

Sampling, Experiments, and Probability

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Lecturer in AI and Machine Learning for Sustainable Construction

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Learning Objectives

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After this lecture, you should be able to:

Describe the sample space for a random experiment

Compute relative frequency and empirical probability

Understand probability rules for events and combinations

Explain the law of large numbers

Understand conditional probability and independence

Use Bayes' theorem for real-world applications

This lecture is adapted from Chapters 6 and 7 of R. A. Poldrack [1].

Learning Objectives

These learning objectives are carefully chosen to focus on practical understanding rather than mathematical rigor. They align with the chapter's goals while remaining accessible to non-technical students.

Key teaching points:

- ▶ Emphasize practical understanding over mathematical formalism
- ▶ Focus on concepts that will be useful in business and data analysis
- ▶ Build foundation for later statistical concepts

Probability

Introduction

Probability theory is the branch of mathematics that deals with chance and uncertainty. It forms an important part of the foundation for statistics, because it provides us with the mathematical tools to describe uncertain events.

- ▶ Historical Origins

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Probability theory is the branch of mathematics that deals with chance and uncertainty. It forms an important part of the foundation for statistics, because it provides us with the mathematical tools to describe uncertain events.

- ▶ Historical Origins

- Developed by mathematicians studying gambling
- Key advances from Pascal and Fermat's correspondence
- Evolved into fundamental tool for statistics

- ▶ Modern Applications

- Business decision-making under uncertainty
- Weather forecasting and risk assessment
- Medical diagnosis and testing
- Data analysis and machine learning

Introduction

The study of probability arose in part due to interest in understanding games of chance, like cards or dice. These games provide useful examples of many statistical concepts, because when we repeat these games the likelihood of different outcomes remains (mostly) the same.

Historical context:

- ▶ Early probability theory developed by mathematicians studying gambling
- ▶ Pascal and Fermat's correspondence about gambling problems
- ▶ Evolution into a fundamental tool for statistics and data analysis

Key points to emphasize:

- ▶ Probability helps us quantify uncertainty
- ▶ Games of chance provide consistent, repeatable examples
- ▶ Forms the foundation for all statistical analysis
- ▶ Relevant to business decisions under uncertainty

Introduction

Teaching tip: Start by asking students about their intuitive understanding of probability - they likely encounter it daily in weather forecasts, sports statistics, or business reports.

Common misconceptions to address:

- ▶ Probability is not just about gambling
- ▶ While based in mathematics, focus will be on practical understanding
- ▶ Importance in modern data analysis and decision making

What is Probability?

- ▶ A number describing the likelihood of an event occurring
- ▶ Ranges from 0 (impossibility) to 1 (certainty)
- ▶ Sometimes expressed as percentages (0% to 100%)

Examples from everyday life:

- ▶ Weather forecast: “20% chance of rain today”
- ▶ Sports: Steph Curry’s 91% free throw success rate
- ▶ Medical tests: PSA test with 80% sensitivity

Informally, we usually think of probability as a number that describes the likelihood of some event occurring, which ranges from zero (impossibility) to one (certainty). Sometimes probabilities will instead be expressed in percentages, which range from zero to one hundred.

Key concepts to emphasize:

What is Probability?

1. Probability scale:

- ▶ 0 = impossible (e.g., rolling a 7 on a six-sided die)
- ▶ 1 = certain (e.g., rolling a number between 1 and 6 on a six-sided die)
- ▶ Most real-world events fall between these extremes

2. Everyday encounters with probability:

- ▶ Weather forecasts: Percentage chance of rain
- ▶ Sports statistics: Player performance rates
- ▶ Medical tests: Accuracy rates
- ▶ Insurance: Risk assessments

3. Common misconceptions:

- ▶ A 20% chance of rain doesn't mean it will rain 20% of the day
- ▶ Probabilities don't predict individual outcomes, only long-term patterns

What is Probability?

- ▶ Even very unlikely events can happen (and do happen regularly)

4. Historical context:

- ▶ Early probability theory developed through analysis of games of chance
- ▶ Modern applications far beyond gambling
- ▶ Critical role in scientific research and data analysis

Teaching tips:

- ▶ Ask students about their daily encounters with probability
- ▶ Discuss how they interpret weather forecasts
- ▶ Challenge intuitive misconceptions about probability
- ▶ Connect to real-world decision-making under uncertainty

Time allocation: Spend about 3-4 minutes on this slide to establish fundamental concepts that will be built upon throughout the lecture.

Key Terms

1. Experiment

Any activity that produces or observes an outcome

- ▶ Simple Examples:

Key Terms

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1. Experiment

Any activity that produces or observes an outcome

- ▶ Simple Examples:
 - Flipping a coin
 - Rolling a die
 - Drawing a card
- ▶ Real-world Examples:
 - Trying a new route to work
 - Testing a medical treatment
 - Measuring customer satisfaction

2. Sample Space

Set of all possible outcomes

Key Terms

- ▶ Discrete Sets:

Key Terms

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2. Sample Space

Set of all possible outcomes

Key Terms

- ▶ Discrete Sets:
 - Coin flip: {heads, tails}
 - Six-sided die: {1,2,3,4,5,6}
 - Card draw: {52 possible cards}
- ▶ Continuous Sets:
 - Time to work: all real numbers > 0
 - Temperature readings
 - Stock prices

3. Event

A subset of the sample space

- ▶ Single Events:

Key Terms

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 - Flipping a coin
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 - Time to work: all real numbers > 0
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 - Stock prices

3. Event

A subset of the sample space

- ▶ Single Events:
 - Getting heads in a coin flip
 - Rolling a 4 on a die

Key Terms

- Drawing the ace of spades
- ▶ Compound Events:
 - Rolling an even number
 - Drawing a red card
 - Arriving at work in under 20 minutes

To formalize probability theory, we need these precise definitions:

An experiment is any activity that produces or observes an outcome. Examples are flipping a coin, rolling a 6-sided die, or trying a new route to work to see if it's faster than the old route.

The sample space is the set of possible outcomes for an experiment. We represent these by listing them within a set of squiggly brackets. For a coin flip, the sample space is {heads, tails}. For a six-sided die, the sample space is each of the possible numbers that can appear: {1,2,3,4,5,6}. For the amount of time it takes to get to work, the sample space is all possible

Key Terms

real numbers greater than zero (since it can't take a negative amount of time to get somewhere, at least not yet).

An event is a subset of the sample space. In principle it could be one or more of possible outcomes in the sample space, but here we will focus primarily on elementary events which consist of exactly one possible outcome.

Formal Properties of Probability

Kolmogorov's axioms define what makes a value a probability:

1. Non-negativity: Probability cannot be negative

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1. Non-negativity: Probability cannot be negative
 - ▶ $P(E_i) \geq 0$
 - ▶ Example: Can't have -10% chance of rain
 - ▶ All probabilities must be zero or positive
2. Total Probability: All outcomes sum to 1

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- ▶ All probabilities must be zero or positive

2. Total Probability: All outcomes sum to 1

- ▶ $\sum_{i=1}^N P(E_i) = 1$
- ▶ Example: Rolling a die
 - $P(1) + P(2) + P(3) + P(4) + P(5) + P(6) = 1$
 - Each $P(\text{number}) = 1/6$, so $6 \cdot (1/6) = 1$

3. Upper Bound: Individual probability ≤ 1

- ▶ $P(E_i) \leq 1$
- ▶ Follows from rules 1 and 2

Formal Properties of Probability

- ▶ Example: Can't have 120% chance of success

Why These Rules Matter:

- ▶ Ensure mathematical consistency
- ▶ Enable probability calculations
- ▶ Form foundation for statistics

These formal features of probability were first defined by the Russian mathematician Andrei Kolmogorov. These are the features that a value has to have if it is going to be a probability.

Let's say that we have a sample space defined by N independent events, E_1, E_2, \dots, E_N , and X is a random variable denoting which of the events has occurred. $P(X = E_i)$ is the probability of event i .

Formal Properties of Probability

The second point means that if we take the probability of each E_i and add them up, they must sum to 1. The third point is implied by the second; since they must sum to one, and they can't be negative, then any particular probability cannot exceed one.

How Do We Determine Probabilities?

Three main approaches:

Personal Belief

- ▶ Based on knowledge and experience

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- ▶ Cannot verify through experiments

Empirical Frequency

- ▶ Based on actual data collection

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- ▶ Example: Rain in San Francisco

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Empirical Frequency

- ▶ Based on actual data collection
- ▶ Example: Rain in San Francisco
 - 73 rainy days in 2017
 - $P(\text{rain}) = 73/375$
- ▶ Requires sufficient data

Classical Probability

How Do We Determine Probabilities?

- ▶ Based on equally likely outcomes

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Classical Probability

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- ▶ Based on equally likely outcomes
- ▶ Example: Fair six-sided die

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- ▶ Example: Rain in San Francisco
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Classical Probability

How Do We Determine Probabilities?

- ▶ Based on equally likely outcomes
- ▶ Example: Fair six-sided die
 - $P(\text{rolling a 6}) = 1/6$
- ▶ Mathematical approach

Probability Distributions: Free Throw Example

Steph Curry's free throw success in 4 attempts:

```
curry_df <- tibble(  
  numSuccesses = seq(0, 4)  
) |>  
  mutate(  
    Probability = dbinom(numSuccesses, size = 4, prob = 0.91),  
    CumulativeProbability = pbinom(numSuccesses, size = 4, prob = 0.91)  
  )  
  
kable(curry_df, caption='Simple and cumulative probability distributions',  
      digits=4)
```

numSuccesses	Probability	CumulativeProbability
0	0.0001	0.0001
1	0.0027	0.0027

Probability Distributions: Free Throw Example

numSuccesses	Probability	CumulativeProbability
2	0.0402	0.0430
3	0.2713	0.3143
4	0.6857	1.0000

- Understanding the Table:

Probability Distributions: Free Throw Example

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- Understanding the Table:

- numSuccesses: Number of successful free throws
- Probability: Chance of exactly that many successes
- CumulativeProbability: Chance of that many or fewer successes

- Key Insights:

- Most likely outcome: 4 successes (0.6853)
- Very unlikely to make 0-2 shots (0.0421)
- Shows why Curry is considered elite

1. Personal Belief:

Probability Distributions: Free Throw Example

- ▶ Used when we can't do the actual experiment
- ▶ Example: What if Bernie Sanders had been the Democratic nominee in 2016?
- ▶ Based on knowledge of politics, polls, historical data
- ▶ Limitations: Subjective, can vary between experts
- ▶ Often the only available method for unique events

2. Empirical Frequency:

- ▶ Most scientific approach when data is available
- ▶ San Francisco rain example:
 - Define the experiment: Check daily rain data
 - Count outcomes: 73 rainy days in 2017
 - Calculate probability: $73/365 = 0.2$
- ▶ Advantages:
 - Based on actual data

Probability Distributions: Free Throw Example

- Can be verified and repeated

- ▶ Limitations:

- Requires sufficient data

- Past data may not predict future events

- Sample size affects accuracy

3. Classical Probability:

- ▶ Based on equally likely outcomes

- ▶ Examples from games of chance:

- Die rolls: Each number has $1/6$ probability

- Coin flips: Heads and tails each $1/2$

- ▶ Advantages:

- Can calculate without data collection

- Precise mathematical basis

Probability Distributions: Free Throw Example

- ▶ Limitations:
 - Requires truly equal probabilities
 - Rare in real-world situations

Teaching tips:

- ▶ Start with personal belief examples to engage students
- ▶ Use San Francisco rain data to show how empirical probability works
- ▶ Use dice/coins to demonstrate classical probability
- ▶ Emphasize that different methods suit different situations

Time allocation: 8 minutes for this section

- ▶ 2-3 minutes for personal belief
- ▶ 3-4 minutes for empirical frequency with SF example
- ▶ 2-3 minutes for classical probability

Law of Large Numbers

As we increase the number of trials, our empirical probability approaches the true probability.

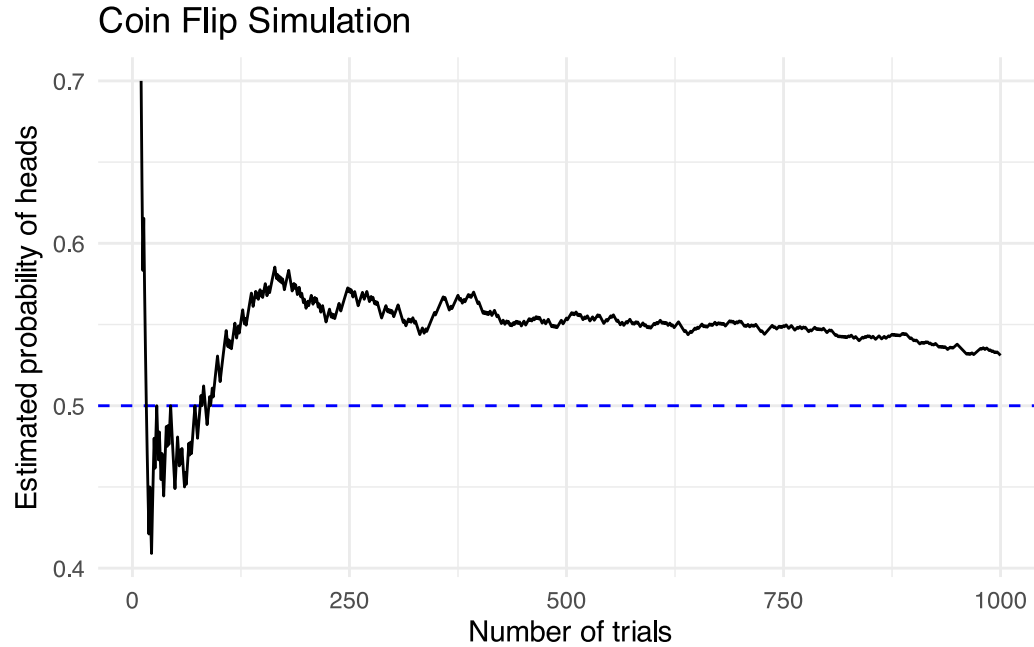
```
set.seed(12345)
nsamples <- 1000
sampDf <- tibble(
  trial_number = seq(nsamples),
  outcomes = rbinom(nsamples, 1, 0.5)
) |>
  mutate(mean_probability = cumsum(outcomes) / seq_along(outcomes))

ggplot(sampDf |> slice(10:nsamples),
  aes(x = trial_number, y = mean_probability)) +
  geom_hline(yintercept = 0.5, color = "blue", linetype = "dashed") +
  geom_line() +
  labs(
```

Law of Large Numbers

```
x = "Number of trials",  
y = "Estimated probability of heads",  
title = "Coin Flip Simulation"  
) +  
theme_minimal()
```

Law of Large Numbers



- Understanding the Graph:

Law of Large Numbers

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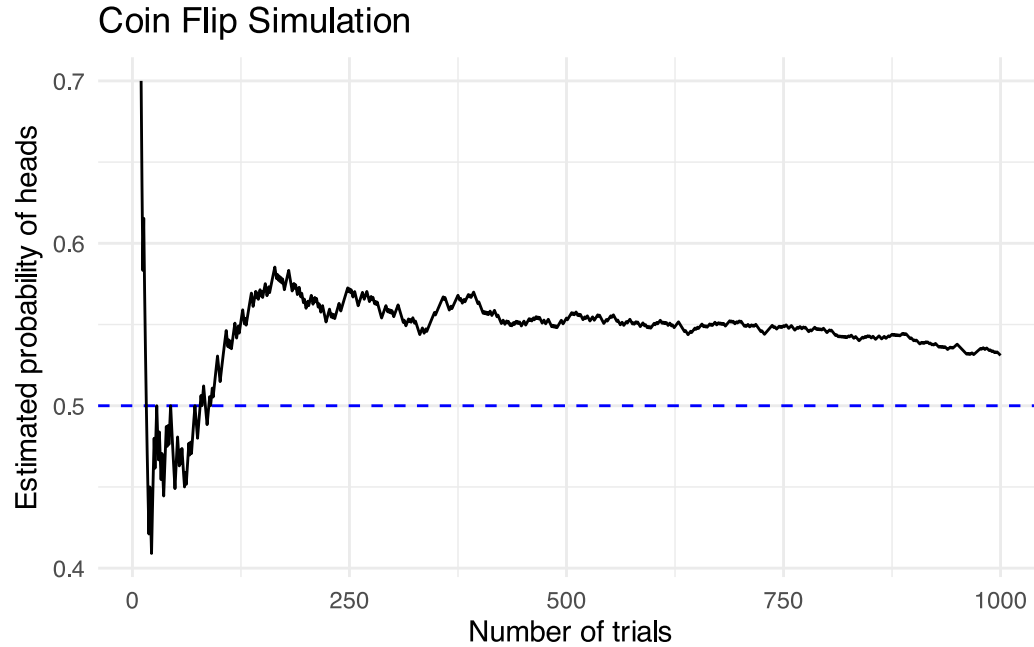
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Law of Large Numbers



- Understanding the Graph:
 - Blue line: True probability (0.5)
 - Black line: Observed probability

Law of Large Numbers

- High variability with small samples
- Converges to true value over time
- ▶ The “Law of Small Numbers”:
 - Common mistake: treating small samples like large ones
 - Term coined by Kahneman and Tversky
 - Even trained researchers make this error
 - Early results can be misleading

Real-World Example: 2017 Alabama Senate Election

- ▶ Early results highly volatile
 - Initial large lead for Jones
 - Switched to Moore leading
 - Finally Jones won
- ▶ Perfect illustration of why we need sufficient data

Law of Large Numbers

- ▶ Applies to:
 - Opinion polls
 - Medical studies
 - Market research

The Law of Large Numbers is a fundamental principle in probability theory that helps us understand why empirical probability works. It shows that as we increase our sample size, our observed probability gets closer to the true probability.

Key Points: 1. Coin Flip Simulation:

- ▶ Blue dashed line shows true probability (0.5)
- ▶ Black line shows observed probability
- ▶ Notice high variability with small samples
- ▶ Convergence to true probability with more flips

Law of Large Numbers

2. Alabama Senate Election Example:

- ▶ December 2017 special election between Doug Jones and Roy Moore
- ▶ Early in the evening, vote counts were especially volatile
- ▶ Initial large lead for Jones
- ▶ Switched to long period where Moore had the lead
- ▶ Finally Jones took the lead to win the race
- ▶ Perfect illustration of why early results can be misleading

3. The “Law of Small Numbers”:

- ▶ Term coined by Kahneman and Tversky
- ▶ Common mistake: treating small samples like large ones
- ▶ Even trained researchers make this error
- ▶ Important implications for research and decision-making

Law of Large Numbers

4. Practical Implications:

- ▶ Need large samples for reliable probability estimates
- ▶ Early results or small samples can be very misleading
- ▶ Particularly important in:
 - Opinion polls
 - Medical studies
 - Market research
 - Quality control

Teaching Tips:

- ▶ Use interactive examples to demonstrate variability
- ▶ Connect to students' experience with sports statistics
- ▶ Discuss implications for research and decision-making
- ▶ Emphasize why we need sufficient data for reliable conclusions

Law of Large Numbers

Time allocation: 5 minutes

- ▶ 2 minutes for coin flip simulation
- ▶ 2 minutes for Alabama election example
- ▶ 1 minute for implications and discussion

Classical Probability: de Méré's Problem

A famous gambling problem that helped develop probability theory:

1. First Game: At least one six in four dice rolls

Classical Probability: de Méré's Problem

A famous gambling problem that helped develop probability theory:

1. First Game: At least one six in four dice rolls
 - ▶ de Méré's calculation: $4 \cdot \frac{1}{6} = 2/3$
 - ▶ Actual probability: $1 - \left(\frac{5}{6}\right)^4 = 0.517$
 - ▶ He made money on this bet!
2. Second Game: At least one double-six in 24 rolls of two dice
 - ▶ de Méré's calculation: $24 \cdot \frac{1}{36} = 2/3$
 - ▶ Actual probability: $1 - \left(\frac{35}{36}\right)^{24} = 0.491$
 - ▶ He lost money on this bet

de Méré's Problem: Visual Analysis

```
imgmtx <- matrix(0, nrow = 6, ncol = 6)
imgmtx[, 1] <- 1
imgmtx[6, ] <- 1

plot <-
  imgmtx |>
  melt() |>
  ggplot(aes(Var1, Var2, fill = value)) +
  scale_fill_gradientn(colours=c("#0000FFFF", "#FFFFFF", "#FF0000FF")) +
  geom_raster(interpolate = FALSE)

for (i in seq(0.5, 6.5)) {
  plot <- plot + geom_hline(yintercept = i, color = "white")
  plot <- plot + geom_vline(xintercept = i, color = "white")
  for (j in seq(0.5, 6.5)) {
```

de Méré's Problem: Visual Analysis

```
plot <- plot + annotate(  
  "text",  
  x = i + 0.5, y = 6.5 - j,  
  label = sprintf("%d,%d", i + 0.5, j + 0.5),  
  color = "white")  
}  
}
```

```
plot +  
  theme_minimal() +  
  theme(  
    axis.line = element_blank(),  
    axis.text.x = element_blank(),  
    axis.text.y = element_blank(),  
    axis.ticks = element_blank(),
```

de Méré's Problem: Visual Analysis

```
    legend.position = "none"  
  ) +  
  labs(  
    x = "Throw 1",  
    y = "Throw 2"  
  )
```

de Méré's Problem: Visual Analysis

	1,1	2,1	3,1	4,1	5,1	6,1
	1,2	2,2	3,2	4,2	5,2	6,2
Throw 2	1,3	2,3	3,3	4,3	5,3	6,3
	1,4	2,4	3,4	4,4	5,4	6,4
	1,5	2,5	3,5	4,5	5,5	6,5
	1,6	2,6	3,6	4,6	5,6	6,6
	Throw 1					

- Matrix shows all possible outcomes of two dice throws

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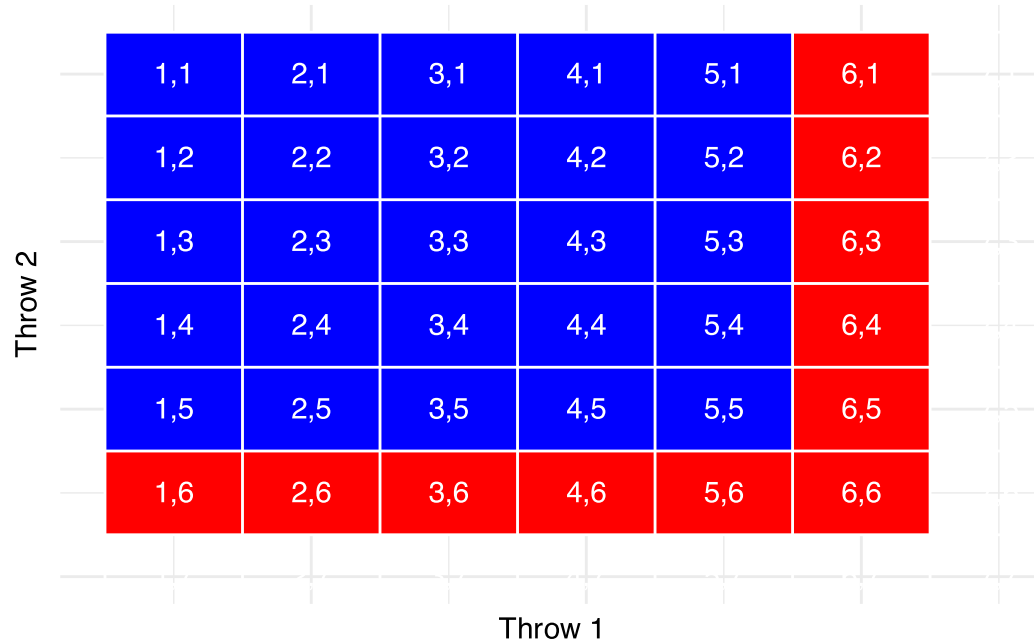
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Throw 2	1,3	2,3	3,3	4,3	5,3	6,3
	1,4	2,4	3,4	4,4	5,4	6,4
	1,5	2,5	3,5	4,5	5,5	6,5
	1,6	2,6	3,6	4,6	5,6	6,6
	Throw 1					

- ▶ Matrix shows all possible outcomes of two dice throws
- ▶ Red cells: Getting a six on either throw

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	1,2	2,2	3,2	4,2	5,2	6,2
Throw 2	1,3	2,3	3,3	4,3	5,3	6,3
	1,4	2,4	3,4	4,4	5,4	6,4
	1,5	2,5	3,5	4,5	5,5	6,5
	1,6	2,6	3,6	4,6	5,6	6,6
	Throw 1					

- ▶ Matrix shows all possible outcomes of two dice throws
- ▶ Red cells: Getting a six on either throw
- ▶ Blue cells: No sixes

de Méré's Problem: Visual Analysis

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de Méré's Problem: Visual Analysis

de Méré's Problem: Visual Analysis

```
imgmtx <- matrix(0, nrow = 6, ncol = 6)
imgmtx[, 1] <- 1
imgmtx[6, ] <- 1

plot <-
  imgmtx |>
  melt() |>
  ggplot(aes(Var1, Var2, fill = value)) +
  scale_fill_gradientn(colours=c("#0000FFFF", "#FFFFFF", "#FF0000FF")) +
  geom_raster(interpolate = FALSE)

for (i in seq(0.5, 6.5)) {
  plot <- plot + geom_hline(yintercept = i, color = "white")
  plot <- plot + geom_vline(xintercept = i, color = "white")
  for (j in seq(0.5, 6.5)) {
```


de Méré's Problem: Visual Analysis

```
plot <- plot + annotate(  
  "text",  
  x = i + 0.5, y = 6.5 - j,  
  label = sprintf("%d,%d", i + 0.5, j + 0.5),  
  color = "white")  
}  
}
```

```
plot +  
  theme_minimal() +  
  theme(  
    axis.line = element_blank(),  
    axis.text.x = element_blank(),  
    axis.text.y = element_blank(),  
    axis.ticks = element_blank(),
```

de Méré's Problem: Visual Analysis

```
    legend.position = "none"  
  ) +  
  labs(  
    x = "Throw 1",  
    y = "Throw 2"  
  )
```

de Méré's Problem: Visual Analysis

	1,1	2,1	3,1	4,1	5,1	6,1
	1,2	2,2	3,2	4,2	5,2	6,2
Throw 2	1,3	2,3	3,3	4,3	5,3	6,3
	1,4	2,4	3,4	4,4	5,4	6,4
	1,5	2,5	3,5	4,5	5,5	6,5
	1,6	2,6	3,6	4,6	5,6	6,6
	Throw 1					

- ▶ Matrix shows all possible outcomes of two dice throws
- ▶ Red cells: Getting a six on either throw
- ▶ Blue cells: No sixes

de Méré's Problem: Visual Analysis

- ▶ White cell (6,6): Double six counted only once

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de Méré's Problem: Visual Analysis

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}
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de Méré's Problem: Visual Analysis

```
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```

de Méré's Problem: Visual Analysis

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	1,4	2,4	3,4	4,4	5,4	6,4
	1,5	2,5	3,5	4,5	5,5	6,5
	1,6	2,6	3,6	4,6	5,6	6,6
	Throw 1					

- ▶ Matrix shows all possible outcomes of two dice throws
- ▶ Red cells: Getting a six on either throw
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de Méré's Problem: Visual Analysis

- ▶ White cell (6,6): Double six counted only once
- ▶ Shows why simple addition is wrong

This historical example introduces several key probability concepts:

1. The Problem:

- ▶ Chevalier de Méré was a French gambler
- ▶ Played two different dice games
- ▶ Consulted mathematician Blaise Pascal
- ▶ Led to development of probability theory

2. de Méré's Error:

- ▶ Simply added individual probabilities
- ▶ Didn't account for overlap in multiple events
- ▶ Shows why we need formal probability rules

de Méré's Problem: Visual Analysis

- ▶ Common mistake even today

3. Pascal's Solution:

- ▶ Instead of calculating success directly
- ▶ Calculated probability of no success
- ▶ Then used complement rule: $P(\text{success}) = 1 - P(\text{nosuccess})$
- ▶ For first game: $1 - \left(\frac{5}{6}\right)^4 = 0.517$
- ▶ For second game: $1 - \left(\frac{35}{36}\right)^{24} = 0.491$

4. Key Lessons:

- ▶ Simple addition of probabilities often wrong
- ▶ Multiple events require careful calculation
- ▶ Sometimes easier to calculate complement
- ▶ Small differences in probability matter

de Méré's Problem: Visual Analysis

- ▶ Mathematical analysis can reveal gambling errors

Teaching Tips:

- ▶ Use this to introduce probability rules
- ▶ Show why intuition can be misleading
- ▶ Demonstrate practical value of mathematical analysis
- ▶ Connect to modern probability applications

Time allocation: 7 minutes

- ▶ 2 minutes for historical context
- ▶ 3 minutes for calculations
- ▶ 2 minutes for implications

Conditional Probability

The probability of an event occurring, given that another event has occurred.

- ▶ Formula: $P(A|B) = \frac{P(A \cap B)}{P(B)}$

Conditional Probability

The probability of an event occurring, given that another event has occurred.

- ▶ Formula: $P(A|B) = \frac{P(A \cap B)}{P(B)}$
 - $P(A | B)$ reads as “probability of A given B”
 - $P(A \cap B)$ is the joint probability
 - $P(B)$ is the overall probability of B
- ▶ Visual Representation:
 - Total population splits into groups (e.g., voters by party)
 - Each group further splits by outcome (e.g., voting choice)
 - Conditional probability focuses on one branch

Health Data Example

NHANES data on physical activity and diabetes:

```
# Summarize NHANES data for diabetes and physical activity
NHANES_diabetes_activity <-
  NHANES |>
  distinct(ID, .keep_all = TRUE) |>
  drop_na(PhysActive, Diabetes)

NHANES_diabetes_stats_by_activity <-
  NHANES_diabetes_activity |>
  count(Diabetes, PhysActive) |>
  mutate(
    prob = n / sum(n)
  )
```


Health Data Example

```
kable(NHANES_diabetes_stats_by_activity, caption='Joint probabilities for  
Diabetes and Physical Activity')
```

Diabetes	PhysActive	n	prob
No	No	2123	0.3900423
No	Yes	2770	0.5089105
Yes	No	349	0.0641191
Yes	Yes	201	0.0369282

- Understanding the Data:

Health Data Example

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- ▶ Understanding the Data:
 - Joint probabilities show overlap between conditions
 - Can calculate: $P(\text{diabetes} \mid \text{inactive})$
 - Shows real-world health relationships
- ▶ Key Insights:
 - Physical activity associated with lower diabetes risk

Health Data Example

- Example of how conditional probability informs health research
- Useful for public health recommendations

So far we have limited ourselves to simple probabilities - that is, the probability of a single event or combination of events. However, we often wish to determine the probability of some event given that some other event has occurred, which are known as conditional probabilities.

Let's take the 2016 US Presidential election as an example. There are two simple probabilities that we could use to describe the electorate. First, we know the probability that a voter in the US is affiliated with the Republican party: $p(\text{Republican}) = 0.44$. We also know the probability that a voter cast their vote in favor of Donald Trump: $p(\text{Trump voter}) = 0.46$. However, let's say that we want to know the following: What is the probability that a person cast their vote for Donald Trump, given that they are a Republican?

Health Data Example

To compute the conditional probability of A given B (which we write as $P(A|B)$, “probability of A, given B”), we need to know the joint probability (that is, the probability of both A and B occurring) as well as the overall probability of B.

Independence

Two events are independent if:

$$P(A \mid B) = P(A)$$

Example 1: Political Independence

- ▶ California vs proposed state of Jefferson
- ▶ $P(\textit{Jeffersonian}) = 0.014$
- ▶ $P(\textit{Californian}) = 0.986$
- ▶ Not independent: If you're Jeffersonian, you can't be Californian!

Independence: Health Example

NHANES data on physical activity and mental health:

```
# compute probabilities for mental health and physical activity
NHANES_adult <-
  NHANES |>
  dplyr::filter(
    Age >= 18,
    !is.na(PhysActive),
    !is.na(DaysMentHlthBad)
  ) |>
  mutate(badMentalHealth = DaysMentHlthBad > 7,
         badMentalHealth = case_when(
           badMentalHealth == TRUE ~ "Bad Mental Health",
           badMentalHealth == FALSE ~ "Good Mental Health"
         ))
```

Independence: Health Example

```
NHANES_mentalhealth_by_physactive_counts <- NHANES_adult |> tabyl(PhysActive,
badMentalHealth) |> adorn_totals(c("row", "col"))

kable(NHANES_mentalhealth_by_physactive_counts, caption='Mental health status
by physical activity level')
```

PhysActive	Bad Mental Health	Good Mental Health	Total
No	629	2510	3139
Yes	471	3095	3566
Total	1100	5605	6705

► Testing Independence:

- Compare $P(\text{bad mental health} \mid \text{active})$ vs $P(\text{bad mental health})$
- If equal, variables would be independent
- Data shows they are not independent

Independence: Health Example

→ Physical and mental health are related

The term “independent” has a very specific meaning in statistics, which is somewhat different from the common usage of the term. Statistical independence between two variables means that knowing the value of one variable doesn’t tell us anything about the value of the other.

Looking at it this way, we see that many cases of what we would call “independence” in the real world are not actually statistically independent. For example, there is currently a move by a small group of California citizens to declare a new independent state called Jefferson, which would comprise a number of counties in northern California and Oregon. If this were to happen, then the probability that a current California resident would now live in the state of Jefferson would be $P(\text{Jeffersonian})=0.014$, whereas the probability that they would remain a California resident would be $P(\text{Californian})=0.986$.

Independence: Health Example

The new states might be politically independent, but they would not be statistically independent, because if we know that a person is Jeffersonian, then we can be sure that they are not Californian! Statistical independence refers to the case where one cannot predict anything about one variable from the value of another variable. For example, knowing a person's hair color is unlikely to tell you whether they prefer chocolate or strawberry ice cream.

Bayes' Rule

A powerful tool for updating probabilities based on new evidence:

- ▶ Basic Form: $P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$

Bayes' Rule

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A powerful tool for updating probabilities based on new evidence:

- ▶ Basic Form: $P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$
- ▶ Expanded Form: $P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A|B) \cdot P(B) + P(A|\text{neg } B) \cdot P(\text{neg } B)}$

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A powerful tool for updating probabilities based on new evidence:

- ▶ Basic Form: $P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A)}$
- ▶ Expanded Form: $P(B|A) = \frac{P(A|B) \cdot P(B)}{P(A|B) \cdot P(B) + P(A|\text{neg } B) \cdot P(\text{neg } B)}$
- ▶ Components:
 - $P(B \mid A)$ = Updated probability (posterior)
 - $P(A \mid B)$ = Likelihood of evidence
 - $P(B)$ = Initial probability (prior)
 - $P(A)$ = Overall probability of evidence

Medical Screening Example: PSA Test

- ▶ Given:
 - Sensitivity = $P(\text{positive} \mid \text{cancer}) = 0.8$
 - Specificity = $P(\text{negative} \mid \text{no cancer}) = 0.7$

Bayes' Rule

→ Base rate = $P(\text{cancer}) = 0.058$

► Calculation:

→ $P(\text{cancer} \mid \text{positive}) = \frac{0.8 \cdot 0.058}{0.8 \cdot 0.058 + 0.3 \cdot 0.942}$

→ = 0.14 (only 14% chance of cancer)

→ Shows importance of considering base rates!

In many cases, we know $P(A \mid B)$ but we really want to know $P(B \mid A)$. This commonly occurs in medical screening, where we know $P(\text{positive test result} \mid \text{disease})$ but what we want to know is $P(\text{disease} \mid \text{positive test result})$.

For example, some doctors recommend that men over the age of 50 undergo screening using a test called prostate specific antigen (PSA) to screen for possible prostate cancer. Before a test is approved for use in medical practice, the manufacturer needs to test two aspects of the test's performance:

1. Sensitivity - how likely is it to find the disease when it is present

Bayes' Rule

2. Specificity - how likely is it to give a negative result when there is no disease present

For the PSA test, sensitivity is about 80% and specificity is about 70%. However, these don't answer the question that the physician wants to answer for any particular patient: what is the likelihood that they actually have cancer, given that the test comes back positive?

Using Bayes' rule with these numbers: $P(\text{cancer} \mid \text{test}) = \frac{0.8 \cdot 0.058}{0.8 \cdot 0.058 + 0.3 \cdot 0.942} = 0.14$

That's pretty small – do you find that surprising? Many people do, and in fact there is a substantial psychological literature showing that people systematically neglect base rates (i.e. overall prevalence) in their judgments.

Odds and Odds Ratios

Converting between probability and odds:

- ▶ Formulas:

Odds and Odds Ratios

Odds and Odds Ratios

Odds and Odds Ratios

Converting between probability and odds:

- ▶ Formulas:

- Odds = $\frac{P(event)}{P(not\ event)}$

- Probability = $\frac{odds}{1+odds}$

- Odds Ratio = $\frac{posterior\ odds}{prior\ odds}$

- ▶ PSA Test Example Calculations:

- Prior odds = $\frac{0.058}{1-0.058} = 0.061$

- Posterior odds = $\frac{0.14}{1-0.14} = 0.16$

- Odds ratio = $\frac{0.16}{0.061} = 2.62$

Interpreting Results:

- ▶ Prior odds: 1:16 chance of cancer before test
- ▶ Posterior odds: 1:6 chance after positive test

Odds and Odds Ratios

- ▶ Odds ratio of 2.62 means:
 - Risk increased 2.62 times
 - But absolute risk still low (14%)
 - Shows why screening rare conditions is problematic

The result in the PSA example showed that the likelihood that the individual has cancer based on a positive PSA test result is still fairly low (0.14), even though it's more than twice as big as it was before we knew the test result. We would often like to quantify the relation between probabilities more directly, which we can do by converting them into odds which express the relative likelihood of something happening or not.

In our PSA example:

$$\text{Prior odds} = P(\text{cancer})/P(\text{not cancer}) = \frac{0.058}{1-0.058} = 0.061$$

$$\text{Posterior odds} = \frac{0.14}{1-0.14} = 0.16$$

Odds and Odds Ratios

$$\text{Odds ratio} = \frac{0.16}{0.061} = 2.62$$

This tells us that the odds of having cancer are increased by 2.62 times given the positive test result. An odds ratio is an example of what we will later call an effect size, which is a way of quantifying how relatively large any particular statistical effect is.

As an aside, this is a reason why many medical researchers have become increasingly wary of the use of widespread screening tests for relatively uncommon conditions; most positive results will turn out to be false positives, resulting in unnecessary followup tests with possible complications, not to mention added stress for the patient.

Summary

- ▶ Probability quantifies uncertainty

Summary

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- ▶ Three ways to determine probabilities

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- ▶ Conditional probability for related events

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- ▶ Bayes' rule for updating beliefs

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- ▶ Probability quantifies uncertainty
- ▶ Three ways to determine probabilities
- ▶ Conditional probability for related events
- ▶ Bayes' rule for updating beliefs
- ▶ Importance of base rates

Key takeaways from this lecture:

1. Probability theory provides mathematical tools to describe uncertain events
2. We can determine probabilities through:
 - ▶ Personal belief (subjective but sometimes necessary)
 - ▶ Empirical frequency (based on observed data)
 - ▶ Classical probability (based on equally likely outcomes)
3. The law of large numbers shows how empirical probability converges to true probability

Summary

4. Conditional probability helps us understand related events
5. Bayes' rule allows us to update probabilities based on new evidence
6. Base rates are crucial but often neglected in probability judgments

Questions?

Thank you for your attention!

Suggested readings for students interested in learning more:

- ▶ The Drunkard's Walk: How Randomness Rules Our Lives, by Leonard Mlodinow
- ▶ Ten Great Ideas about Chance, by Persi Diaconis and Brian Skyrms

[1] R. A. Poldrack, *Statistical Thinking. Analyzing Data in an Uncertain World*. Princeton: Princeton University Press, 2023. [Online]. Available: <https://statsthinking21.github.io/statsthinking21-core-site/>