

## CHAPTER 1

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# Bayes' Theorem

Let's say that you are holding two bags of marbles. You know that one bag contains 60 white marbles and 40 red marbles, and you know that the other holds 10 white marbles and 90 red marbles. You don't know which is which, and you can't see the marbles.

Your friend says, "Guess which bag is mostly red marbles." You pick one.

"What is the probability that this is the bag that is mostly red marbles?" You think to yourself "There is a 50 percent chance that this bag is mostly red marbles, and there is also a 50 percent probability that it is the mostly-white-marbles bag."

You then pick one marble from the bag: it is red. Now you must update your beliefs. It is more likely that this is the mostly-red-marbles bag. What is the probability now?

Bayes Theorem gives you the rule for updating your beliefs based on new data.

### 1.1 Bayes Theorem

Let's say you have two events or conditions C and D. C is "The person has a cough" and D is "The person is waiting to see a doctor."

Using the chain rule of probability, we now have two ways to calculate  $p(C \text{ AND } D)$ :

$$p(C \text{ AND } D) = p(C|D)p(D)$$

(The probability the person is at the doctor multiplied by the probability they have a cough if they are at the doctor.)

or

$$p(C \text{ AND } D) = p(C|D)p(D)$$

(The probability the person has a cough multiplied by the probability they are at the doctor if they have a cough.) See Figure 1.1

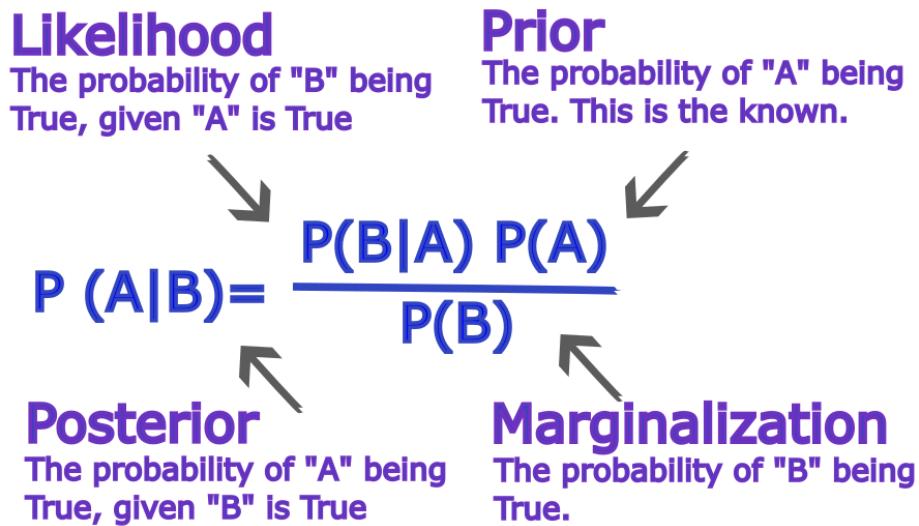


Figure 1.1: A labelled figure of Bayes's Theorem Equation.

Thus:

$$p(D|C) = \frac{p(C|D)p(D)}{P(C)}$$

Now, you can calculate  $p(D|C)$  (in this case, the probability that you are waiting to see a doctor given that you have a cough.) if you know:

- $p(C|D)$  (The probability that you have a cough given that you are waiting to see a doctor)
- $p(D)$  (The probability that you are waiting for a doctor for any reason.)
- $p(C)$  (The probability that you have a cough anywhere)

Pretty much all modern statistical methods (including most artificial intelligence) are based on this formula, which is known as Bayes' Theorem. It was written down by Thomas Bayes before he died in 1761. It was then found and published after his death.

## 1.2 Using Bayes' Theorem

Back to the example at the beginning. To review:

- There are two bags that look exactly the same.
- Bag W has 60 white marbles and 40 red marbles.

- Bag R has 10 white marbles and 90 red marbles.
- You pull one marble from the selected bag: it is red.

What is the probability that the selected bag is Bag R? Intuitively, you know that the probability is now more than 0.5. What is the exact number?

In terms of conditional probability, we say we are looking for “the probability that the selected bag is Bag R, given that you drew a red marble”, or  $p(B_R|D_R)$ , where  $B_R$  is “the selected bag is Bag R” and  $D_R$  is “you drew a red marble from the selected bag”.

From Bayes' Theorem, we can write:

$$p(B_R|D_R) = \frac{P(D_R|B_R)p(B_R)}{P(D_R)}$$

$P(D_R|B_R)$  is just the probability of drawing a red marble given that the selected bag is Bag R. That is easy to calculate: There are 100 marbles in the bag, and 90 are red. Thus,  $P(D_R|B_R) = 0.9$ .

$P(B_R)$  is just the probability that you chose Bag R before you drew out a marble. Both bags look the same, so  $P(B_R) = 0.5$ . This is called *the prior*, because it represents what you thought the probability was before you got more information.

$P(D_R)$  is the probability of drawing a red marble. There was 0.5 probability that you put your hand into Bag W (in which 40 of the 100 marbles are red) and a 0.5 probability that you put your hand into Bag R (in which 90 of the 100 marbles are red). So

$$P(D_R) = 0.5 \frac{40}{100} + 0.5 \frac{90}{100} = 0.65$$

Putting it together:

$$p(B_R|D_R) = \frac{P(D_R|B_R)p(B_R)}{P(D_R)} = \frac{(0.9)(0.5)}{0.65} = \frac{9}{13} \approx 0.69$$

Thus, given that you have pulled a red marble, there is about a 69% chance that you have selected the bag with 90 red marbles.

### 1.3 Confidence

Bayes' Theorem, then, is about updating your beliefs based on evidence. Before you drew out the red marble, you selected one bag thinking it might contain 90 red marbles. How certain were you? 0.0 being complete disbelief and 1.0 entirely confidence, you were 0.5. After pulling out the red marble, you were about 0.69 confident that you had chosen the bag with 90 red marbles.

The question "How confident are you in your guess?" is very important in some situations. For example in medicine, diagnoses often lead to risky interventions. Few diagnoses come with 100% confidence. All doctors should know how to use Bayes' Theorem.

In a trial, a jury is asked to determine if the accused person is guilty of a crime. Few jurors are ever 100% certain. In some trials, Bayes' Theorem is an exceptionally important tool.

### 1.4 The Monty Hall Problem

The Monty Hall Problem is a popular example in discrete probability and probability theory that highlights an application of Bayes' theorem.

Here's the scenario<sup>1</sup>

- A contestant is presented with three doors. Behind one door is a brand new car; behind the other two doors are goats.
- The contestant selects one of the three doors, say Door A.
- The host, Monty Hall, who knows what is behind each door, then opens one of the remaining two doors, say Door B, revealing a goat.
- The contestant is then offered the choice to either stick with Door A or switch to the other remaining unopened Door C.

At first glance, many people assume that after Monty opens a door, there are two doors left and hence the probability of winning the car is  $1/2$  regardless of whether one switches or stays. However, conditional probability and Bayes' Theorem reveal a different result.

Originally, the probability that you picked the right door, Door A, is  $P(A \text{ has the car}) = \frac{1}{3}$ .

Then, Monty Hall reveals Door B to contain a goat behind it. This changes things, as Door A remains a probability of  $\frac{1}{3}$ , while Door C, the unopened door, now contains the summed probability of the other two doors,  $\frac{2}{3}$ .

Proving this with Bayes' Theorem:

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<sup>1</sup>A few videos and a movie excerpt on this subject are linked in your digital resources.

$$\begin{aligned} P(\text{Car behind C} \mid \text{Monty opens B}) &= \frac{P(\text{Monty opens B} \mid \text{Car behind C}) P(\text{Car behind C})}{P(\text{Monty opens B})} \\ &= \frac{P(\text{Monty opens B} \mid \text{Car behind A}) P(\text{Car behind A}) + P(\text{Monty opens B} \mid \text{Car behind B}) P(\text{Car behind B})}{P(\text{Monty opens B} \mid \text{Car behind A}) P(\text{Car behind A}) + P(\text{Monty opens B} \mid \text{Car behind B})} \\ &= \frac{\frac{1}{3}}{\left(\frac{1}{2}\right)\left(\frac{1}{3}\right) + 0 \cdot \left(\frac{1}{3}\right) + 1 \cdot \left(\frac{1}{3}\right)} \\ &= \frac{\frac{1}{3}}{\frac{1}{6} + \frac{1}{3}} \\ &= \frac{\frac{1}{3}}{\frac{1}{2}} \\ &= \frac{2}{3} \end{aligned}$$

Thus, it is always in your interest to switch. If you ever have the luxury to be on a game show, make sure to use Bayes' Theorem before making your guesses.

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*This is a draft chapter from the Kontinua Project. Please see our website (<https://kontinua.org/>) for more details.*



## APPENDIX A

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# Answers to Exercises





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