

CE49X: Statistical Analysis I

Core Topics in Descriptive Statistics, Probability, and Distributions

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- 1 Descriptive Statistics
- 2 Probability Review
- 3 Discrete Random Variables and Distributions
- 4 Expectation and Variance Concepts
- 5 Continuous Random Variables and Distributions
- 6 Moments and Summary Measures
- 7 Conclusion

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What is Descriptive Statistics?

- Methods for summarizing and describing data
- Transforms raw data into meaningful insights
- Foundation for inferential statistics and decision-making

Key Components:

- **Central Tendency:** Where is the center?
- **Spread/Variability:** How dispersed is the data?
- **Shape:** Is the distribution symmetric or skewed?
- **Visualization:** Graphical representations

Engineering Context

Analyzing material strengths, load measurements, experimental results

Measures of Central Tendency

Mean (Arithmetic Average):

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

Median: Middle value when data is ordered

- Robust to outliers
- Better for skewed distributions

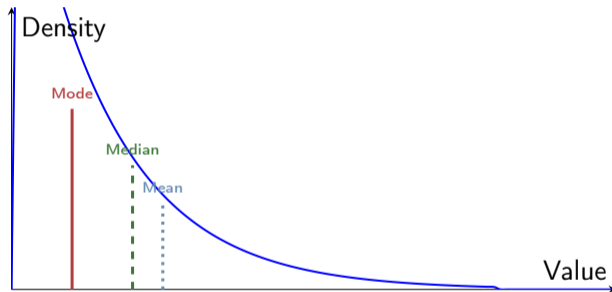
Mode: Most frequently occurring value

- Can be multiple modes (bimodal, multimodal)
- Useful for categorical data

When to Use Which?

Mean: Symmetric distributions; Median: Skewed data or outliers; Mode: Categorical data

Right-Skewed Distribution



Key Insight: In right-skewed distributions: $\text{Mode} < \text{Median} < \text{Mean}$

Measures of Spread

Range: $R = x_{\max} - x_{\min}$

- Simple but sensitive to outliers

Variance:

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

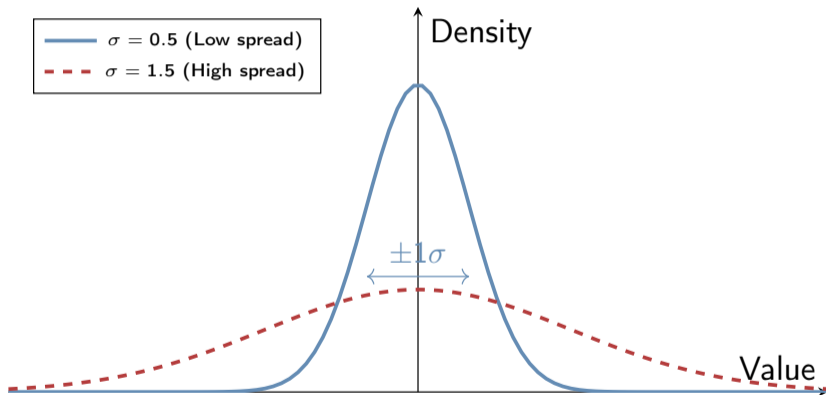
Standard Deviation: $s = \sqrt{s^2}$

- Same units as original data
- Most commonly used measure of spread

Interquartile Range (IQR): $IQR = Q_3 - Q_1$

- Robust to outliers
- Measures middle 50% of data

Comparing Distributions with Different Spreads



Key Insight: Larger σ means more spread, flatter distribution

Quantiles and Percentiles

Definition: The p -th percentile is a value below which $p\%$ of the data falls

Key Quantiles:

- Q_1 (25th percentile): First quartile
- Q_2 (50th percentile): Median
- Q_3 (75th percentile): Third quartile

Five-Number Summary:

Min, Q_1 , Median, Q_3 , Max

Engineering Example

For concrete strength data: Min=25 MPa, Q_1 =30 MPa, Median=35 MPa, Q_3 =40 MPa, Max=48 MPa

Shape Measures: Skewness and Kurtosis

Skewness: Measures asymmetry of distribution

$$\text{Skewness} = \frac{\mathbb{E}[(X - \mu)^3]}{\sigma^3}$$

- Positive skew: Long right tail (mean > median)
- Negative skew: Long left tail (mean < median)
- Zero skew: Symmetric (mean \approx median)

Kurtosis: Measures tail heaviness

$$\text{Kurtosis} = \frac{\mathbb{E}[(X - \mu)^4]}{\sigma^4}$$

- High kurtosis: Heavy tails, more outliers
- Low kurtosis: Light tails, fewer outliers
- Normal distribution: Kurtosis = 3

Data Visualization: Histograms

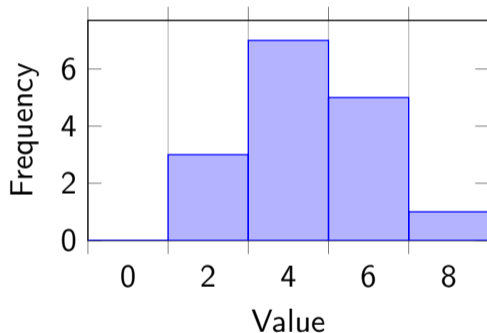
Histogram: Bar chart showing frequency distribution

Components:

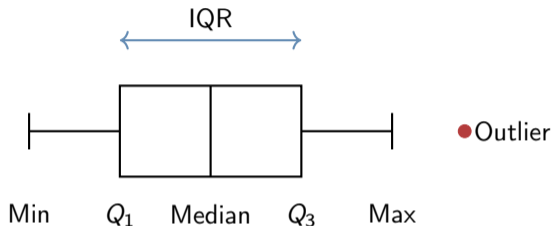
- Bins: Intervals that group data
- Height: Frequency or density
- Shows shape of distribution

Key Insights:

- Central tendency
- Spread
- Skewness
- Outliers
- Modality



Boxplot (Box-and-Whisker Plot): Displays five-number summary



Advantages:

- Clearly shows median and quartiles
- Identifies outliers
- Compact representation
- Easy comparison between groups

Example: Concrete Compressive Strength

Testing 50 concrete cylinders yields (in MPa):

$$\bar{x} = 35.2, \quad s = 3.8, \quad \text{Median} = 35.5$$

$$Q_1 = 32.5, \quad Q_3 = 37.8, \quad \text{Skewness} = -0.15$$

Interpretation:

- Mean strength around 35 MPa
- Standard deviation of 3.8 MPa indicates moderate variability
- Near-symmetric distribution (skewness ≈ 0)
- $\text{IQR} = 5.3$ MPa shows middle 50% spread

Engineering Decision:

- Check if mean exceeds design specification
- Assess if variability is acceptable for quality control
- Identify any outliers indicating quality issues

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Probability: The Logic of Uncertainty

Why Probability?

- Engineering systems operate under uncertainty
- Loads, material properties, environmental conditions vary
- Probability provides rigorous framework for quantifying uncertainty

Key Concepts:

- **Sample Space (S):** Set of all possible outcomes
- **Event (A):** Subset of sample space
- **Probability ($\mathbb{P}(A)$):** Measure of likelihood

Probability Axioms (Kolmogorov)

1. $0 \leq \mathbb{P}(A) \leq 1$ for any event A
2. $\mathbb{P}(S) = 1$ (something must happen)
3. If A_1, A_2, \dots are disjoint, then $\mathbb{P}(\bigcup A_i) = \sum \mathbb{P}(A_i)$

Sample Spaces and Events

Example 1: Quality Control

Testing a component: $S = \{\text{Pass}, \text{Fail}\}$

Event A : Component passes, $\mathbb{P}(A) = 0.95$

Example 2: Die Roll

Rolling a die: $S = \{1, 2, 3, 4, 5, 6\}$

Event A : Even number, $A = \{2, 4, 6\}$, $\mathbb{P}(A) = 3/6 = 0.5$

Example 3: Load Measurement

$S = [0, \infty)$ (all non-negative real numbers)

Event A : Load exceeds 100 kN, $A = (100, \infty)$

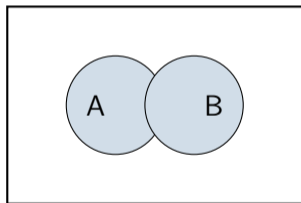
Operations on Events:

- Union: $A \cup B$ (A or B occurs)
- Intersection: $A \cap B$ (Both A and B occur)
- Complement: A^c (A does not occur), $\mathbb{P}(A^c) = 1 - \mathbb{P}(A)$

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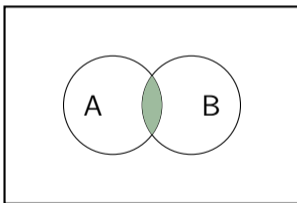
Venn Diagrams for Events

Union: $A \cup B$



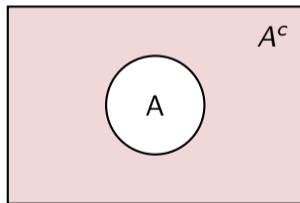
(A or B)

Intersection: $A \cap B$



(Both A and B)

Complement: A^c



(Not A)

Conditional Probability

Definition: Probability of A given that B has occurred

$$\mathbb{P}(A | B) = \frac{\mathbb{P}(A \cap B)}{\mathbb{P}(B)}, \quad \mathbb{P}(B) > 0$$

Intuition: Update probability based on new information

- B is the new sample space
- $A \cap B$ is the favorable outcomes within B

Example: Quality Control

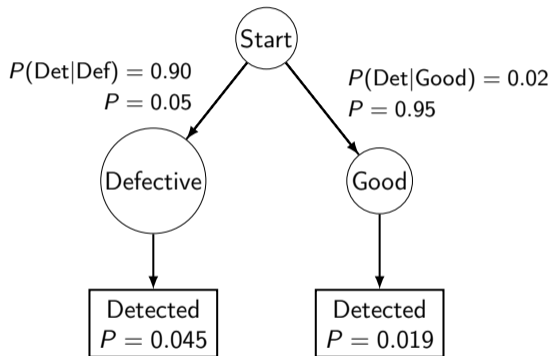
- $\mathbb{P}(\text{Defective}) = 0.05$
- $\mathbb{P}(\text{Detected} | \text{Defective}) = 0.90$
- $\mathbb{P}(\text{Detected} | \text{Good}) = 0.02$

What is $\mathbb{P}(\text{Detected and Defective})$?

$$\mathbb{P}(\text{Detected} \cap \text{Defective}) = \mathbb{P}(\text{Detected} | \text{Defective}) \cdot \mathbb{P}(\text{Defective}) = 0.90 \times 0.05 = 0.045$$

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Quality Control Example



Total Probability: $\mathbb{P}(\text{Detected}) = 0.045 + 0.019 = 0.064$

Independence

Definition: Events A and B are independent if:

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

Equivalently: $\mathbb{P}(A|B) = \mathbb{P}(A)$ (knowing B doesn't change probability of A)

Examples of Independence:

- Two separate coin flips
- Strengths of components from different production batches
- Earthquakes in different regions

Examples of Dependence:

- Weather on consecutive days
- Strength of adjacent concrete sections (same pour)
- Multiple tests on the same specimen

Common Mistake

Disjoint events are NOT independent! If $A \cap B = \emptyset$ and $\mathbb{P}(A), \mathbb{P}(B) > 0$, then $\mathbb{P}(A|B) = 0 \neq \mathbb{P}(A)$

Law of Total Probability

Setup: Partition sample space into events B_1, B_2, \dots, B_n where:

- $B_i \cap B_j = \emptyset$ for $i \neq j$ (disjoint)
- $\bigcup_{i=1}^n B_i = S$ (exhaustive)

Law of Total Probability:

$$\mathbb{P}(A) = \sum_{i=1}^n \mathbb{P}(A | B_i) \mathbb{P}(B_i)$$

Example: Two Suppliers

Factory gets components from Supplier 1 (60%) and Supplier 2 (40%).

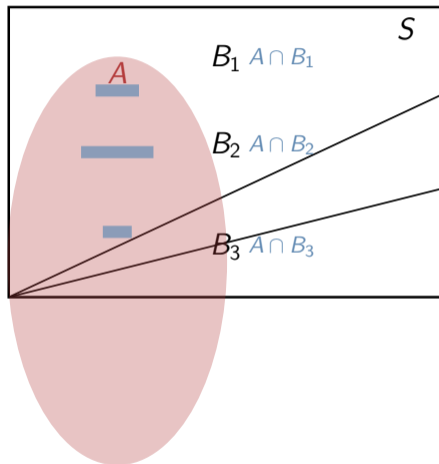
Defect rates: Supplier 1 (2%), Supplier 2 (5%).

What is overall defect rate?

$$\begin{aligned} \mathbb{P}(D) &= \mathbb{P}(D | S_1) \mathbb{P}(S_1) + \mathbb{P}(D | S_2) \mathbb{P}(S_2) \\ &= 0.02 \times 0.6 + 0.05 \times 0.4 = 0.012 + 0.020 = 0.032 = 3.2\% \end{aligned}$$

Visualizing Law of Total Probability

Partitioning the Sample Space



$$\mathbb{P}(A) = \mathbb{P}(A \cap B_1) + \mathbb{P}(A \cap B_2) + \mathbb{P}(A \cap B_3)$$

Bayes' Theorem: Updates probabilities based on new evidence

$$\begin{aligned}\mathbb{P}(B_i | A) &= \frac{\mathbb{P}(A | B_i)\mathbb{P}(B_i)}{\mathbb{P}(A)} \\ &= \frac{\mathbb{P}(A | B_i)\mathbb{P}(B_i)}{\sum_{j=1}^n \mathbb{P}(A | B_j)\mathbb{P}(B_j)}\end{aligned}$$

Terminology:

- $\mathbb{P}(B_i)$: Prior probability (before observing A)
- $\mathbb{P}(B_i | A)$: Posterior probability (after observing A)
- $\mathbb{P}(A | B_i)$: Likelihood

Example: Diagnostic Testing

Test for structural damage: Sensitivity = 95%, Specificity = 90%

Prevalence of damage = 5%

If test is positive, what is probability of actual damage?

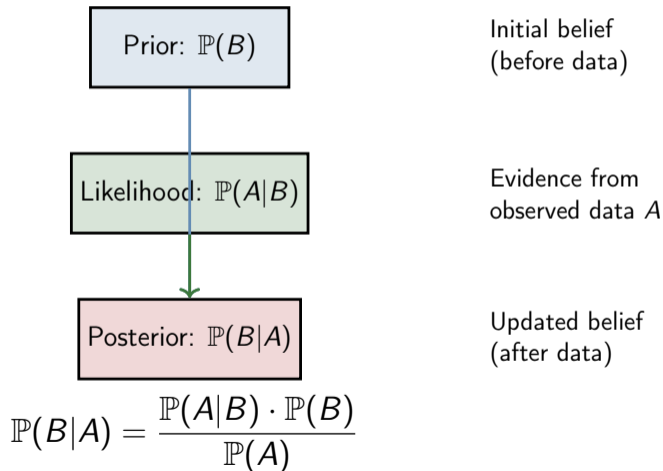
$$\mathbb{P}(\text{Damage} | +) = \frac{0.95 \times 0.05}{0.95 \times 0.05 + 0.10 \times 0.95} = \frac{0.0475}{0.1425} \approx 0.333$$

Only 33% probability despite positive test! (Low prevalence effect)

Visualizing Bayes' Theorem

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The Bayesian Update Process



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Random Variables

Definition: A random variable X is a function from sample space S to real numbers \mathbb{R} : $X : S \rightarrow \mathbb{R}$

Types:

- **Discrete:** Takes countable values (often integers)
- **Continuous:** Takes values in an interval

Why Random Variables?

- Assign numerical values to outcomes
- Enable mathematical operations and analysis
- Bridge between probability and statistics

Examples

- X = Number of defective items in a batch (discrete)
- Y = Time until failure of a component (continuous)
- Z = Load on a bridge (continuous)

Probability Mass Function (PMF)

Definition: For discrete random variable X , the PMF is:

$$p_X(x) = \mathbb{P}(X = x)$$

Properties:

- ① $p_X(x) \geq 0$ for all x
- ② $\sum_{\text{all } x} p_X(x) = 1$

Cumulative Distribution Function (CDF):

$$F_X(x) = \mathbb{P}(X \leq x) = \sum_{t \leq x} p_X(t)$$

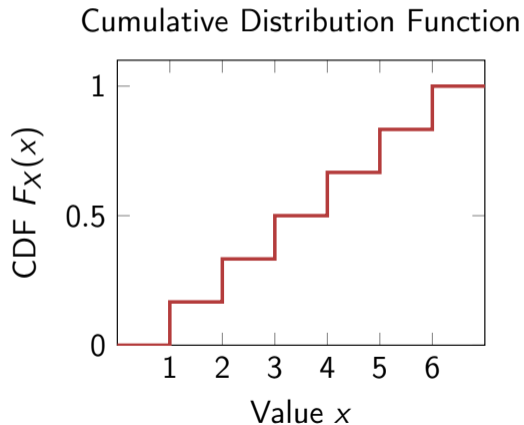
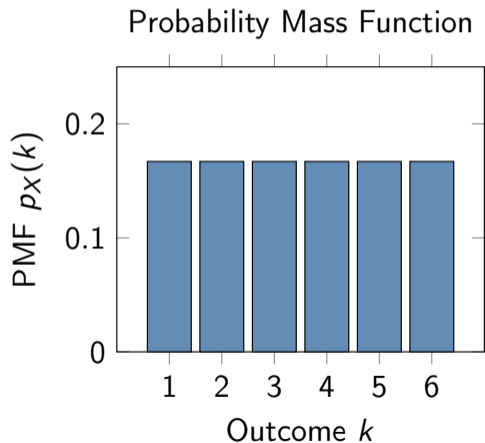
Properties: Non-decreasing, right-continuous, $\lim_{x \rightarrow -\infty} F(x) = 0$, $\lim_{x \rightarrow \infty} F(x) = 1$

Example: Rolling a Die

$X \sim \text{Uniform}\{1, 2, 3, 4, 5, 6\}$: $p_X(k) = 1/6$ for $k = 1, \dots, 6$

$F_X(3.5) = \mathbb{P}(X \leq 3.5) = \mathbb{P}(X \in \{1, 2, 3\}) = 3/6 = 0.5$

Example: Fair Die Roll



Bernoulli Distribution

Definition: Models a single trial with two outcomes (success/failure)

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

PMF:

$$p_X(x) = \begin{cases} p & \text{if } x = 1 \\ 1 - p & \text{if } x = 0 \end{cases}$$

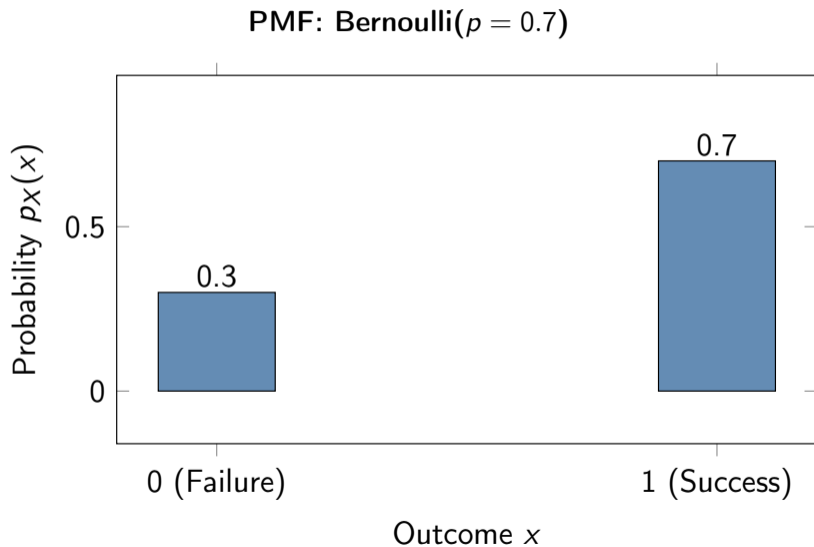
Or compactly: $p_X(x) = p^x(1-p)^{1-x}$ for $x \in \{0, 1\}$

Properties:

- $\mathbb{E}[X] = p$
- $\text{Var}(X) = p(1-p)$

Engineering Examples

- Component passes inspection ($p = 0.95$)
- Weld is defective ($p = 0.02$)
- Structure survives earthquake ($p = 0.98$)



Binomial Distribution

Story: Number of successes in n independent Bernoulli(p) trials

$$X \sim \text{Binomial}(n, p)$$

PMF:

$$p_X(k) = \binom{n}{k} p^k (1-p)^{n-k}, \quad k = 0, 1, \dots, n$$

where $\binom{n}{k} = \frac{n!}{k!(n-k)!}$

Properties:

- $\mathbb{E}[X] = np$
- $\text{Var}(X) = np(1-p)$

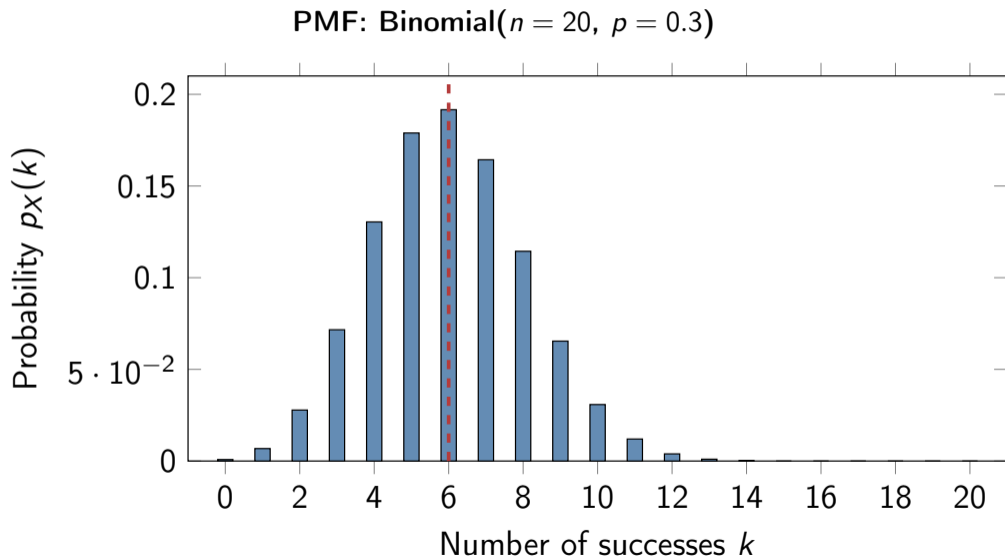
Example

Test 20 components, each passes with probability 0.95

$$X \sim \text{Bin}(20, 0.95), \mathbb{E}[X] = 20 \times 0.95 = 19$$

$$\mathbb{P}(X = 20) = (0.95)^{20} \approx 0.358$$

Visualizing Binomial Distribution



Hypergeometric Distribution

Story: Sampling without replacement from finite population

Population: N total objects, K are successes; Draw n objects without replacement; X = successes in sample

$$X \sim \text{HGeom}(N, K, n)$$

PMF:

$$p_X(k) = \frac{\binom{K}{k} \binom{N-K}{n-k}}{\binom{N}{n}}$$

Properties:

- $\mathbb{E}[X] = n \cdot \frac{K}{N}$
- $\text{Var}(X) = n \cdot \frac{K}{N} \cdot \frac{N-K}{N} \cdot \frac{N-n}{N-1}$

Example

Batch of 100 parts, 5 defective. Sample 10 parts.

$$X \sim \text{HGeom}(100, 5, 10), \mathbb{E}[X] = 10 \times \frac{5}{100} = 0.5$$

Poisson Distribution

Story: Number of rare events in fixed time/space interval

$$X \sim \text{Poisson}(\lambda)$$

where $\lambda > 0$ is the rate parameter (average number of events)

PMF:

$$p_X(k) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad k = 0, 1, 2, \dots$$

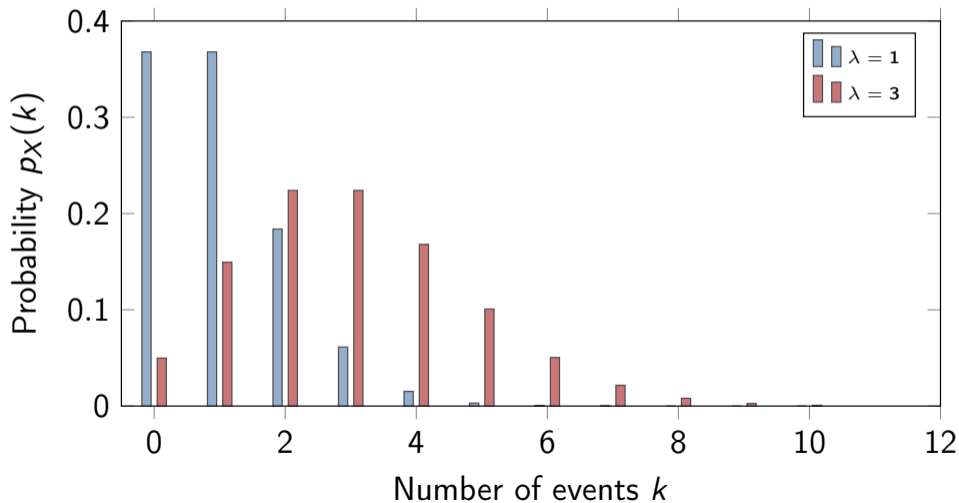
Properties:

- $\mathbb{E}[X] = \lambda$
- $\text{Var}(X) = \lambda$ (unique property!)
- Approximates Binomial when n large, p small, $np = \lambda$ moderate

Engineering Examples

- Number of trucks crossing bridge per hour ($\lambda = 50$)
- Number of accidents per year at intersection ($\lambda = 3$)
- Number of defects per 100m of pipeline ($\lambda = 0.5$)

Comparing Poisson PMFs for Different λ



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Expectation: The Average Value

Definition: Expected value (mean) of discrete random variable X :

$$\mathbb{E}[X] = \sum_x x \cdot p_X(x)$$

For continuous X with PDF f_X :

$$\mathbb{E}[X] = \int_{-\infty}^{\infty} x \cdot f_X(x) dx$$

Interpretation:

- Long-run average value
- Center of mass of distribution
- "Typical" value (but may never actually occur!)

Example: Die Roll

$X \sim \text{Uniform}\{1, 2, 3, 4, 5, 6\}$

$$\mathbb{E}[X] = 1 \cdot \frac{1}{6} + 2 \cdot \frac{1}{6} + \cdots + 6 \cdot \frac{1}{6} = \frac{21}{6} = 3.5$$

Properties of Expectation

Linearity of Expectation: For any constants a, b and random variables X, Y :

$$\mathbb{E}[aX + bY] = a\mathbb{E}[X] + b\mathbb{E}[Y]$$

Key Points:

- Works for ANY random variables (independent or not!)
- Most useful property for calculations
- Extends to any finite number of variables

Example

$X \sim \text{Bin}(100, 0.3)$ represents number of defective items.

Write $X = X_1 + X_2 + \dots + X_{100}$ where $X_i \sim \text{Bern}(0.3)$

By linearity:

$$\mathbb{E}[X] = \mathbb{E}[X_1] + \mathbb{E}[X_2] + \dots + \mathbb{E}[X_{100}] = 100 \times 0.3 = 30$$

No need to sum over all possible values!

Non-Linearity

$\mathbb{E}[X^2] \neq (\mathbb{E}[X])^2$ in general!

Law of the Unconscious Statistician (LOTUS)

LOTUS: To find $\mathbb{E}[g(X)]$ for function g :

$$\mathbb{E}[g(X)] = \sum_x g(x) \cdot p_X(x) \quad (\text{discrete})$$

$$\mathbb{E}[g(X)] = \int_{-\infty}^{\infty} g(x) \cdot f_X(x) dx \quad (\text{continuous})$$

Key Insight: Don't need to find distribution of $g(X)$!

Example

$X \sim \text{Uniform}\{1, 2, 3, 4, 5, 6\}$. Find $\mathbb{E}[X^2]$:

$$\begin{aligned} \mathbb{E}[X^2] &= 1^2 \cdot \frac{1}{6} + 2^2 \cdot \frac{1}{6} + \cdots + 6^2 \cdot \frac{1}{6} \\ &= \frac{1 + 4 + 9 + 16 + 25 + 36}{6} = \frac{91}{6} \approx 15.17 \end{aligned}$$

Applications:

- Computing variance: $\text{Var}(X) = \mathbb{E}[X^2] - (\mathbb{E}[X])^2$
- Finding moments: $\mathbb{E}[X^n]$
- Expected value of transformations

Variance: Measuring Spread

Definition: Variance measures average squared deviation from mean

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

Computational Formula:

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

Standard Deviation: $\text{SD}(X) = \sqrt{\text{Var}(X)}$ (same units as X)

Properties:

- $\text{Var}(aX + b) = a^2 \text{Var}(X)$ (constants: b shifts, a scales)
- $\text{Var}(X + Y) = \text{Var}(X) + \text{Var}(Y)$ if X, Y independent
- $\text{Var}(X) \geq 0$ always

Example: Die Roll

$X \sim \text{Uniform}\{1, 2, 3, 4, 5, 6\}$, $\mathbb{E}[X] = 3.5$, $\mathbb{E}[X^2] = 15.17$
 $\text{Var}(X) = 15.17 - (3.5)^2 = 15.17 - 12.25 = 2.92$

Binomial Variance

$X \sim \text{Bin}(n, p)$: Write $X = X_1 + \cdots + X_n$, $X_i \sim \text{Bern}(p)$ independent

$\mathbb{E}[X] = np$ (by linearity)

$\text{Var}(X) = \text{Var}(X_1) + \cdots + \text{Var}(X_n)$ (by independence)
 $= n \cdot p(1 - p) = np(1 - p)$

Geometric Distribution

$X \sim \text{Geom}(p)$: Number of trials until first success

PMF: $\mathbb{P}(X = k) = (1 - p)^{k-1}p$ for $k = 1, 2, 3, \dots$

$\mathbb{E}[X] = \frac{1}{p}$ (e.g., if $p = 0.1$, expect 10 trials)

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

Memoryless property: $\mathbb{P}(X > n + k \mid X > n) = \mathbb{P}(X > k)$

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Definition: Random variable X is continuous if it can take any value in an interval

Probability Density Function (PDF): $f_X(x)$

- NOT a probability! $f_X(x)$ can be > 1
- $\mathbb{P}(a \leq X \leq b) = \int_a^b f_X(x) dx$
- $\mathbb{P}(X = x) = 0$ for any specific value x

Properties of PDF:

- 1 $f_X(x) \geq 0$ for all x
- 2 $\int_{-\infty}^{\infty} f_X(x) dx = 1$

CDF: $F_X(x) = \mathbb{P}(X \leq x) = \int_{-\infty}^x f_X(t) dt$

Relationship: $f_X(x) = \frac{d}{dx} F_X(x)$

Uniform Distribution

Uniform Distribution on $[a, b]$: $X \sim \text{Unif}(a, b)$

All values equally likely in the interval

PDF:

$$f_X(x) = \begin{cases} \frac{1}{b-a} & \text{if } a \leq x \leq b \\ 0 & \text{otherwise} \end{cases}$$

CDF:

$$F_X(x) = \begin{cases} 0 & \text{if } x < a \\ \frac{x-a}{b-a} & \text{if } a \leq x \leq b \\ 1 & \text{if } x > b \end{cases}$$

Properties:

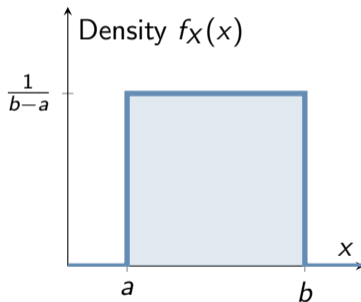
- $\mathbb{E}[X] = \frac{a+b}{2}$ (midpoint)
- $\text{Var}(X) = \frac{(b-a)^2}{12}$

Example

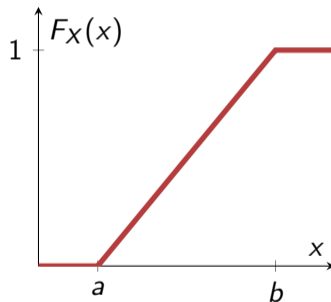
Random position on 10m beam: $X \sim \text{Unif}(0, 10)$

PDF and CDF for Uniform($a = 1, b = 4$)

Probability Density Function



Cumulative Distribution Function



Key: All values in $[a, b]$ equally likely; constant PDF

Normal Distribution

Normal (Gaussian) Distribution: $X \sim \mathcal{N}(\mu, \sigma^2)$

Most important distribution in statistics!

PDF:

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Properties:

- $\mathbb{E}[X] = \mu$ (location parameter)
- $\text{Var}(X) = \sigma^2$ (scale parameter)
- Symmetric around μ
- Bell-shaped curve

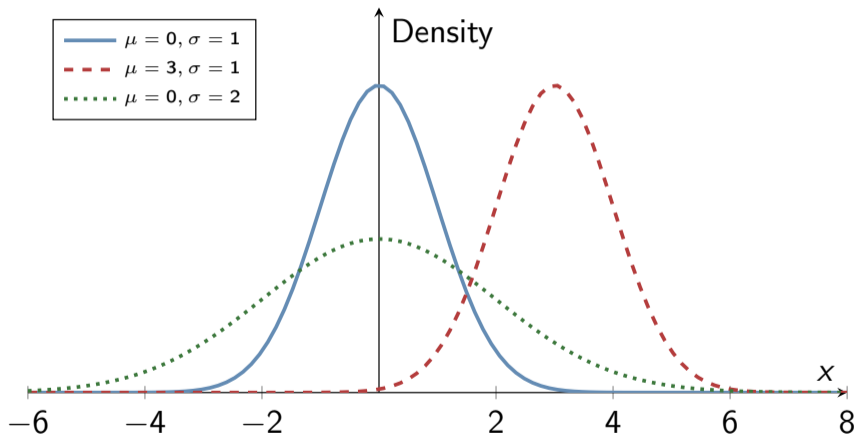
Standard Normal: $Z \sim \mathcal{N}(0, 1)$

$$Z = \frac{X - \mu}{\sigma}$$

CDF denoted $\Phi(z)$, used for calculations

Visualizing Normal Distribution

Effect of Parameters μ and σ

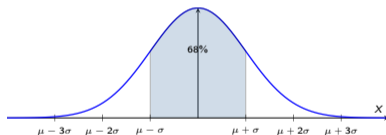


Key Insights: μ shifts location, σ controls spread

Normal Distribution: The 68-95-99.7 Rule

Empirical Rule: For $X \sim \mathcal{N}(\mu, \sigma^2)$:

- $\mathbb{P}(\mu - \sigma \leq X \leq \mu + \sigma) \approx 0.68$ (68%)
- $\mathbb{P}(\mu - 2\sigma \leq X \leq \mu + 2\sigma) \approx 0.95$ (95%)
- $\mathbb{P}(\mu - 3\sigma \leq X \leq \mu + 3\sigma) \approx 0.997$ (99.7%)



Example

Steel yield strength: $X \sim \mathcal{N}(250, 15^2)$ MPa

About 95% of specimens have strength between $250 - 30 = 220$ and $250 + 30 = 280$ MPa

Exponential Distribution

Exponential Distribution: $X \sim \text{Expo}(\lambda)$

Models time until an event occurs (waiting times, lifetimes)

PDF:

$$f_X(x) = \lambda e^{-\lambda x}, \quad x \geq 0$$

CDF:

$$F_X(x) = 1 - e^{-\lambda x}, \quad x \geq 0$$

Properties:

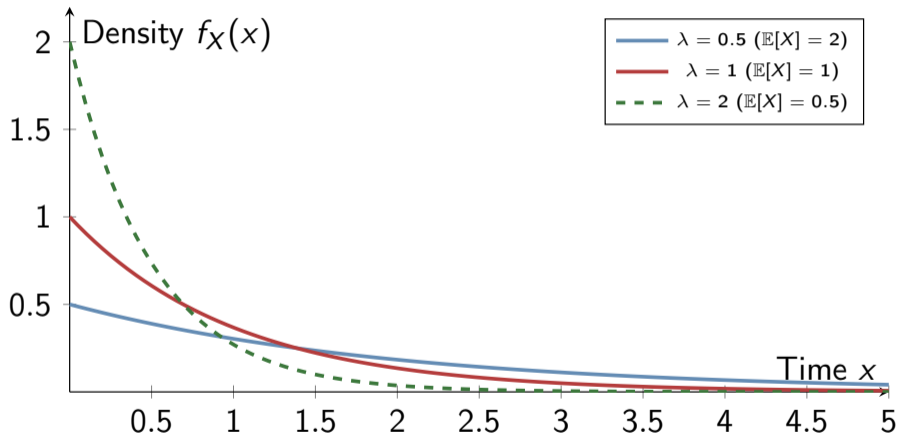
- $\mathbb{E}[X] = \frac{1}{\lambda}$ (average waiting time)
- $\text{Var}(X) = \frac{1}{\lambda^2}$
- Memoryless: $\mathbb{P}(X > s + t \mid X > s) = \mathbb{P}(X > t)$
- Related to Poisson: If events follow $\text{Poisson}(\lambda)$, inter-arrival times follow $\text{Expo}(\lambda)$

Example

Time until component failure: $X \sim \text{Expo}(0.01)$ hours

$$\mathbb{E}[X] = 100 \text{ hours}, \quad \mathbb{P}(X > 100) = e^{-1} \approx 0.368$$

PDF for Different Rate Parameters λ



Memoryless Property: Past doesn't affect future waiting time

Continuous RVs: Expected Value and Variance

Expected Value:

$$\mathbb{E}[X] = \int_{-\infty}^{\infty} x \cdot f_X(x) dx$$

LOTUS for Continuous:

$$\mathbb{E}[g(X)] = \int_{-\infty}^{\infty} g(x) \cdot f_X(x) dx$$

Variance:

$$\text{Var}(X) = \mathbb{E}[X^2] - (\mathbb{E}[X])^2 = \int_{-\infty}^{\infty} (x - \mu)^2 f_X(x) dx$$

All properties from discrete case carry over:

- Linearity: $\mathbb{E}[aX + bY] = a\mathbb{E}[X] + b\mathbb{E}[Y]$
- $\text{Var}(aX + b) = a^2\text{Var}(X)$
- If X, Y independent: $\text{Var}(X + Y) = \text{Var}(X) + \text{Var}(Y)$

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Definition of Moments

Raw Moments (about origin):

$$\mu'_n = \mathbb{E}[X^n]$$

- $\mu'_1 = \mathbb{E}[X]$ (mean)
- $\mu'_2 = \mathbb{E}[X^2]$
- $\mu'_3 = \mathbb{E}[X^3]$
- $\mu'_n = \mathbb{E}[X^n]$

Central Moments (about mean μ):

$$\mu_n = \mathbb{E}[(X - \mu)^n]$$

- $\mu_1 = 0$ (always)
- $\mu_2 = \text{Var}(X)$ (variance)
- μ_3 related to skewness
- μ_4 related to kurtosis

Intuition: Moments are summary statistics that capture key features of distribution

Mean and Variance (1st and 2nd Moments)

Mean (1st Raw Moment):

$$\mu = \mathbb{E}[X] = \mu'_1$$

- Center of distribution
- Expected value, average

Variance (2nd Central Moment):

$$\sigma^2 = \text{Var}(X) = \mathbb{E}[(X - \mu)^2] = \mu_2$$

Using computational formula:

$$\text{Var}(X) = \mathbb{E}[X^2] - (\mathbb{E}[X])^2 = \mu'_2 - (\mu'_1)^2$$

- Spread of distribution
- Average squared deviation from mean
- Units: (original units)²

Standard Deviation: $\sigma = \sqrt{\text{Var}(X)}$ (same units as X)

Skewness (3rd Moment)

Skewness: Measures asymmetry of distribution

$$\text{Skewness} = \frac{\mathbb{E}[(X - \mu)^3]}{\sigma^3} = \frac{\mu_3}{\sigma^3}$$

Interpretation:

- Skewness = 0: Symmetric
- Skewness > 0: Right-skewed (long right tail)
- Skewness < 0: Left-skewed (long left tail)



Engineering Relevance:

- Extreme loads often right-skewed
- Material strengths may be left-skewed
- Affects reliability calculations

Kurtosis (4th Moment)

Kurtosis: Measures tail heaviness / peakedness

$$\text{Kurtosis} = \frac{\mathbb{E}[(X - \mu)^4]}{\sigma^4} = \frac{\mu_4}{\sigma^4}$$

Excess Kurtosis: Kurtosis - 3 (so Normal has excess kurtosis 0)

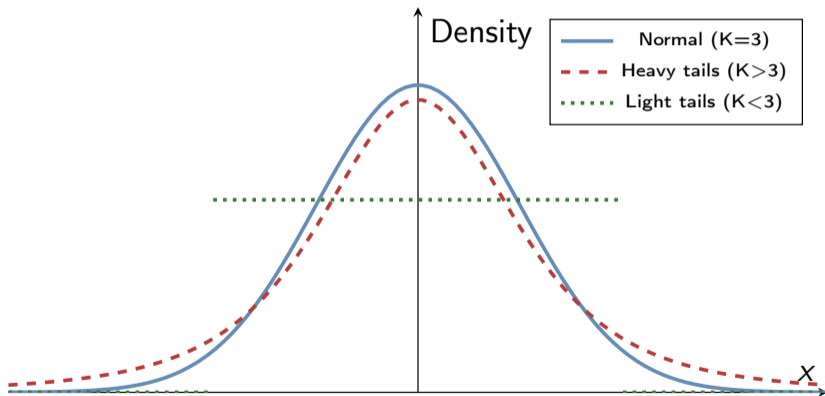
Interpretation:

- Normal distribution: Kurtosis = 3
- Kurtosis > 3 (leptokurtic): Heavy tails, more outliers
- Kurtosis < 3 (platykurtic): Light tails, fewer outliers

Engineering Relevance:

- High kurtosis: Greater risk of extreme events
- Important for safety and reliability analysis
- Affects probability of exceeding design thresholds

Comparing Distributions with Different Kurtosis



Key: High kurtosis means more probability in tails (extreme values)

Moment Generating Functions (MGFs)

Definition: For random variable X , $M_X(t) = \mathbb{E}[e^{tX}]$ (exists if finite for t near 0)

Why "Moment Generating"?

$$\begin{aligned} M_X(t) &= \mathbb{E}[e^{tX}] = \mathbb{E}\left[1 + tX + \frac{t^2 X^2}{2!} + \frac{t^3 X^3}{3!} + \dots\right] \\ &= 1 + t\mathbb{E}[X] + \frac{t^2}{2!}\mathbb{E}[X^2] + \frac{t^3}{3!}\mathbb{E}[X^3] + \dots \end{aligned}$$

Taking derivatives at $t = 0$:

$$\mathbb{E}[X^n] = \left. \frac{d^n}{dt^n} M_X(t) \right|_{t=0}$$

Key Properties:

- Uniquely determines distribution
- $M_{aX+b}(t) = e^{bt} M_X(at)$
- If X, Y independent: $M_{X+Y}(t) = M_X(t) \cdot M_Y(t)$

MGF Examples

Bernoulli(p)

$$M_X(t) = (1 - p) + pe^t$$

Binomial(n, p)

$$M_X(t) = ((1 - p) + pe^t)^n$$

Note: MGF of sum of n independent Bernoullis!

Poisson(λ)

$$M_X(t) = e^{\lambda(e^t - 1)}$$

Normal(μ, σ^2)

$$M_X(t) = e^{\mu t + \frac{\sigma^2 t^2}{2}}$$

Using MGFs to Find Moments

Exponential(λ)

$$M_X(t) = \frac{\lambda}{\lambda - t}, \quad t < \lambda$$

Example: Poisson(λ)

$$M_X(t) = e^{\lambda(e^t - 1)}$$

First moment (mean):

$$M'_X(t) = \lambda e^t \cdot e^{\lambda(e^t - 1)}$$

$$\mathbb{E}[X] = M'_X(0) = \lambda e^0 \cdot e^0 = \lambda$$

Second moment:

$$M''_X(t) = [\lambda e^t]^2 e^{\lambda(e^t - 1)} + \lambda e^t e^{\lambda(e^t - 1)}$$

$$\mathbb{E}[X^2] = M''_X(0) = \lambda^2 + \lambda$$

Variance:

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

Poisson has unique property: mean = variance!

Summary of Key Distributions

Distribution	Parameters	Mean	Variance
Bernoulli	p	p	$p(1 - p)$
Binomial	n, p	np	$np(1 - p)$
Poisson	λ	λ	λ
Geometric	p	$1/p$	$(1 - p)/p^2$
Uniform	a, b	$(a + b)/2$	$(b - a)^2/12$
Normal	μ, σ^2	μ	σ^2
Exponential	λ	$1/\lambda$	$1/\lambda^2$

Remember:

- Choose distribution based on problem context
- Discrete: Count data (Bernoulli, Binomial, Poisson)

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Summary: Statistical Analysis Core Topics

What We Covered:

- ➊ **Descriptive Statistics:** Mean, median, variance, skewness, kurtosis, visualization
- ➋ **Probability Review:** Sample spaces, conditional probability, Bayes' theorem
- ➌ **Discrete Distributions:** Bernoulli, Binomial, Hypergeometric, Poisson
- ➍ **Expectation & Variance:** Linearity, LOTUS, computational methods
- ➎ **Continuous Distributions:** Uniform, Normal (68-95-99.7 rule), Exponential
- ➏ **Moments & MGFs:** Summary measures, skewness, kurtosis, moment generating functions

Key Takeaways:

- Statistical methods provide tools to understand and quantify uncertainty
- Choose appropriate distributions based on problem context
- Expectation and variance are fundamental summary statistics
- MGFs provide powerful technique for deriving moments

Next Steps and Applications

Where to Go from Here:

- **Joint Distributions:** Multiple random variables, correlation
- **Sampling Distributions:** Sample mean, Central Limit Theorem
- **Statistical Inference:** Hypothesis testing, confidence intervals
- **Regression:** Modeling relationships between variables

Engineering Applications:

- Reliability analysis and design
- Quality control and process monitoring
- Risk assessment and decision-making
- Data-driven modeling and prediction

Practice Recommendation

Work through examples with real engineering data using Python (NumPy, Pandas, SciPy, Matplotlib) to solidify these concepts!

Thank You!

Questions?

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