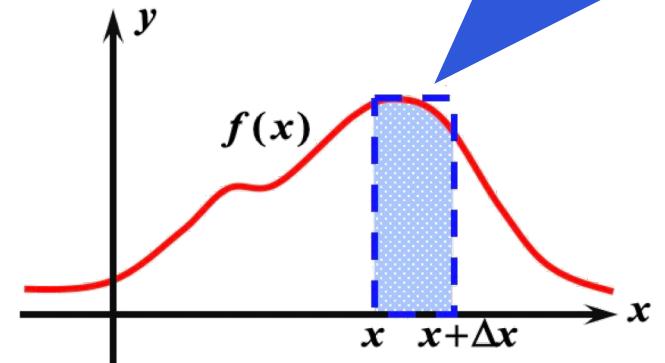
$$P(a \leq X \leq b) = \int_a^b f(x)dx$$

for any $-\infty < a \leq b < \infty$. The function f is called the **probability density function (PDF, 概率密度函数)** of X .

It is not difficult to see that the PDF, like the PMF, has these properties:

- **Non-negativity (非负性):** $f(x) \geq 0, \forall x \in \mathbb{R}$;
- **Normalization (规范性):** $\int_{-\infty}^{\infty} f(x)dx = 1$.
- Note that for any $x \in \mathbb{R}$, we have $P(X = x) = \int_x^x f(u)du = 0$.
- Thus, different from the PMF, $f(x)$ does not reflect the probability of X taking the value x .

$P(x < X \leq x + \Delta x) \approx$
The area of this rectangle



- The larger $f(x)$ is, the greater the probability that X takes a value near x .
- $f(x)$ reflects the degree to which the probability is concentrated around x .



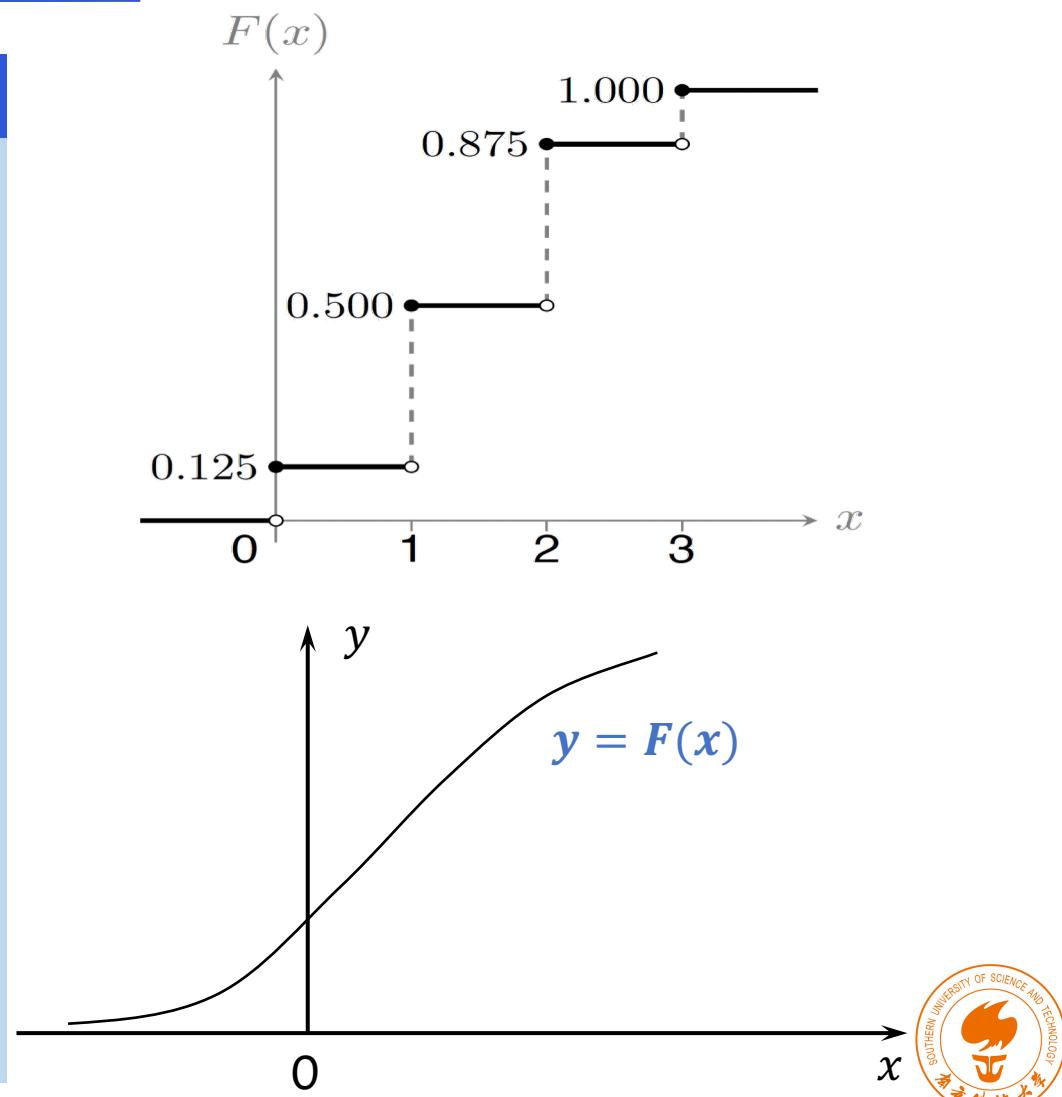
2.1.2 Description of Probability Distribution

Cumulative Distribution Function

For a random variable X , either discrete or continuous, its **cumulative distribution function (CDF, 累积分布函数)** is defined as

$$F(x) = P(X \leq x), \forall x \in \mathbb{R}.$$

- For a **discrete r.v.**, its CDF is a step function (阶梯函数), which is $F(x) = \sum_{a_i \leq x} p(a_i)$.
- For a **continuous r.v.**, its CDF is a continuous function, which is $F(x) = \int_{-\infty}^x f(u)du$. Consequently, $f(x) = F'(x)$.
- The CDF is **non-decreasing** and **right-continuous**.
- The maximum of the CDF is $F(\infty) = \lim_{x \rightarrow \infty} F(x) = 1$.
- The minimum of the CDF is $F(-\infty) = \lim_{x \rightarrow -\infty} F(x) = 0$.
- For any real numbers $a < b$, $P(a < X \leq b) = F(b) - F(a)$.



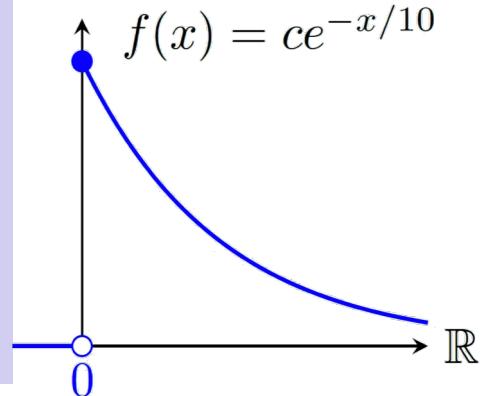
2.1.2 Description of Probability Distribution

Example 3.3

- Suppose that the lifespan in years of a certain household appliance is a r.v. with PDF given by

$$f(x) = \begin{cases} ce^{-x/10}, & x \geq 0 \\ 0, & x < 0 \end{cases}.$$

- What is the probability that an appliance will function between 1 and 2 years?



Solution



2.1.3 Expectation and Variance

- A probability distribution provides a comprehensive and complete description of a r.v., however, sometimes we may want to describe the r.v. from specific aspects with just a few numbers.
- These numbers should be simple, clear, distinctive, and intuitive.
- The most commonly used numerical characteristics are the **mathematical expectation (数学期望)** and **variance (方差)**.

Mathematical Expectation

The **mathematical expectation (数学期望)** of a random variable X is denoted as $E(X)$:

- If X is a **discrete r.v.** with PMF $p(x_k) = p_k = P(X = x_k)$, $k = 1, 2, \dots$, given $\sum_{k=1}^{\infty} |x_k| p_k < \infty$, then

$$E(X) \triangleq \sum_{k=1}^{\infty} x_k p(X = x_k) = \sum_{k=1}^{\infty} x_k p_k.$$

- If X is a **continuous r.v.** with PDF $f(x)$, given $\int_{-\infty}^{\infty} |x| f(x) dx < \infty$, then

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

Also called the mean (均值), expectation (期望), expected value (期望值).



2.1.3 Expectation and Variance

- Simply put, the expectation is the **weighted average** of all possible values of a random variable.
- Expectation represents the **average result** or **long-term value** that we can anticipate from a series of random events, and it has wide applications in real life.
 - In the insurance industry, expectation can be used for setting the premium setting.
 - In the financial sector, investors use expectation to predict investment returns.

Example 3.3 (Continued)

- A store adopts a ‘use first, pay later’ approach for selling the household appliance, with the payment amount determined based on the lifespan X of the appliance.

Lifespan (year)	$X \leq 1$	$1 < X \leq 2$	$2 < X \leq 3$	$X > 3$
Payment	1500	2000	2500	3000

- What’s the expected return for the store to sell a random appliance?



2.1.3 Expectation and Variance

Solution



2.1.3 Expectation and Variance

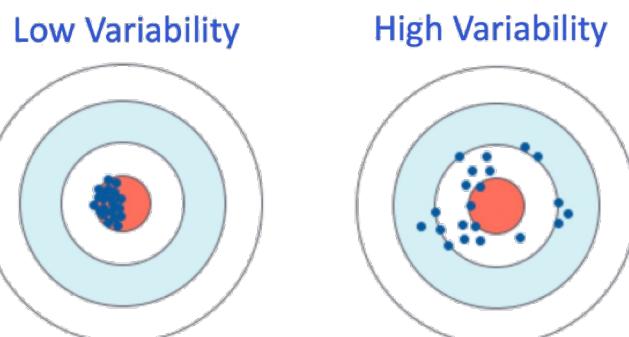
- While expectation represents the **average result**, we are also interested in the **stability/variability** (稳定性/波动性) of the result.
- **Variance (方差)** describes the variability of a random variable around its expectation.

Variance and Standard Deviation

If a r.v. X satisfies that $E(X^2) < \infty$, then

$$\text{Var}(X) \triangleq E(X - E(X))^2$$

is called the **variance (方差)** of X , and $\text{SD}(X) \triangleq \sqrt{\text{Var}(X)}$ is called the **standard deviation (SD, 标准差)**.



Q: Why not use $E|X - E(X)|$ to describe the variability?

- Specifically, by the definition of expectation:

- If X is a **discrete r.v.** with PMF $p(x_k) = p_k = P(X = x_k)$, $k = 1, 2, \dots$, then $\text{Var}(X) = \sum_{k=1}^{\infty} [x_k - E(X)]^2 \cdot p_k$.

- If X is a **continuous r.v.** with PDF $f(x)$, then $\text{Var}(X) = \int_{-\infty}^{\infty} [x - E(X)]^2 f(x) dx$.



2.1.3 Expectation and Variance

Example 3.4

- Suppose that the time deviation (in seconds) of two brands of watches are summarized below

Deviation	-3	-2	-1	0	1	2	3
Prob. (Brand A)	0.10	0.15	0.15	0.20	0.15	0.15	0.10
Prob. (Brand B)	0.15	0.10	0.10	0.30	0.10	0.10	0.15

- Which brand has better quality?



Solution



2.1.3 Expectation and Variance

- There are some basic properties of the expectation and variance:
 - For any constants a, b , $E(aX + b) = aE(X) + b$.
 - For any constants a, b , $\text{Var}(aX + b) = a^2\text{Var}(X)$, and thus $\text{SD}(aX + b) = a\text{SD}(X)$.
 - $\text{Var}(X) = E(X^2) - [E(X)]^2$.

Proof: Without loss of generality, show the case for a discrete r.v. with PMF $p(x_k) = p_k = P(X = x_k)$.

Let $\mu \triangleq E(X)$, then

$$\begin{aligned}\text{Var}(X) &= E(X - E(X))^2 = \sum_{k=1}^{\infty} (x_k - \mu)^2 p_k \\ &= \sum_{k=1}^{\infty} (x_k^2 - 2\mu x_k + \mu^2) p_k = \sum_{k=1}^{\infty} x_k^2 p_k - 2\mu \sum_{k=1}^{\infty} x_k p_k + \mu^2 \\ &= E(X^2) - 2\mu^2 + \mu^2 = E(X^2) - [E(X)]^2.\end{aligned}$$



Chapter 2 Random Variables and Distributions

- 2.1 Introduction
- 2.2 Common Discrete Distributions
- 2.3 Common Continuous Distributions
- 2.4 Transformation of Random Variables



2.2 Common Discrete Distributions

- Bernoulli distribution (伯努利分布) is the simplest discrete distribution.

Bernoulli Trial and Bernoulli Distribution

- If a random experiment only have two possible outcomes, A and \bar{A} , then the experiment is called a **Bernoulli trial** (伯努利试验).
- If a random variable X only takes values 0 and 1, and $P(X = 1) = p$, $P(X = 0) = 1 - p$, then X is called to follow a **Bernoulli distribution** (伯努利分布) with parameter p , denoted as

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

- The PMF of $\text{Bernoulli}(p)$ can be expressed as

$$p(x) = p^x(1 - p)^{1-x}, x = 0, 1.$$

- The expectation and variance of $X \sim \text{Bernoulli}(p)$:

$$E(X) = p, \text{Var}(X) = p(1 - p).$$

Jacob Bernoulli
(1655-1705)

A - success
 \bar{A} - failure



JAC. BERNOULLI, MATH. P.P.

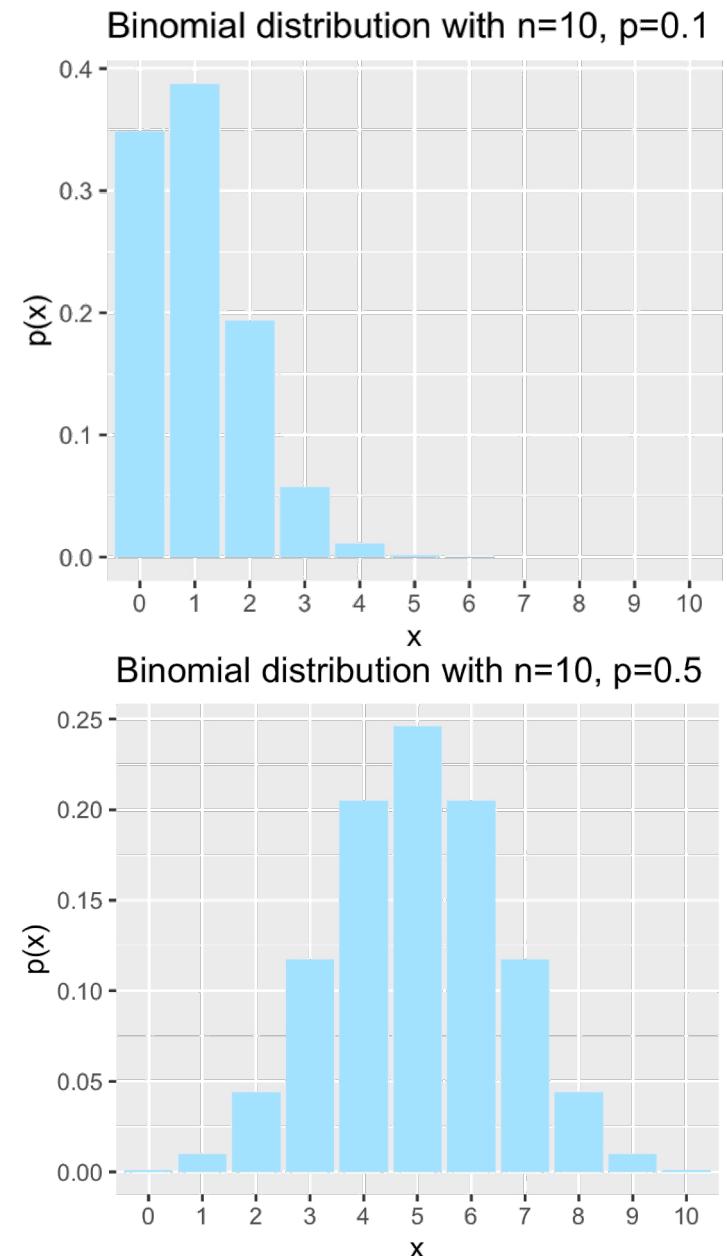
- The Bernoulli distribution is the foundation of many classical probability distributions, such as the binomial distribution (二项分布), the geometric distribution (几何分布), etc.



2.2 Common Discrete Distributions

n -Fold Bernoulli Trial and Binomial Distribution

- An **n -fold Bernoulli trial** (n 重伯努利试验) is an experiment that repeats a Bernoulli trial n times independently. Note:
 - “**independently**” suggests that the result of each Bernoulli trial would not affect each other.
 - “**repeat**” suggests that the probability of event A in each Bernoulli trial, i.e., $P(A) = p$, remains the same.
- Let X be a r.v. that records the number of times event A happens in an n -fold Bernoulli trial, then X is called to follow a **binomial distribution** (二项分布) with parameter n and p , denoted as
$$X \sim \text{Binomial}(n, p) \text{ (or } \text{Bin}(n, p), \text{B}(n, p)\text{)}.$$
- The PMF of $\text{Binomial}(p)$ can be derived as
$$p(x) = \binom{n}{x} p^x (1-p)^{n-x} = C_n^x p^x (1-p)^{n-x}, x = 0, 1, 2, \dots, n.$$



2.2 Common Discrete Distributions

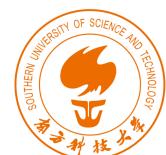
Example 3.5

- A factory has 80 pieces of the same type of equipment, each operating independently, with a failure probability of 0.01.
- A single maintainer can only repair one piece of equipment at a time. The factory is considering two strategies for allocating maintainers:
 - Allocate 4 maintainers, with each responsible for maintaining 20 pieces of equipment.
 - Allocate 3 maintainers, with them jointly responsible for maintaining all 80 pieces of equipment.
- Please compare these two strategies in terms of the probability that a piece of equipment cannot be repaired in time when a failure occurs.



2.2 Common Discrete Distributions

Solution



2.2 Common Discrete Distributions

- The expectation and variance of $X \sim \text{Binomial}(n, p)$ can be derived to be

$$E(X) = np, \text{Var}(X) = np(1 - p).$$

Proof: By the definition of expectation, we have:

$$\begin{aligned} E(X) &= \sum_{k=0}^n k \cdot P(X = k) = \sum_{k=1}^n k \cdot \binom{n}{k} p^k (1 - p)^{n-k} = \sum_{k=1}^n k \cdot \frac{n!}{k! (n - k)!} p^k (1 - p)^{n-k} \\ &= np \sum_{k=1}^n \frac{(n - 1)!}{(k - 1)! (n - k)!} p^{k-1} (1 - p)^{n-k} = np \sum_{k=0}^{n-1} \binom{n - 1}{k} p^k (1 - p)^{n-k-1} \\ &\quad \text{binomial expansion} \quad \text{(二项式展开)} \\ &= np[(1 - p) + p]^{n-1} = np. \end{aligned}$$

The variance can also be derived similarly, details are not shown here.

Easier derivations are available once we introduce the independence between random variables.



2.2 Common Discrete Distributions

Geometric Distribution

- Suppose that a Bernoulli trial is repeated independently until A occurs, let X be a r.v. that records the number of trials required, then X is called to follow a **geometric distribution** (几何分布) with parameter p , denoted as

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

- The PMF of $\text{Geometric}(p)$ can be derived as

$$p(x) = p(1 - p)^{x-1}, x = 1, 2, \dots.$$

- The expectation and variance of $X \sim \text{Geometric}(p)$:

$$E(X) = \frac{1}{p}, \text{Var}(X) = \frac{1-p}{p^2}.$$

- The geometric distribution is the only discrete distribution which has the **memoryless property** (无记忆性), i.e., for $X \sim \text{Geometric}(p)$ and any positive integers m, n , we have

$$P(X > m + n | X > m) = P(X > n).$$

Example 3.6

- A gambler at a casino is betting on 'big' in a game of 'big or small,' but the table has shown 'small' for ten consecutive rounds.
- The gambler believes that since 'small' has come up so many times already, the probability of another 'small' is very low.
- He is considering betting all his money on 'big' to try to win back his losses. What do you think?



Gambler's Fallacy
(赌徒谬误)



2.2 Common Discrete Distributions

- Some probability distributions can be directly derived from the data generation mechanism itself, such as the Bernoulli distribution, binomial distribution, geometric distribution.
- Some other probability distributions are first derived mathematically or summarized from data, and later found to describe many real-world patterns.
- The Poisson distribution is an example of the second type which was first introduced by [Siméon-Denis Poisson](#) when he study the number of wrongful convictions in a given country.

Poisson Distribution

- Let X be a discrete r.v. with support $\{0, 1, 2, \dots\}$, if its PMF is

$$p(x) = P(X = x) = \frac{\lambda^x}{x!} e^{-\lambda}, x = 0, 1, 2, \dots,$$

- where $\lambda > 0$ is a constant, then X is said to follow a [Poisson distribution](#) (柏松分布) with parameter λ , denoted by $X \sim \text{Poisson}(\lambda)$.

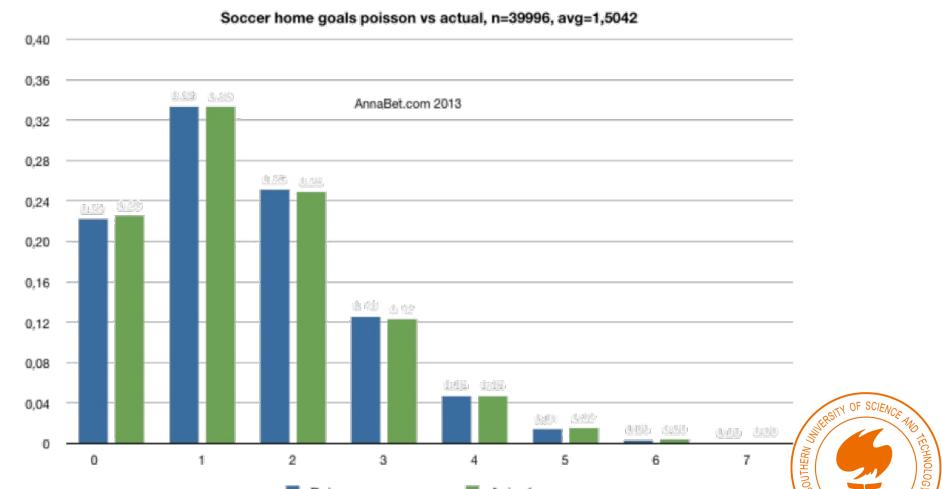


Siméon-Denis Poisson
西莫恩·德尼·泊松
(1781-1840)



2.2 Common Discrete Distributions

- While the Poisson distribution was initially introduced to solve a legal and criminal justice problem, it is widely used in various fields latter. Examples:
 - In 1860, an American astronomer fitted the Poisson distribution to the number of stars found in a space.
 - In 1898, a Russian economist showed that the frequency with which soldiers in the Prussian army accidentally killed by horse kicks could be well modeled by a Poisson distribution.
- Poisson distribution is used to describe the number of events occurring in a **fixed interval of time /space** if the events occur with a **constant rate** and **independently**. Examples:
 - The number of customers entering a store each day.
 - The number of traffic accidents at an intersection each year.
 - The number of typos on a page of a book.
 - The number of goals in a World Cup soccer match.
 - The number of mutations on a strand of DNA per unit length.



2.2 Common Discrete Distributions

- The expectation and variance of $X \sim \text{Poisson}(\lambda)$ can be derived to be

$$E(X) = \lambda, \text{Var}(X) = \lambda.$$

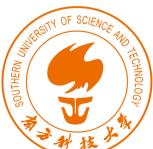
Proof: By the definition of expectation, we have:

$$E(X) = \sum_{k=0}^{\infty} k \cdot P(X = k) = \sum_{k=1}^{\infty} k \cdot \frac{\lambda^k}{k!} e^{-\lambda} = \lambda e^{-\lambda} \sum_{k=0}^{\infty} \frac{\lambda^k}{k!} = \lambda.$$

$$E(X^2) = \sum_{k=0}^{\infty} k^2 \cdot P(X = k) = \sum_{k=1}^{\infty} k^2 \cdot \frac{\lambda^k}{k!} e^{-\lambda} = e^{-\lambda} \left[\sum_{k=1}^{\infty} \frac{(k-1)\lambda^k}{(k-1)!} + \sum_{k=1}^{\infty} \frac{\lambda^k}{(k-1)!} \right] = \lambda^2 + \lambda.$$

$$\text{Var}(X) = E(X^2) - [E(X)]^2 = \lambda.$$

- The parameter λ is also called the **intensity** (泊松强度) of the Poisson distribution.



2.2 Common Discrete Distributions

Example 3.7

- A Council is considering whether to base a recovery vehicle (救援车辆) on a stretch of road to help clear incidents as quickly as possible.
- Records show that, on average, the number of incidents during the morning rush hour is 5.
- The Council won't base a recovery vehicle on the road if the probability of having more than 5 incidents during the morning rush hour is less than 30%.
- Based on this information, should the Council provide a vehicle?



2.2 Common Discrete Distributions

Solution



2.2 Common Discrete Distributions

- The Poisson distribution can be obtained derived as a limiting case of the binomial distribution.

Proof: Consider the number of events within a unit time interval $[0, 1]$ and divide it into n subintervals:

$$\left[0, \frac{1}{n}\right], \left[\frac{1}{n}, \frac{2}{n}\right], \dots, \left[\frac{i-1}{n}, \frac{i}{n}\right], \dots, \left[\frac{n-1}{n}, 1\right].$$

Several assumptions are made:

1. Let n be large so that each subinterval is very short, making it impossible for two or more events to occur within any subinterval (i.e., either no event occurs or exactly one event occurs).
2. The probability of an event occurring is proportional to the length of the subinterval, i.e., λ/n .
3. Whether an event occurs in a subinterval is independent of the others.

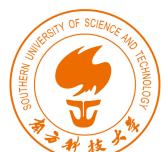
Let X be the number of events within $[0, 1]$, by the assumptions above, we have $X \sim \text{Binomial}\left(n, \frac{\lambda}{n}\right)$. So

$$P(X = x) = \binom{n}{x} \left(\frac{\lambda}{n}\right)^x \left(1 - \frac{\lambda}{n}\right)^{n-x}.$$

Let $n \rightarrow \infty$, it is not difficult to get

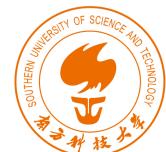
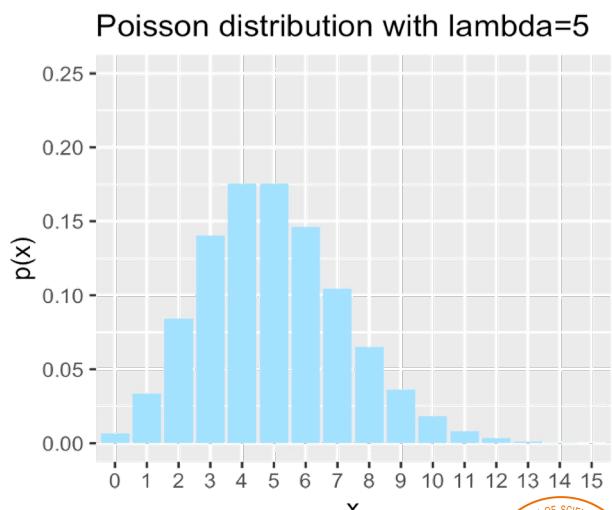
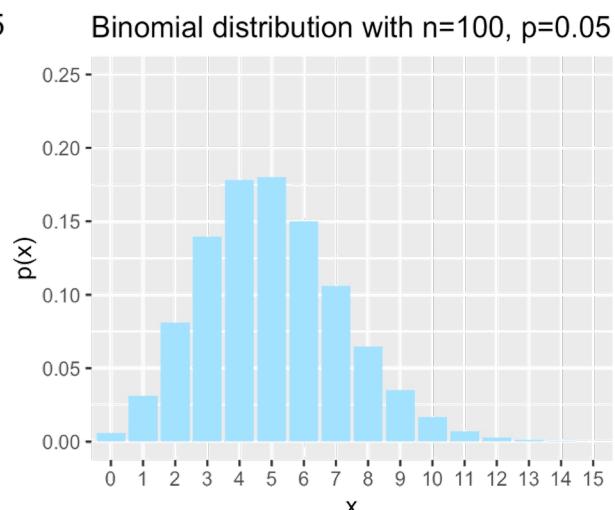
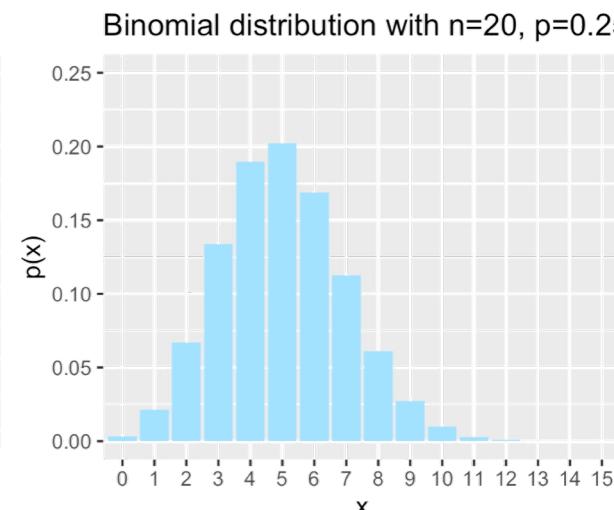
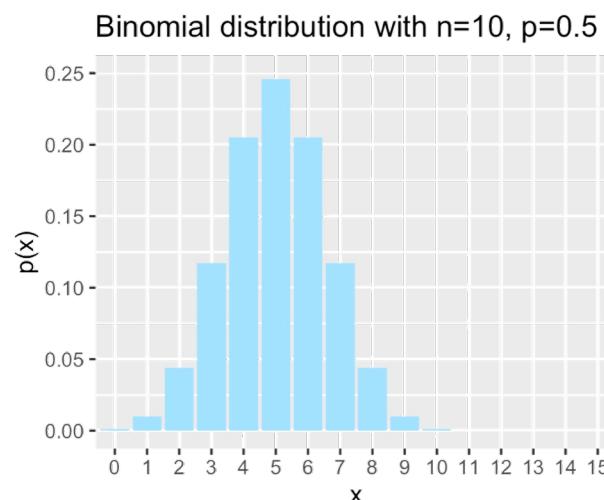
$$\lim_{n \rightarrow \infty} P(X = x) = \lim_{n \rightarrow \infty} \binom{n}{x} \left(\frac{\lambda}{n}\right)^x \left(1 - \frac{\lambda}{n}\right)^{n-x} = \frac{\lambda^x}{x!} e^{-\lambda}.$$

Poisson Theorem
(泊松定理)



2.2 Common Discrete Distributions

- The theorem suggests that for an n -fold Bernoulli trial with large n and small p , the binomial distribution $\text{Binomial}(n, p)$ can be approximated by the Poisson distribution $\text{Poisson}(np)$.
- How large should n be and how small should p be?
- A rule of thumb is that when $n > 100$ and $p < 0.05$, the Poisson distribution provides a good approximation to the binomial distribution.



2.2 Common Discrete Distributions

Example 3.8

- An insurance company has launched a life insurance policy where each participant is required to pay a premium of \$12 on January 1st.
- If a participant dies within the year, his/her family can receive a compensation of \$2,000 from the insurance company.
- Suppose 2,500 people participate in this insurance, and the probability of death for each person within the year is 0.002.
- What is the probability that the insurance company's profit from this life insurance policy is no less than \$20,000?



2.2 Common Discrete Distributions

Solution



2.2 Common Discrete Distributions

- In summary, we introduced the following discrete distributions:

Distribution	PMF	Expectation	Variance
Bernoulli(p)	$p(x) = p^x(1-p)^{1-x}, x = 0, 1$	p	$p(1-p)$
binomial(n, p)	$p(x) = \binom{n}{x} p^x(1-p)^{n-x}, x = 0, 1, 2, \dots, n$	np	$np(1-p)$
Geometric(p)	$p(x) = p(1-p)^{x-1}, x = 1, 2, \dots$	$1/p$	$(1-p)/p$
Poisson(λ)	$p(x) = P(X = x) = \frac{\lambda^x}{x!} e^{-\lambda}, x = 0, 1, 2, \dots$	λ	λ

- There are many other discrete distributions that are not covered, for example:

- **Hypergeometric distribution (超几何分布)**: describes the number of successes in the first m trials of an n -fold Bernoulli trial.
- **Negative binomial distribution (负二项分布)**: a generalization of the geometric distribution, which describes the number of Bernoulli trials required until a predefined number r of successes occurs.

