04: Conditional Probability and Bayes

Lisa Yan and Jerry Cain
September 21, 2020
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Conditional Probability
Dice, our misunderstood friends

Roll two 6-sided dice, yielding values $D_1$ and $D_2$.

Let $E$ be event: $D_1 + D_2 = 4$.

What is $P(E)$?

$|S| = 36$
$E = \{(1,3), (2,2), (3,1)\}$

$P(E) = \frac{3}{36} = \frac{1}{12}$

Let $F$ be event: $D_1 = 2$.

What is $P(E, \text{given } F \text{ already observed})$?

$S = \{(2,1), (2,2), (2,3), (2,4), (2,5), (2,6)\}$
$E = \{(2,2)\}$

$P(E, \text{given } F \text{ already observed}) = \frac{1}{6}$
Conditional Probability

The **conditional probability** of $E$ given $F$ is the probability that $E$ occurs given that $F$ has already occurred. This is known as conditioning on $F$.

Written as: $P(E|F)$

Means: “$P(E$, given $F$ already observed)”

Sample space $\rightarrow$ all possible outcomes consistent with $F$ (i.e. $S \cap F$)

Event $\rightarrow$ all outcomes in $E$ consistent with $F$ (i.e. $E \cap F$)
Conditional Probability, equally likely outcomes

The **conditional probability** of $E$ given $F$ is the probability that $E$ occurs given that $F$ has already occurred. This is known as conditioning on $F$.

With **equally likely outcomes**:

$$P(E|F) = \frac{\# \text{ of outcomes in } E \text{ consistent with } F}{\# \text{ of outcomes in } S \text{ consistent with } F} = \frac{|E \cap F|}{|S \cap F|}$$

$$P(E|F) = \frac{|EF|}{|F|}$$

$|S| = 50$

$P(E) = \frac{8}{50} \approx 0.16$

$P(E|F) = \frac{3}{14} \approx 0.21$
Slicing up the spam

24 emails are sent, 6 each to 4 users.
- 10 of the 24 emails are spam.
- All possible outcomes are equally likely.

Let \( E \) = user 1 receives 3 spam emails.

What is \( P(E) \)?

Let \( F \) = user 2 receives 6 spam emails.

What is \( P(E|F) \)?

Let \( G \) = user 3 receives 5 spam emails.

What is \( P(G|F) \)?
Slicing up the spam

24 emails are sent, 6 each to 4 users.
- 10 of the 24 emails are spam.
- All possible outcomes are equally likely.

Let $E = \text{user 1 receives 3 spam emails.}$

What is $P(E)$?

$P(E) = \frac{\binom{10}{3} \binom{14}{3}}{\binom{24}{6}}$

$\approx 0.3245$

Let $F = \text{user 2 receives 6 spam emails.}$

What is $P(E|F)$?

$P(E|F) = \frac{\binom{4}{3} \binom{14}{3}}{\binom{18}{6}}$

$\approx 0.0784$

Let $G = \text{user 3 receives 5 spam emails.}$

What is $P(G|F)$?

$P(G|F) = \frac{\binom{4}{5} \binom{14}{1}}{\binom{18}{6}}$

$= 0$

No way to choose 5 spam from 4 remaining spam emails!
Conditional probability in general

General definition of conditional probability:

\[ P(E|F) = \frac{P(EF)}{P(F)} \]

The Chain Rule (aka Product rule):

\[ P(EF) = P(F)P(E|F) \]

These properties hold even when outcomes are not equally likely.
Netflix and Learn

Let $E$ = a user watches Life is Beautiful.

What is $P(E)$?

Equally likely outcomes?

$S = \{\text{watch, not watch}\}$

$E = \{\text{watch}\}$

$P(E) = 1/2$ ?

$P(E) = \lim_{n \to \infty} \frac{n(E)}{n} \approx \frac{\# \text{ people who have watched movie}}{\# \text{ people on Netflix}}$

$= \frac{10,234,231}{50,923,123} \approx 0.20$
Let $E$ be the event that a user watches the given movie.

\[
P(E|F) = \frac{P(EF)}{P(F)} \quad \text{Definition of Cond. Probability}
\]

\[
P(E) = 0.19 \\
P(E) = 0.32 \\
P(E) = 0.20 \\
P(E) = 0.09 \\
P(E) = 0.20
\]
Netflix and Learn

Let $E$ = a user watches Life is Beautiful.
Let $F$ = a user watches Amelie.

What is the probability that a user watches Life is Beautiful, given they watched Amelie?

$$P(E|F)$$

$$P(E|F) = \frac{P(EF)}{P(F)} = \frac{\# \text{ people who have watched both}}{\# \text{ people who have watched Amelie}} \approx \frac{\# \text{ people who have watched both}}{\# \text{ people who have watched Amelie}}$$

$$\approx 0.42$$
Let $E$ be the event that a user watches the given movie.
Let $F$ be the event that the same user watches Amelie.

\[
P(E) = 0.19 \quad P(E) = 0.32 \quad P(E) = 0.20 \quad P(E) = 0.09 \quad P(E) = 0.20
\]

\[
P(E|F) = 0.14 \quad P(E|F) = 0.35 \quad P(E|F) = 0.20 \quad P(E|F) = 0.72 \quad P(E|F) = 0.42
\]
Law of Total Probability
Today’s tasks

\[ P(EF) \]

Chain rule (Product rule)

Definition of conditional probability

\[ P(E) \]

Law of Total Probability
Law of Total Probability

**Thm** Let $F$ be an event where $P(F) > 0$. For any event $E$, $P(E) = P(E|F)P(F) + P(E|F^C)P(F^C)$

**Proof**

1. $F$ and $F^C$ are disjoint s.t. $F \cup F^C = S$  
   Def. of complement
2. $E = (EF) \cup (EF^C)$  
   (see diagram)
3. $P(E) = P(EF) + P(EF^C)$  
   Additivity axiom
4. $P(E) = P(E|F)P(F) + P(E|F^C)P(F^C)$  
   Chain rule (product rule)

Note: disjoint sets by definition are mutually exclusive events
General Law of Total Probability

**Thm** For **mutually exclusive events** $F_1, F_2, ..., F_n$

s.t. $F_1 \cup F_2 \cup \cdots \cup F_n = S$,

$$P(E) = \sum_{i=1}^{n} P(E|F_i)P(F_i)$$
Finding $P(E)$ from $P(E|F)$

- Flip a fair coin.
- If heads: roll a fair 6-sided die.
- Else: roll a fair 3-sided die.

You win if you roll a 6. What is $P$(winning)?
Finding $P(E)$ from $P(E|F)$

- Flip a fair coin.
- If heads: roll a fair 6-sided die.
- Else: roll a fair 3-sided die.

You win if you roll a 6. What is $P$(winning)?

1. Define events & state goal

Let: $E$: win, $F$: flip heads

Want: $P$(win) = $P(E)$

2. Identify known probabilities

$P$(win $|$ H) = $P(E|F) = \frac{1}{6}$

$P(H) = P(F) = \frac{1}{2}$

$P$(win $|$ T) = $P(E|F^C) = 0$

$P(T) = P(F^C) = 1 - \frac{1}{2}$

3. Solve

\[
P(E) = P(E|F)P(F) + P(E|F^C)P(F^C) \\
= \frac{1}{6} \cdot \frac{1}{2} + 0 \cdot \left(1 - \frac{1}{2}\right) \\
= \frac{1}{12} \approx 0.083
\]
Finding $P(E)$ from $P(E|F)$, an understanding

- Flip a fair coin.
- If heads: roll a fair 6-sided die.
- Else: roll a fair 3-sided die.

You win if you roll a 6. What is $P($winning$)$?

1. Define events & state goal

Let: $E$: win, $F$: flip heads
Want: $P($win$) = P(E)$

“Probability trees” can help connect your understanding of the experiment with the problem statement.
Bayes’ Theorem
Today’s tasks

- Law of Total Probability
- Chain rule (Product rule)
- Definition of conditional probability
- Bayes’ Theorem
- $P(E|F)$
- $P(\overline{E}|F)$
- $P(E)$
- $P(F|E)$
Thomas Bayes

Rev. Thomas Bayes (~1701-1761):
British mathematician and Presbyterian minister

He looked remarkably similar to Charlie Sheen
(but that’s not important right now)
Detecting spam email

We can easily calculate how many spam emails contain “Dear”:

\[ P(E|F) = P(\text{“Dear”} | \text{Spam email}) \]

But what is the probability that an email containing “Dear” is spam?

\[ P(F|E) = P(\text{Spam email} | \text{“Dear”}) \]
(silent drumroll)
Bayes’ Theorem

Thm  For any events $E$ and $F$ where $P(E) > 0$ and $P(F) > 0$,

$$P(F|E) = \frac{P(E|F)P(F)}{P(E)}$$

Proof

2 steps! See board

Expanded form:

$$P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|F^C)P(F^C)}$$

Proof

1 more step! See board

Lisa Yan and Jerry Cain, CS109, 2020
Detecting spam email

- 60% of all email in 2016 is spam.
- 20% of spam has the word “Dear”
- 1% of non-spam (aka ham) has the word “Dear”

You get an email with the word “Dear” in it. What is the probability that the email is spam?

1. Define events & state goal

Let: \( E \): “Dear”, \( F \): spam
Want: \( P(\text{spam} \mid \text{“Dear”}) = P(F \mid E) \)

2. Identify known probabilities

\[
P(E \mid F) = 0.2, \quad P(E \mid \overline{F}) = 0.01
\]

3. Solve

\[
P(F \mid E) = \frac{P(E \mid F)P(F)}{P(E \mid F)P(F) + P(E \mid \overline{F})P(\overline{F})} = \frac{(0.20)(0.6)}{(0.20)(0.6) + (0.01)(0.4)} 
\]

\( \times 0.967 \)

Bayes’ Theorem
Detecting spam email, an understanding

- 60% of all email in 2016 is spam.
- 20% of spam has the word “Dear”
- 1% of non-spam (aka ham) has the word “Dear”

You get an email with the word “Dear” in it. What is the probability that the email is spam?

1. Define events & state goal

Let: $E$: “Dear”, $F$: spam
Want: $P(\text{spam} | \text{“Dear”}) = P(F|E)$

Note: You should still know how to use Bayes/ Law of Total Probab., but drawing a probability tree can help you identify which probabilities you have. The branches are determined using the problem setup.
Bayes’ Theorem terminology

- 60% of all email in 2016 is spam.
- 20% of spam has the word “Dear”
- 1% of non-spam (aka ham) has the word “Dear”

You get an email with the word “Dear” in it. What is the probability that the email is spam?

Want: $P(F|E)$, posterior

$P(F)$: prior

$P(E|F)$: likelihood

$P(E|F^C)$: non-special term

Posterior

$$P(F|E) = \frac{P(E|F)P(F)}{P(E)}$$

normalization constant

60% of all email in 2016 is spam.

20% of spam has the word “Dear”

1% of non-spam (aka ham) has the word “Dear”

You get an email with the word “Dear” in it.

What is the probability that the email is spam?
04: Conditional Probability and Bayes

Lisa Yan and Jerry Cain
September 21, 2020
This class going forward

Last week
Equally likely events

Today and for most of this course
Not equally likely events

\[ P(E = \text{Evidence} | F = \text{Fact}) \]
(collected from data)

\[ P(F = \text{Fact} | E = \text{Evidence}) \]
(categorize a new datapoint)

\[ P(E \cap F) \quad P(E \cup F) \]
(counting, combinatorics)
Conditional probability in general

General definition of conditional probability:

\[ P(E \mid F) = \frac{P(EF)}{P(F)} \]

The Chain Rule (aka Product rule):

\[ P(EF) = P(F)P(E \mid F) \]

These properties hold even when outcomes are not equally likely.
Think, then Breakout Rooms

Then check out the question on the next slide (Slide 35). Post any clarifications here!

https://us.edstem.org/courses/2678/discussion/128395

Think by yourself: 1 min

Breakout rooms: 4 min. Introduce yourself!
Think, then groups

You have a flowering plant.

Let

\[ E = \text{Flowers bloom} \]
\[ F = \text{Plant was watered} \]
\[ G = \text{Plant got sun} \]

1. How would you write

   i. the probability that the plant got sun, given that it was watered and flowers bloomed?

   \[ P(G \mid FE) = \]

   ii. the probability that the plant got sun and flowers bloomed given that it was watered?

   \[ P(GE \mid F) = \]

2. Using the Venn diagram, compute the above probabilities.


   i. \[ P(GE) = \ldots \cdot P(E) \]

   ii. \[ P(GE \mid F) = P(G \mid EF) \cdot \ldots \]
Think, then groups

You have a flowering plant.

Let
- $E = \text{Flowers bloom}$
- $F = \text{Plant was watered}$
- $G = \text{Plant got sun}$

1. How would you write
   i. the probability that the plant got sun, given that it was watered and flowers bloomed?
   ii. the probability that the plant got sun and flowers bloomed given that it was watered?

2. Using the Venn diagram, compute the above probabilities.

   i. $P(GE) = \underline{P(G|E)} \cdot P(E)$
   ii. $P(GE|F) = P(G|EF) \cdot \underline{P(E|F)}$
Bayes’ Theorem II
Why is Bayes’ so important?

👉 It links belief to evidence in probability!
Bayes’ Theorem

Mathematically:

$$P(F|E) = \frac{P(E|F)P(F)}{P(E)}$$

Real-life application:

Given new evidence $E$, update belief of fact $F$

Prior belief $\rightarrow$ Posterior belief

$$P(F) \rightarrow P(F|E)$$
Zika, an autoimmune disease

A disease spread through mosquito bites. Usually no symptoms; worst case paralysis. During pregnancy: may cause birth defects

If a test returns positive, what is the likelihood you have the disease?
Taking tests: Confusion matrix

Fact, $F$ or $F^C$

- Has disease
- No disease

Evidence, $E$ or $E^C$

- Test positive
- Test negative

| Evidence | Fact | \( P(E|F) \) | \( P(E|F^C) \) |
|----------|------|-----------------|-----------------|
| \( E, \text{Test +} \) | $F$, disease + | True positive | False positive |
| \( E^C, \text{Test -} \) | $F^C$, disease - | False negative | True negative |

If a test returns positive, what is the likelihood you have the disease?
Taking tests: Confusion matrix

Fact, $F$ or $F^C$
- Has disease
- No disease

Evidence, $E$ or $E^C$
- Test positive
- Test negative

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Fact</th>
<th>Evidence, $E$</th>
<th>Test positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$, Test +</td>
<td>$F$, disease +</td>
<td>True positive</td>
<td>$P(E</td>
</tr>
<tr>
<td>$E$, Test +</td>
<td>$F^C$, disease –</td>
<td>False positive</td>
<td>$P(E</td>
</tr>
<tr>
<td>$E^C$, Test –</td>
<td>False negative</td>
<td>$P(E^C</td>
<td>F)$</td>
</tr>
<tr>
<td>$E^C$, Test –</td>
<td>True negative</td>
<td>$P(E^C</td>
<td>F^C)$</td>
</tr>
</tbody>
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If a test returns positive, what is the likelihood you have the disease?
Check out the question on the next slide (Slide 43). Post any clarifications here!

https://us.edstem.org/courses/2678/discussion/128395

Breakout rooms: 5 minutes
Zika Testing

- A test is 98% effective at detecting Zika (“true positive”). \( P(E|F) \)
- However, the test has a “false positive” rate of 1%. \( P(E|\neg F) \)
- 0.5% of the US population has Zika. \( P(F) \)

What is the likelihood you have Zika if you test positive?

Why would you expect this number?

**1. Define events & state goal**

Let: \( E \) = you test positive
\( F \) = you actually have the disease

Want: \( P(\text{disease} | \text{test}+) \) = \( P(F|E) \)
Zika Testing

- A test is 98% effective at detecting Zika ("true positive").
- However, the test has a "false positive" rate of 1%.
- 0.5% of the US population has Zika.

What is the likelihood you have Zika if you test positive? Why would you expect this number?

1. Define events & state goal

Let:
- $E =$ you test positive
- $F =$ you actually have the disease

Want:
- $P($disease | test$+) = P(F|E)$

2. Identify known probabilities

3. Solve

$$P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|F^c)P(F^c)}$$

Bayes’ Theorem

$$P(F|E) = \frac{(0.98)(0.005)}{(0.98)(0.005) + (0.995)(0.01)}$$

$\approx 0.33$
Bayes’ Theorem intuition

Original question:
What is the likelihood you have Zika if you test positive for the disease?
Bayes’ Theorem intuition

Original question: What is the likelihood you have Zika if you test positive for the disease?

Interpretation: Of the people who test positive, how many actually have Zika?
Bayes’ Theorem intuition

Original question:
What is the likelihood you have Zika if you test positive for the disease?

Interpretation:
Of the people who test positive, how many actually have Zika?

The space of facts, conditioned on a positive test result
Zika Testing

- A test is 98% effective at detecting Zika ("true positive").
- However, the test has a "false positive" rate of 1%.
- 0.5% of the US population has Zika.

What is the likelihood you have Zika if you test positive?

Say we have 1000 people:

5 have Zika and test positive
985 do not have Zika and test negative.
10 do not have Zika and test positive.

≈ 0.333
Update your beliefs with Bayes’ Theorem

\[ E = \text{you test positive for Zika} \]
\[ F = \text{you actually have the disease} \]

\[ P(F) \]

I have a 0.5% chance of having Zika.

Take test, results positive

With these test results, I now have a 33% chance of having Zika!!!
Topical probability news: Bayes for COVID-19 testing

How representative are today’s testing rates?

How do we know if a positive test is a true positive or a false positive?

Reasonable Question: Why test if there are errors?

https://covidtracking.com/data
http://med.stanford.edu/news.html
Think

Slide 53 is a question to think over by yourself.
We’ll go over it together afterwards.

Post any clarifications here!

https://us.edstem.org/courses/2678/discussion/128395

Think by yourself: 2 minutes
Why it’s still good to get tested

• A test is 98% effective at detecting Zika (“true positive”).
• However, the test has a “false positive” rate of 1%.
• 0.5% of the US population has Zika.

Let:

\[ E = \text{you test positive} \]
\[ F = \text{you actually have the disease} \]

Let:

\[ E^c = \text{you test negative for Zika with this test.} \]

What is \( P(F|E^c) \)?

\[
P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|F^c)P(F^c)}
\]

Bayes’ Theorem
Why it’s still good to get tested

- A test is 98% effective at detecting Zika (“true positive”).
- However, the test has a “false positive” rate of 1%.
- 0.5% of the US population has Zika.

Let:

- \( E \) = you test positive
- \( F \) = you actually have the disease

Let:

- \( E^C \) = you test negative for Zika with this test.

\[
P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|F^C)P(F^C)} \quad \text{Bayes’ Theorem}
\]

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<th>( F ), disease +</th>
<th>( F^C ), disease -</th>
</tr>
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<tbody>
<tr>
<td>( E ), Test +</td>
<td>True positive</td>
<td>False positive</td>
</tr>
<tr>
<td>( P(E</td>
<td>F) )</td>
<td>0.98</td>
</tr>
</tbody>
</table>

What is \( P(F|E^C) \)?

\[
P(F|E^C) = 1 \quad \text{not true}
\]

\[
= 1 - P(F^C|E^C)
\]
Why it’s still good to get tested

- A test is 98% effective at detecting Zika (“true positive”).
- However, the test has a “false positive” rate of 1%.
- 0.5% of the US population has Zika.

Let: 
- $E = \text{you test positive}$
- $F = \text{you actually have the disease}$

Let: 
- $E^C = \text{you test negative for Zika with this test.}$

What is $P(F|E^C)$?

\[
P(F|E^C) = \frac{P(E^C|F)P(F)}{P(E^C|F)P(F) + P(E^C|F^C)P(F^C)}
\]

Bayes’ Theorem

\[
P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|F^C)P(F^C)}
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<td>F)$</td>
<td>0.98</td>
</tr>
<tr>
<td>$P(E</td>
<td>F^C)$</td>
<td></td>
</tr>
<tr>
<td>$E^C$, Test -</td>
<td>False negative</td>
<td>True negative</td>
</tr>
<tr>
<td>$P(E^C</td>
<td>F)$</td>
<td>0.02</td>
</tr>
<tr>
<td>$P(E^C</td>
<td>F^C)$</td>
<td></td>
</tr>
</tbody>
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Why it’s still good to get tested

$E = \text{you test positive for Zika}$

$F = \text{you actually have the disease}$

$E^C = \text{you test negative for Zika}$

---

I have a 0.5% chance of having Zika disease.

$P(F)$

---

With these test results, I now have a 33% chance of having Zika!!!

$P(F|E)$

---

Take test, results positive

---

Take test, results negative

---

With these test results, I now have a 0.01% chance of having Zika disease!!!

$P(F|E^C)$
Topical probability news: Bayes for COVID-19 testing

- Antibody tests (blood samples) have higher false negative, false positive rates than RT-PCR tests (nasal swab). However, they help explain/identify our body’s reaction to the virus.

- The real world has many more "givens" (current symptoms, existing medical conditions) that improve our belief prior to testing.

- Most importantly, testing gives us a noisy signal of the spread of a disease.
Topical probability news: Sources

COVID-19 Projections  
http://covid19.healthdata.org/

Stanford Medicine (Sept 9 2020)  

Overview of different testing types  
https://www.globalbiotechinsights.com/articles/20247/the-worldwide-test-for-covid-19

Compilation of scientific publications on COVID-19  
https://rega.kuleuven.be/if/corona_covid-19
Monty Hall Problem
Monty Hall Problem

and Wayne Brady
Monty Hall Problem aka Let’s Make a Deal

Behind one door is a prize (equally likely to be any door).

Behind the other two doors is nothing

1. We choose a door
2. Host opens 1 of other 2 doors, revealing nothing
3. We are given an option to change to the other door.

Should we switch?

Note: If we don’t switch, $P(\text{win}) = 1/3$ (random)

We are comparing $P(\text{win})$ and $P(\text{win} | \text{switch})$. 
If we switch

Without loss of generality, say we pick A (out of Doors A,B,C).

A = prize
- Host opens B or C
- We switch
- We always lose

\( P(\text{win} \mid \text{A prize, picked A, switched}) = 0 \)

B = prize
- Host must open C
- We switch to B
- We always win

\( P(\text{win} \mid \text{B prize, picked A, switched}) = 1 \)

C = prize
- Host must open B
- We switch to C
- We always win

\( P(\text{win} \mid \text{C prize, picked A, switched}) = 1 \)

\[
P(\text{win} \mid \text{picked A, switched}) = \frac{1}{3} \times 0 + \frac{1}{3} \times 1 + \frac{1}{3} \times 1 = \frac{2}{3}
\]

You should switch.
Monty Hall, 1000 envelope version

Start with 1000 envelopes (of which 1 is the prize).

1. You choose 1 envelope.
\[
\begin{align*}
\frac{1}{1000} &= P(\text{envelope is prize}) \\
\frac{999}{1000} &= P(\text{other 999 envelopes have prize})
\end{align*}
\]

2. I open 998 of remaining 999 (showing they are empty).
\[
\frac{999}{1000} = P(998 \text{ empty envelopes had prize}) + P(\text{last other envelope has prize})
\]
\[
= P(\text{last other envelope has prize})
\]

3. Should you switch?
   No: \( P(\text{win without switching}) = \frac{1}{\text{original \# envelopes}} \)
   Yes: \( P(\text{win with new knowledge}) = \frac{1}{\text{original \# envelopes} - 1} \)