

Indirect Proofs

Outline for Today

- ***What is an Implication?***
 - Understanding a key type of mathematical statement.
- ***Negations and their Applications***
 - How do you show something is *not* true?
- ***Proof by Contrapositive***
 - What's a contrapositive?
 - And some applications!
- ***Proof by Contradiction***
 - The basic method.
 - And some applications!

Logical Implication

If n is an even integer, then n^2 is an even integer.

An ***implication*** is a statement of the form
“If P is true, then Q is true.”

If n is an even integer, then n^2 is an even integer.

This part of the implication is called the *antecedent*.

This part of the implication is called the *consequent*.

An ***implication*** is a statement of the form
“If P is true, then Q is true.”

If n is an even integer, then n^2 is an even integer.

If m and n are odd integers, then $m+n$ is even.

If you like the way you look that much,
then you should go and love yourself.

An ***implication*** is a statement of the form
“If P is true, then Q is true.”

What Implications Mean

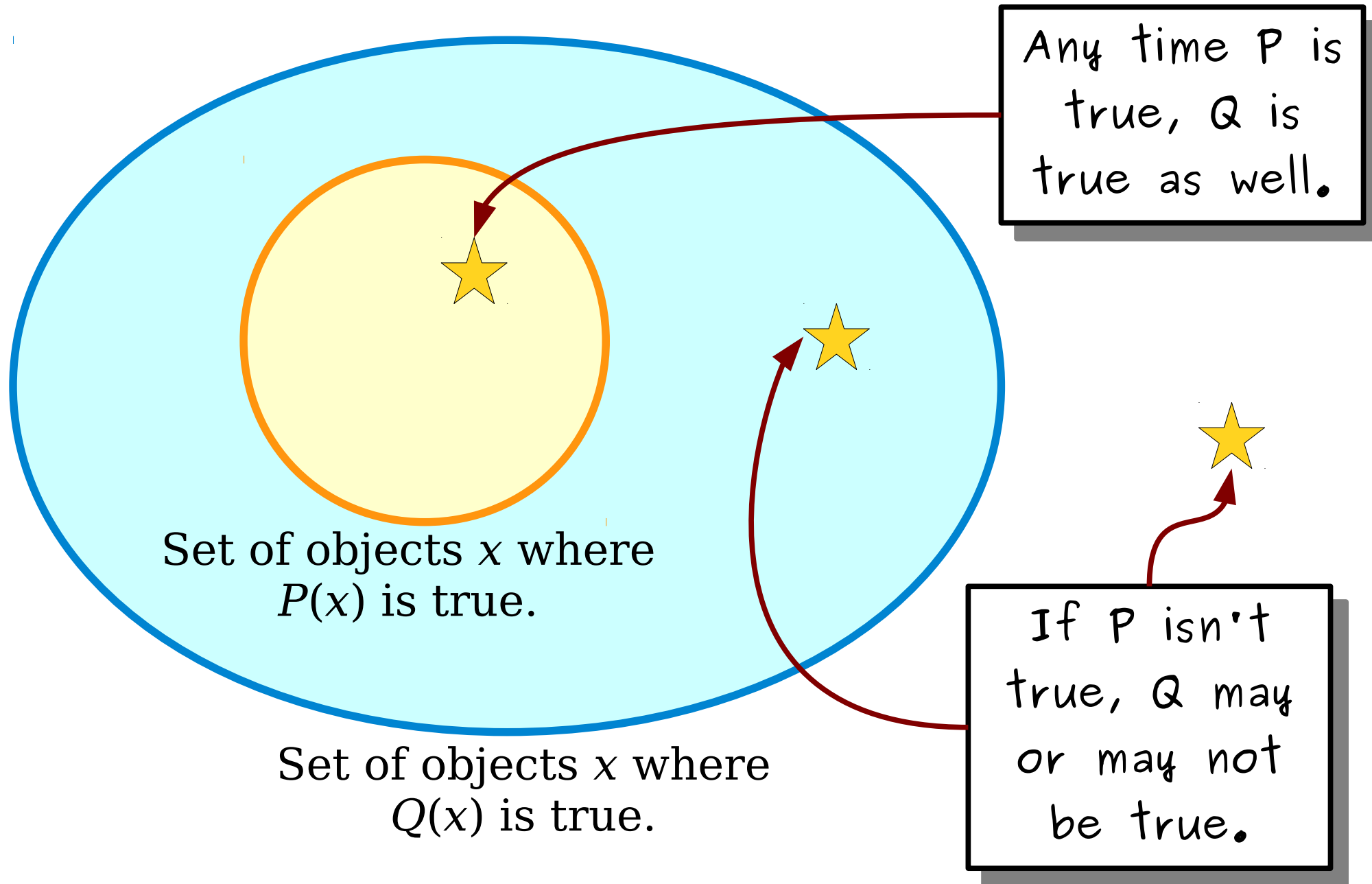
**“If there's a rainbow in the sky,
then it's raining somewhere.”**

- In mathematics, implication is directional.
 - The above statement doesn't mean that if it's raining somewhere, there has to be a rainbow.
- In mathematics, implications only say something about the consequent when the antecedent is true.
 - If there's no rainbow, it doesn't mean there's no rain.
- In mathematics, implication says nothing about causality.
 - Rainbows do not cause rain.

What Implications Mean

- In mathematics, a statement of the form **For any x , if $P(x)$ is true, then $Q(x)$ is true** means that any time you find an object x where $P(x)$ is true, you will see that $Q(x)$ is also true (for that same x).
- There is no discussion of causation here. It simply means that if you find that $P(x)$ is true, you'll find that $Q(x)$ is also true.

Implication, Diagrammatically



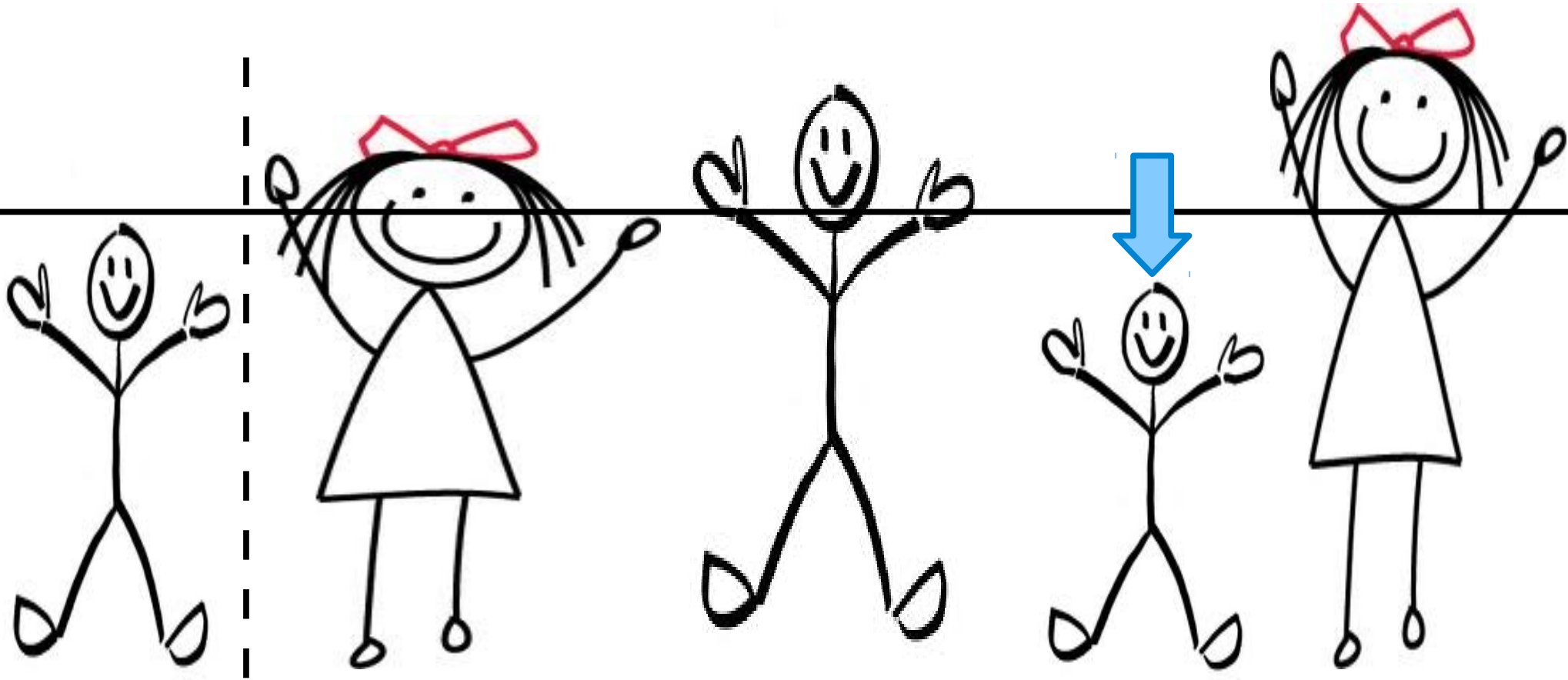
Negations

Negations

- A **proposition** is a statement that is either true or false.
- Some examples:
 - If n is an even integer, then n^2 is an even integer.
 - $\emptyset = \mathbb{R}$.
- The **negation** of a proposition X is a proposition that is true whenever X is false and is false whenever X is true.
- For example, consider the proposition “it is snowing outside.”
 - Its negation is “it is not snowing outside.”
 - Its negation is *not* “it is sunny outside.” ⚠
 - Its negation is *not* “we’re in the Bay Area.” ⚠

How do you find the negation
of a statement?

“All My Friends Are Taller Than Me”



Me

My Friends

The negation of the *universal* statement

Every P is a Q

is the *existential* statement

There is a P that is not a Q .

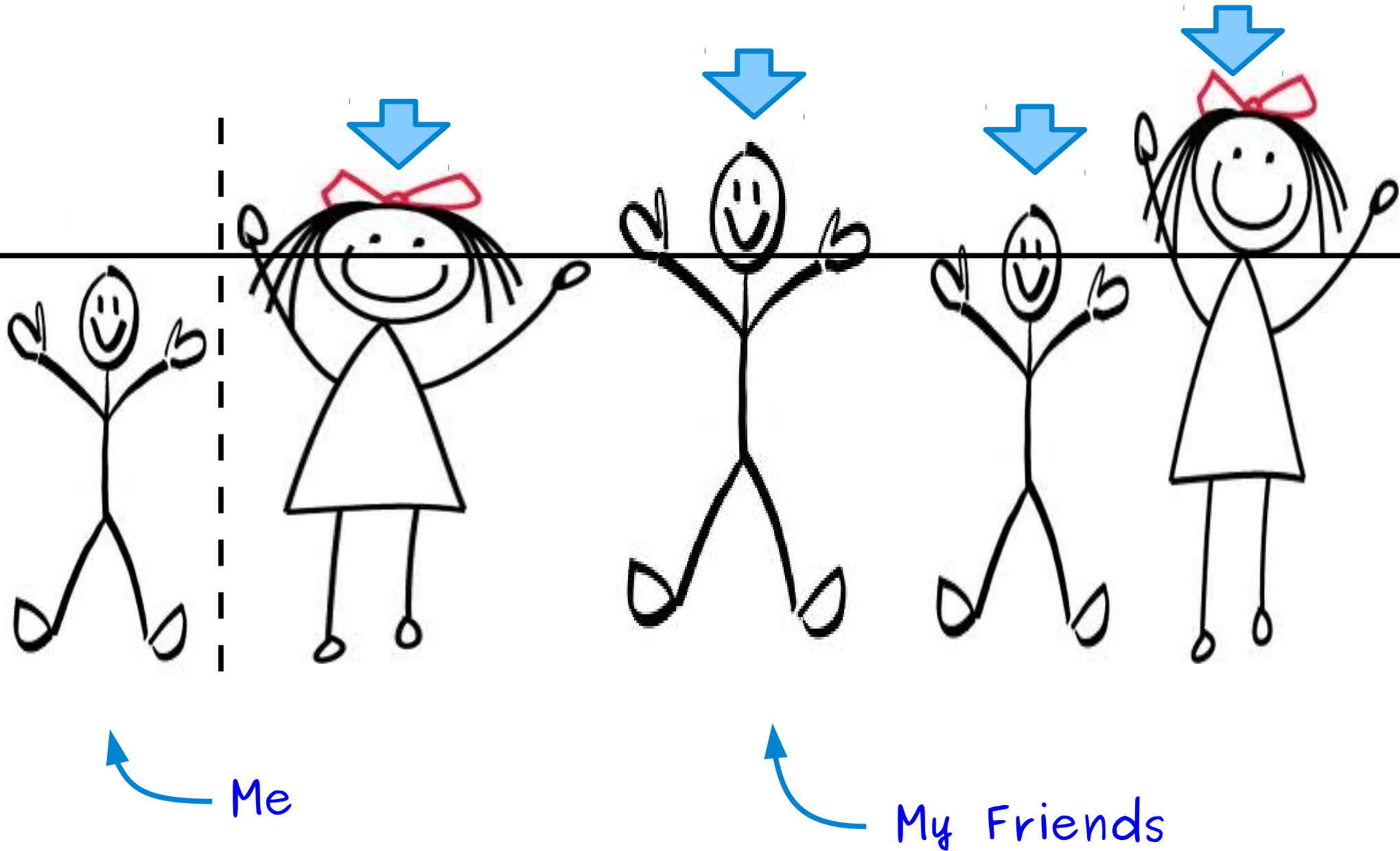
The negation of the *universal* statement

For all x , $P(x)$ is true.

is the *existential* statement

There exists an x where $P(x)$ is false.

“Some Friend Is Shorter Than Me”



The negation of the *existential* statement

There exists a P that is a Q

is the *universal* statement

Every P is not a Q .

The negation of the *existential* statement

There exists an x where $P(x)$ is true

is the *universal* statement

For all x , $P(x)$ is false.

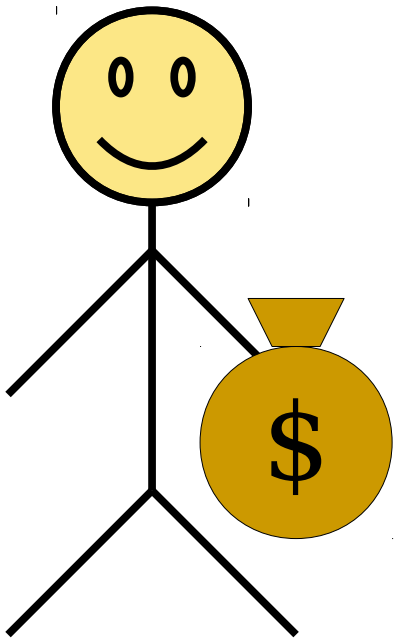
How do you negate an implication?



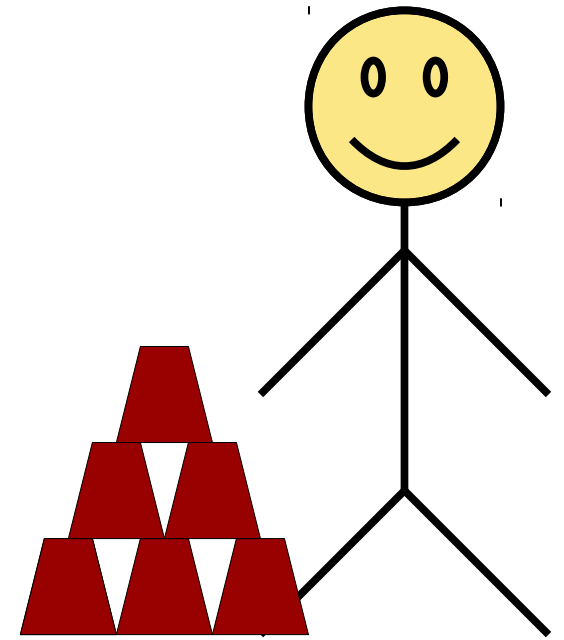
Story Time!

Ancient Contract:

If Nanni pays money to Ea-Nasir, then
Ea-Nasir will give Nanni quality copper ingots.



Nanni



Ea-Nasir

Ancient Contract:

If Nanni pays money to Ea-Nasir, then Ea-Nasir will give Nanni quality copper ingots.

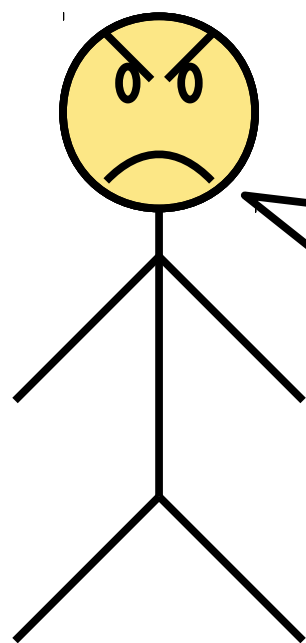
Question: What has to happen for the contract to be broken?

- A) Nanni does not pay Ea-Nasir and Ea-Nasir does not give the ingots.
- B) Nanni does not pay Ea-Nasir and Ea-Nasir gives the ingots.
- C) Nanni pays Ea-Nasir and Ea-Nasir does not give the ingots.
- D) Nanni pays Ea-Nasir and Ea-Nasir gives the ingots.

Respond at pollev.com/cs103

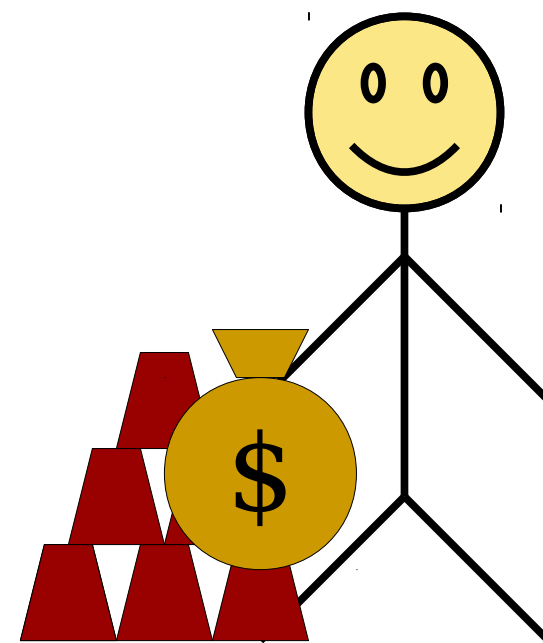
Ancient Contract:

If Nanni pays money to Ea-Nasir, then Ea-Nasir will give Nanni quality copper ingots.



Nanni

I'm going to [complain](#) about this!
(That's a hyperlink. Click it.)



Ea-Nasir

Question: What has to happen for this contract to be broken?

Answer: Nanni pays Ea-Nasir and doesn't get quality copper ingots.

The negation of the statement

**“For any x , if $P(x)$ is true,
then $Q(x)$ is true”**

is the statement

**“There is at least one x where
 $P(x)$ is true and $Q(x)$ is false.”**

***The negation of an implication
is not an implication!***

The negation of the statement

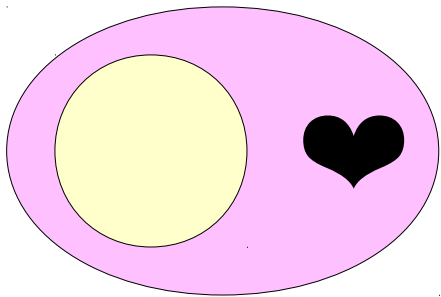
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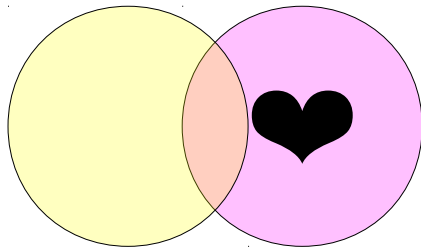
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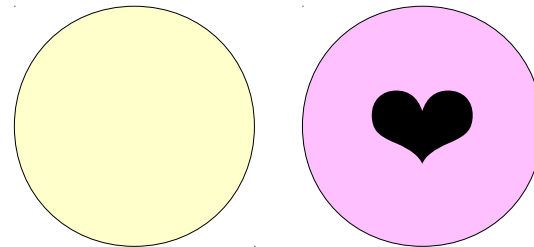
If p is a puppy,
then I do love p !



It's
complicated.



If p is a puppy,
then I don't love p !



How to Negate Universal Statements:

“For all x , $P(x)$ is true”

becomes

“There is an x where $P(x)$ is false.”

How to Negate Existential Statements:

“There exists an x where $P(x)$ is true”

becomes

“For all x , $P(x)$ is false.”

How to Negate Implications:

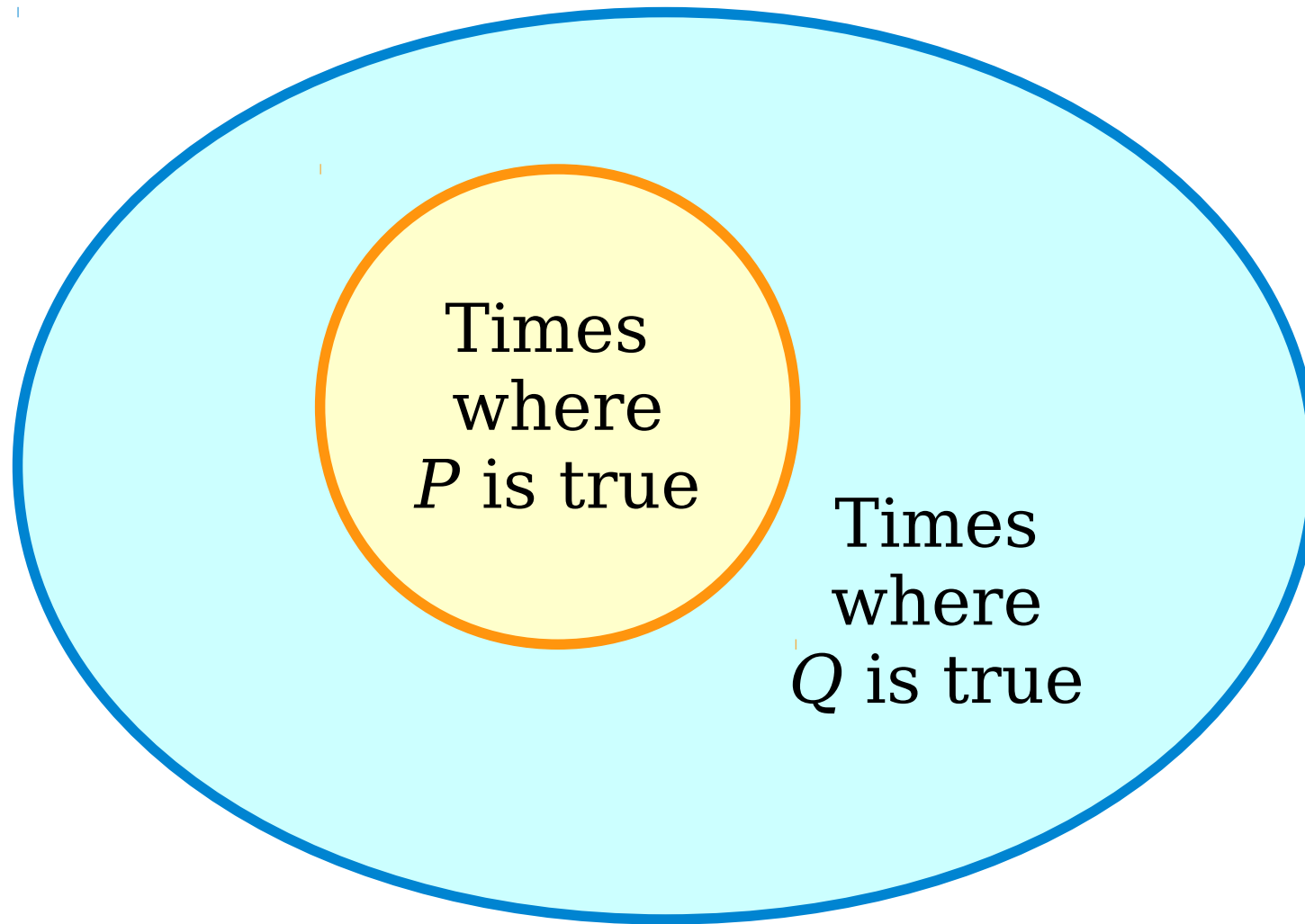
“For every x , if $P(x)$ is true, then $Q(x)$ is true”

becomes

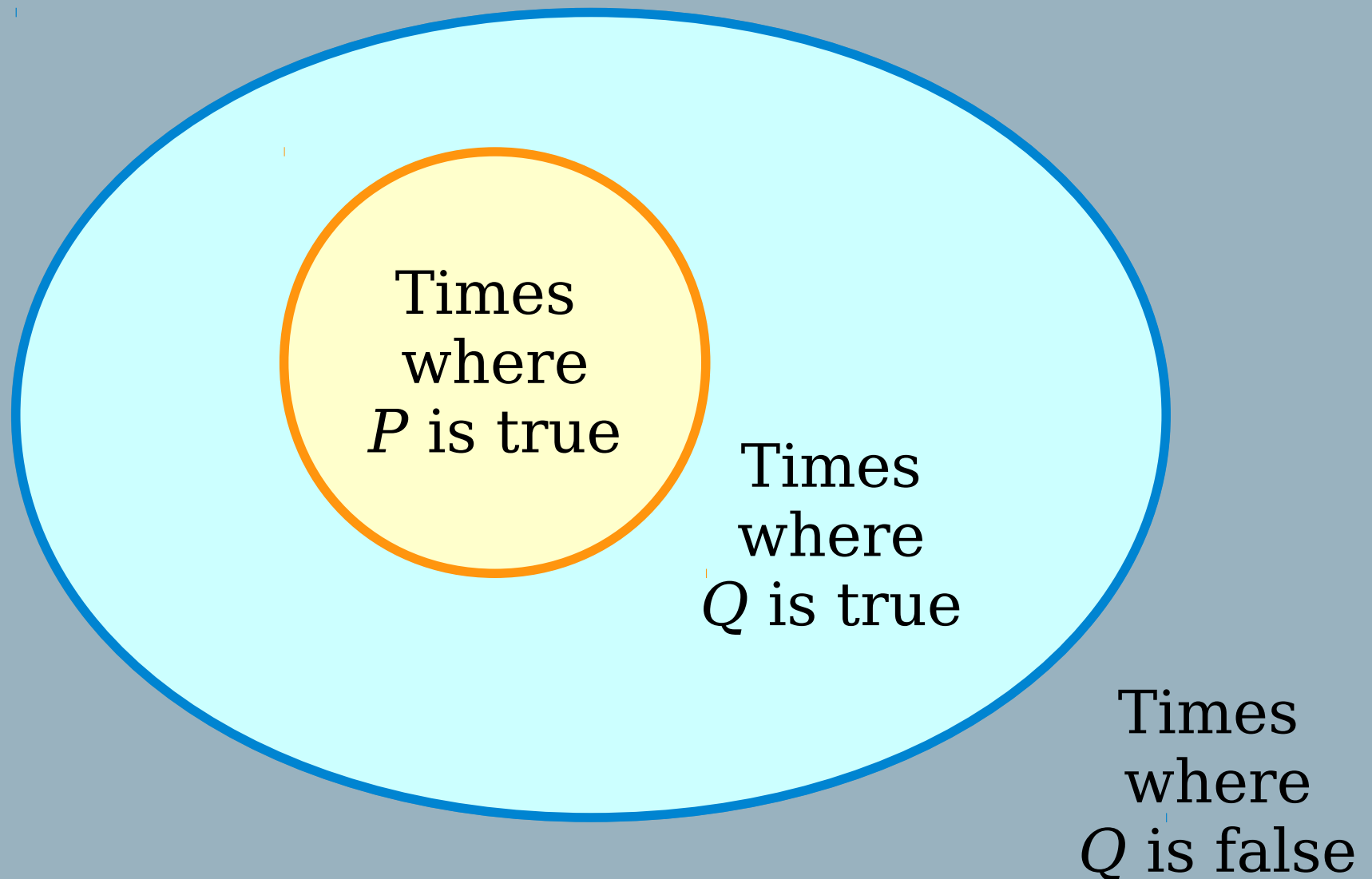
“There is an x where $P(x)$ is true and $Q(x)$ is false.”

Proof by Contrapositive

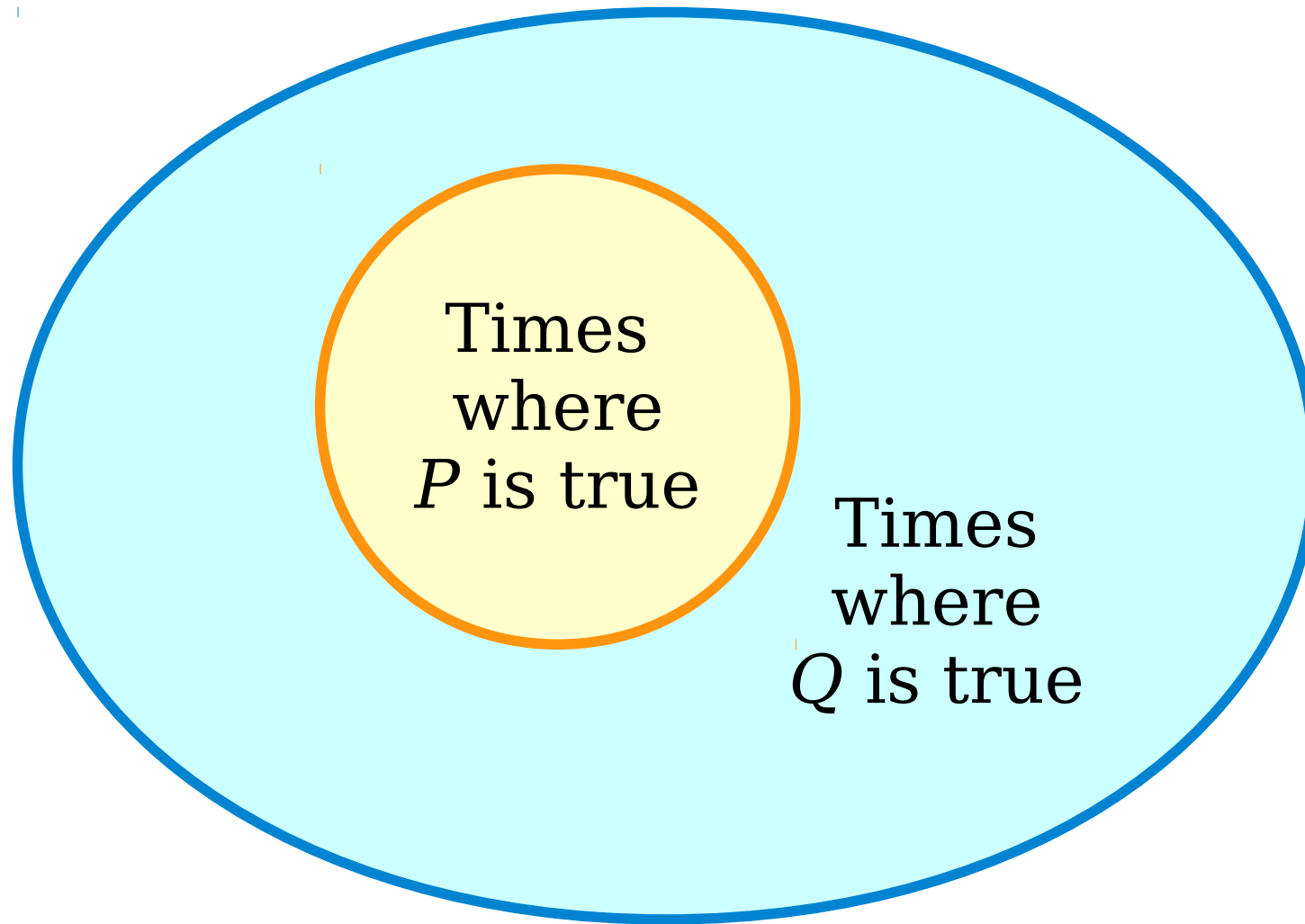
Implication, Diagrammatically



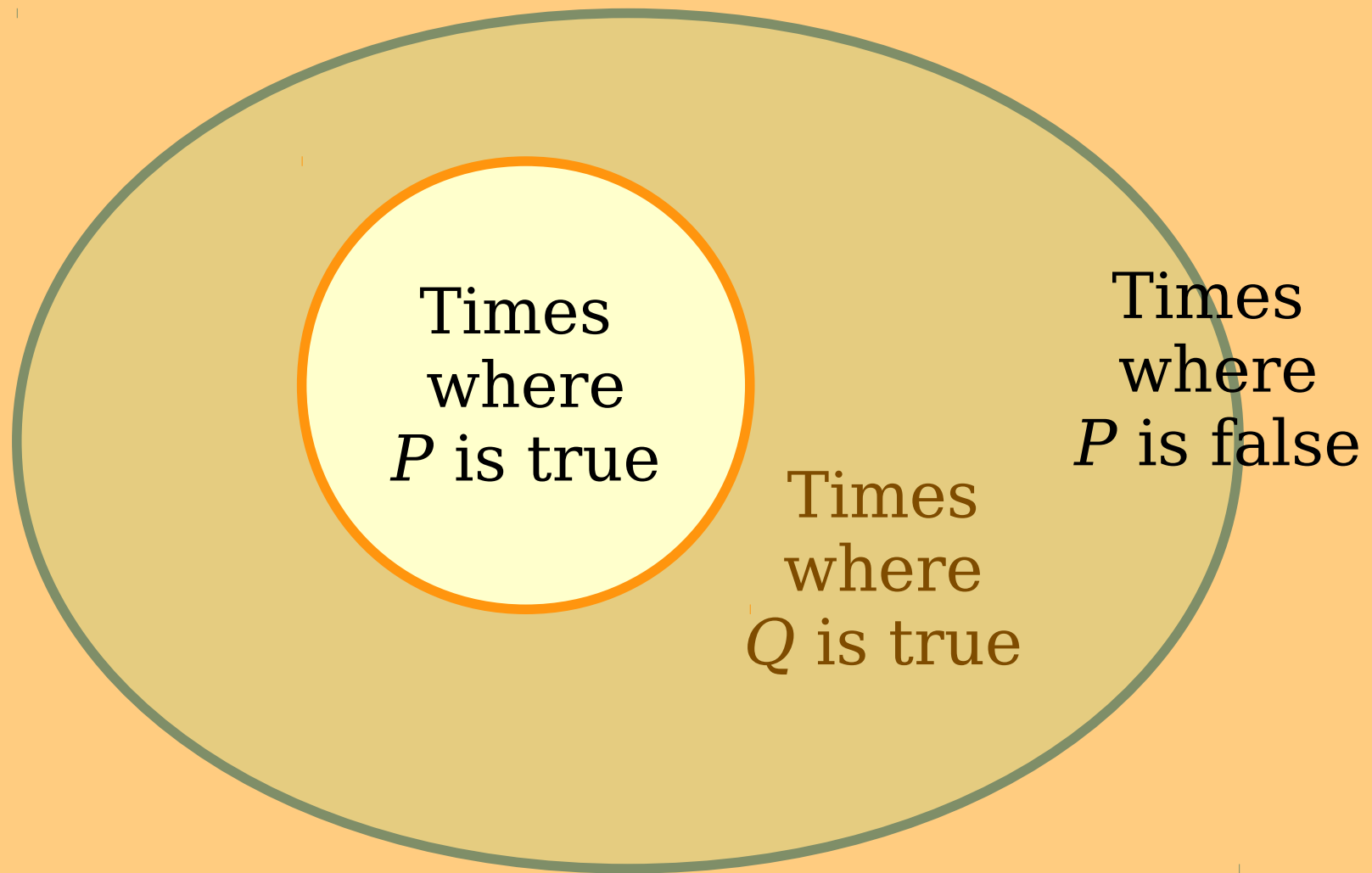
Implication, Diagrammatically



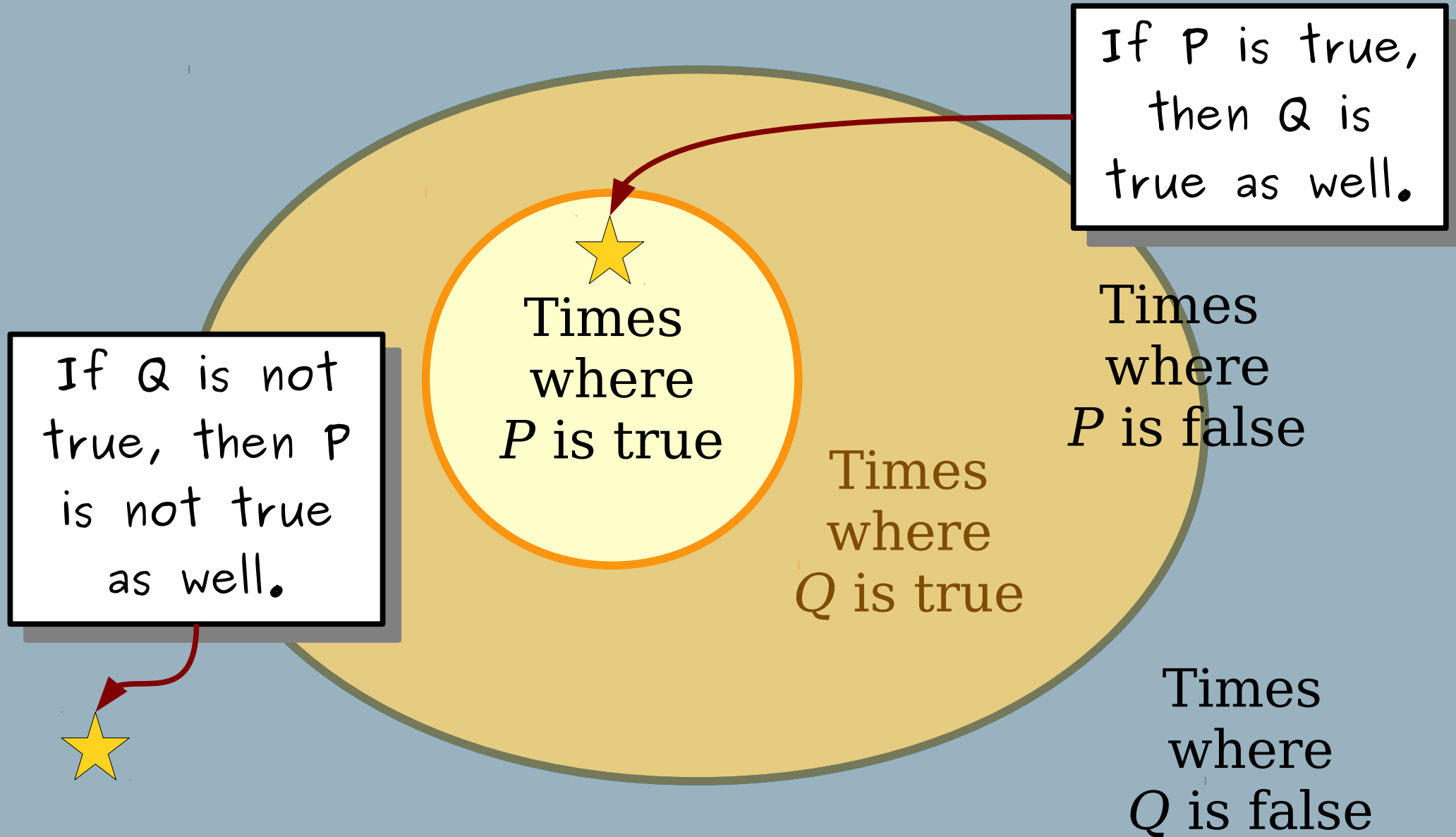
Implication, Diagrammatically



Implication, Diagrammatically



Implication, Diagrammatically



If P is true, then Q is true.

If Q is false, then P is false.

What are the negations of the above two statements?

If P is true, then Q is true.

negates to

P is true and Q is false.

If Q is false, then P is false.

What are the negations of the above two statements?

If P is true, then Q is true.

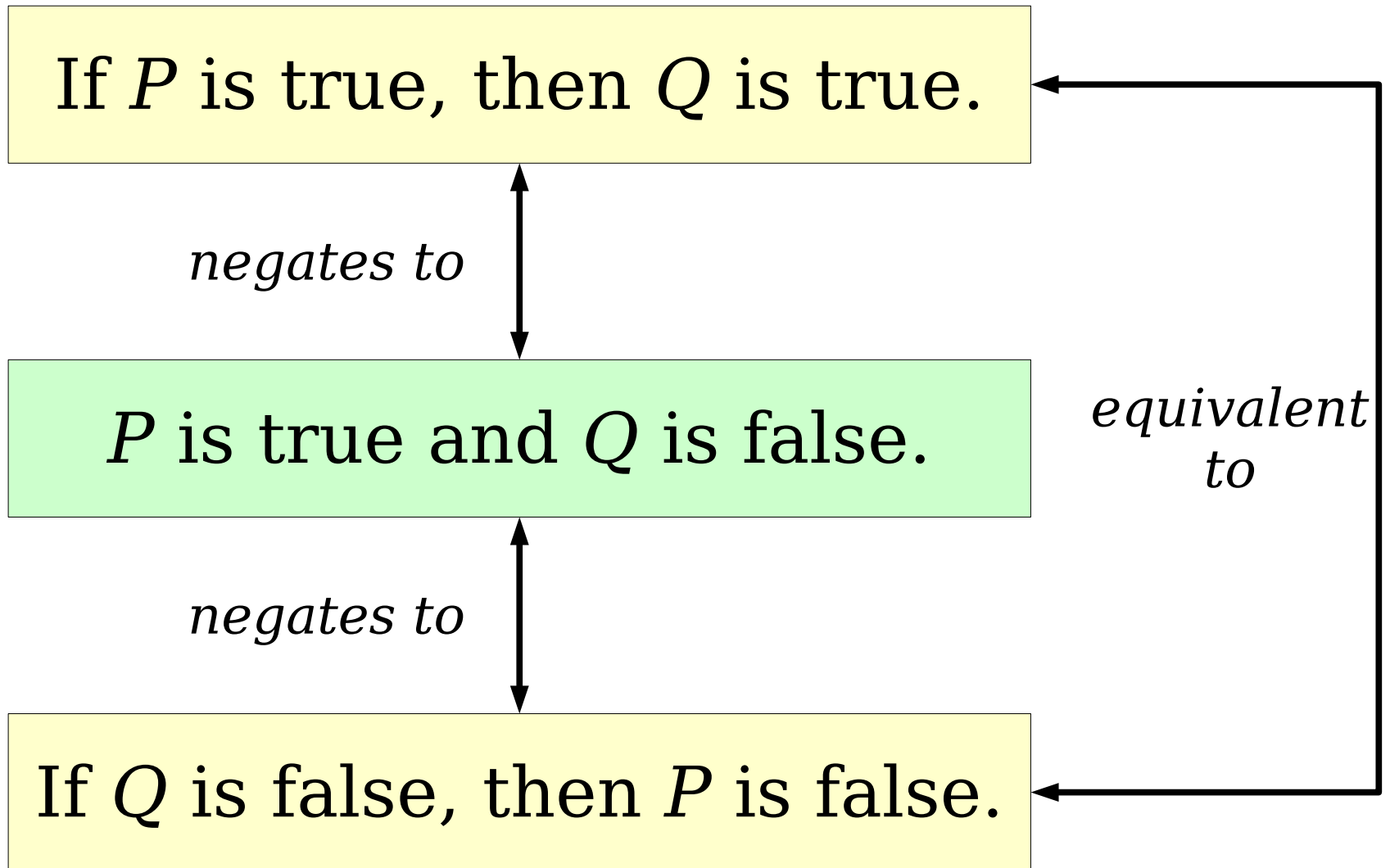
negates to

P is true and Q is false.

negates to

If Q is false, then P is false.

What are the negations of the above two statements?



What are the negations of the above two statements?

The Contrapositive

- The **contrapositive** of the implication

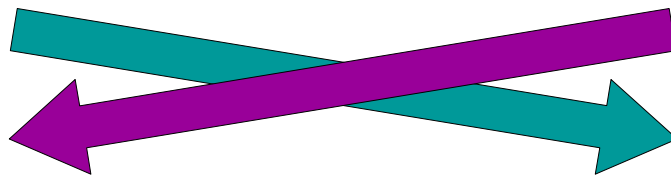
If **P is true**, then **Q is true**

is the implication

If **Q is false**, then **P is false**.

- The contrapositive of an implication means exactly the same thing as the implication itself.

If it's a puppy, then I love it.



If I don't love it, then it's not a puppy.

The Contrapositive

- The **contrapositive** of the implication

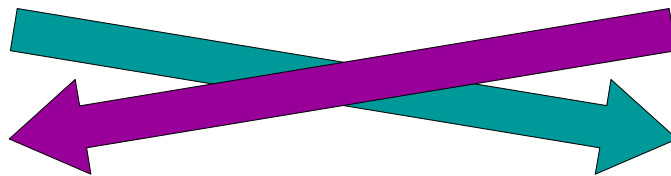
If **P is true**, then **Q is true**

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If **Q is false**, then **P is false**.

- The contrapositive of an implication means exactly the same thing as the implication itself.

If I store cat food inside, then raccoons won't steal it.



If raccoons stole the cat food, then I didn't store it inside.

To prove the statement

“if P is true, then Q is true,”

you can choose to instead prove the
equivalent statement

“if Q is false, then P is false,”

if that seems easier.

This is called a ***proof by contrapositive***.

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

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Proof: We will prove the contrapositive of this statement.

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Proof: We will prove the contrapositive of this statement

This is a courtesy to the reader and says "heads up! we're not going to do a regular old-fashioned direct proof here."

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement.

Question: What is the contrapositive of this statement?

- A) If n^2 is odd, then n is odd.
- B) If n is odd, then n^2 is odd.
- C) If n is even, then n^2 is even.
- D) None of the above.

Respond at pollev.com/cs103

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement,

What is the contrapositive of this statement?

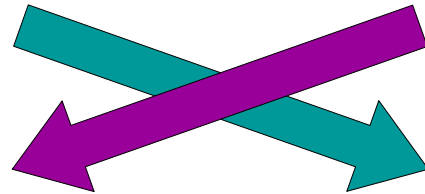
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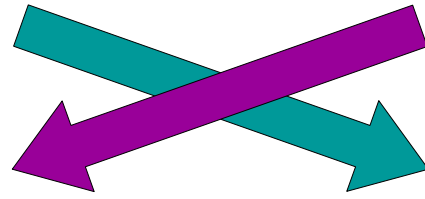


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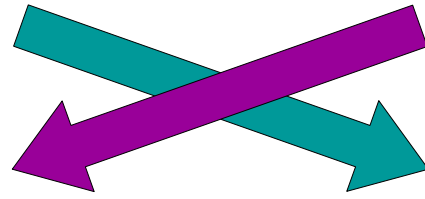
If n is odd, then n^2 is odd.

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd.

What is the contrapositive of this statement?

if n^2 is even, then n is even.



If n is odd, then n^2 is odd.

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd.

Here, we're explicitly writing out the contrapositive. This tells the reader what we're going to prove. It also acts as a sanity check by forcing us to write out what we think the contrapositive is.

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement, that **if n is odd, then n^2 is odd.**

We've said that we're going to prove this new implication, so let's go do it! The rest of this proof will look a lot like a standard direct proof.

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd. So let n be an arbitrary odd integer; we'll show that n^2 is odd as well.

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Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd. So let n be an arbitrary odd integer; we'll show that n^2 is odd as well.

We know that n is odd, which means there is an integer k such that $n = 2k + 1$.

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We know that n is odd, which means there is an integer k such that $n = 2k + 1$. This in turn tells us that

$$n^2 = (2k + 1)^2$$

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We know that n is odd, which means there is an integer k such that $n = 2k + 1$. This in turn tells us that

$$\begin{aligned}n^2 &= (2k + 1)^2 \\ &= 4k^2 + 4k + 1\end{aligned}$$

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Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd. So let n be an arbitrary odd integer; we'll show that n^2 is odd as well.

We know that n is odd, which means there is an integer k such that $n = 2k + 1$. This in turn tells us that

$$\begin{aligned}n^2 &= (2k + 1)^2 \\&= 4k^2 + 4k + 1 \\&= 2(2k^2 + 2k) + 1.\end{aligned}$$

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

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From this, we see that there is an integer m (namely, $2k^2 + 2k$) such that $n^2 = 2m + 1$.

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Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd. So let n be an arbitrary odd integer; we'll show that n^2 is odd.

We know
integer
us that

The general pattern here is the following:

1. Start by announcing that we're going to use a proof by contrapositive so that the reader knows what to expect.

2. Explicitly state the contrapositive of what we want to prove.

3. Go prove the contrapositive.

From th
(namely
means t
to show. ■

Theorem: For any $n \in \mathbb{Z}$, if n^2 is even, then n is even.

Proof: We will prove the contrapositive of this statement, that if n is odd, then n^2 is odd. So let n be an arbitrary odd integer; we'll show that n^2 is odd as well.

We know that n is odd, which means there is an integer k such that $n = 2k + 1$. This in turn tells us that

$$\begin{aligned}n^2 &= (2k + 1)^2 \\ &= 4k^2 + 4k + 1 \\ &= 2(2k^2 + 2k) + 1.\end{aligned}$$

From this, we see that there is an integer m (namely, $2k^2 + 2k$) such that $n^2 = 2m + 1$. That means that n^2 is odd, which is what we needed to show. ■

Biconditionals

- The previous theorem, combined with what we saw on Wednesday, tells us the following:

For any integer n , if n is even, then n^2 is even.

For any integer n , if n^2 is even, then n is even.

- These are two different implications, each going the other way.
- We use the phrase ***if and only if*** to indicate that two statements imply one another.
- For example, we might combine the two above statements to say
for any integer n : n is even if and only if n^2 is even.

Proving Biconditionals

- To prove a theorem of the form
P if and only if Q,
you need to prove two separate statements.
 - First, that if P is true, then Q is true.
 - Second, that if Q is true, then P is true.
- You can use any proof techniques you'd like to show each of these statements.
 - In our case, we used a direct proof for one and a proof by contrapositive for the other.

Let's take a quick break!

Time-Out for Announcements!

Outdoor Activities Guide

- Being on campus means you're less than fifty miles from grassy mountains, redwood forests, Pacific coastline, beautiful wetlands, and more.
- Want to explore the area to see what it has to offer? Check out our (unofficial) Outdoor Activities Guide.

https://cs103.stanford.edu/outdoor_activities

- A sampler of what to check out:
 - Drive to the observatory in the mountains near San Jose and take in the views.
 - Visit a beach with an enormous colony of elephant seals.
 - Walk in redwood forests and pick your own bay leaves.
 - Stroll in the chaparral and see deer and wild turkeys.



California is breathtaking!!



Readings for Today

- On the course website we have some information you should look over.
- First is the ***Proofwriting Checklist***. It contains information about style expectations for proofs. We'll be using this when grading, so be sure to read it over.
- Next is the ***Guide to Office Hours***, which talks about how our office hours work and how to make the most effective use of them.
- Finally is the ***Guide to LaTeX***, which explains how to use LaTeX to typeset your problem sets in a way that's so beautiful it will bring tears to your eyes.

Problem Set One

- Problem Set Zero was due at 4:00PM today.
 - Missed the deadline? Ping us and we'll see what we can do.
- Problem Set One goes out today. It's due next Friday at 4:00PM.
 - Explore the language of set theory and better intuit how it works.
 - Learn more about the structure of mathematical proofs.
 - Write your first “freehand” proofs based on your experiences.
- As always, reach out if you have any questions!

Submitting Assignments

- All assignments should be submitted through GradeScope.
 - The programming portion of the assignment gets submitted separately from the written component.
 - The written component **must** be typed up; handwritten solutions don't scan well and get mangled in GradeScope.
- We don't do late days in CS103. Because submission times are recorded automatically, we're strict about the submission deadlines.
 - **Very good idea:** Leave at least two hours buffer time for your first assignment submission, just in case something goes wrong.
 - **Very bad idea:** Wait until the last minute to submit.
- However, we are pretty generous with how we grade. Your score on the problem sets is the square root of your raw score. So an 81% maps to a 90%, a 50% maps to a 71%, etc. This gives a huge boost even if you need to turn something in that isn't done.

Getting Help

- It is ***completely normal*** in this class to need to get help from time to time.
- Feel free to ask clarifying and conceptual questions on EdStem.
- Need more structured help? We have office hours! Feel free to stop on by.
 - Check out the online “Guide to Office Hours” for more information about how our office hours system works.
 - The OH calendar is available on the course website.

Working in Pairs

- You can work on problem sets individually or in pairs.
- Each person/pair should only submit a single problem set. In other words, if you're working in a pair, you and your partner should agree who will make the submission.
- For more details, check the Syllabus and Honor Code pages on the course website.

Finding a Problem Set Partner

Looking for a problem set partner?

- Meet folks in lecture!
- Meet folks in office hours!
- Check out our [pinned thread on EdStem!](#)
- Fill out our [matchmaking form!](#)

A Note on the Honor Code

Back to CS103!

Proof by Contradiction

*There's something hidden behind one of these doors.
Which door is it hidden behind?*

Door 1



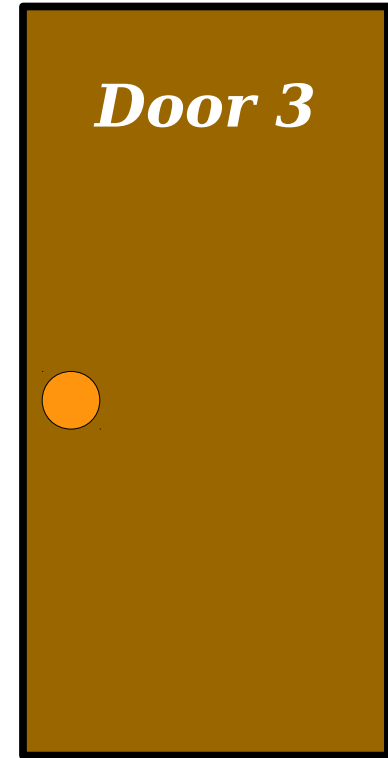
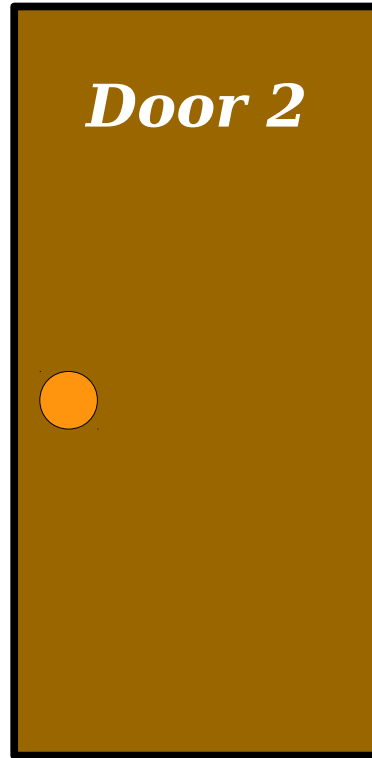
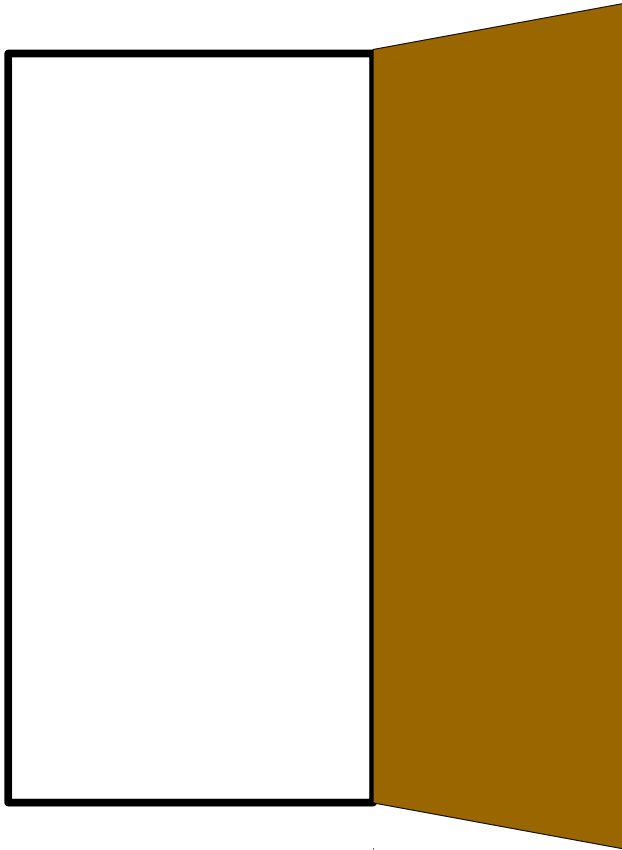
Door 2



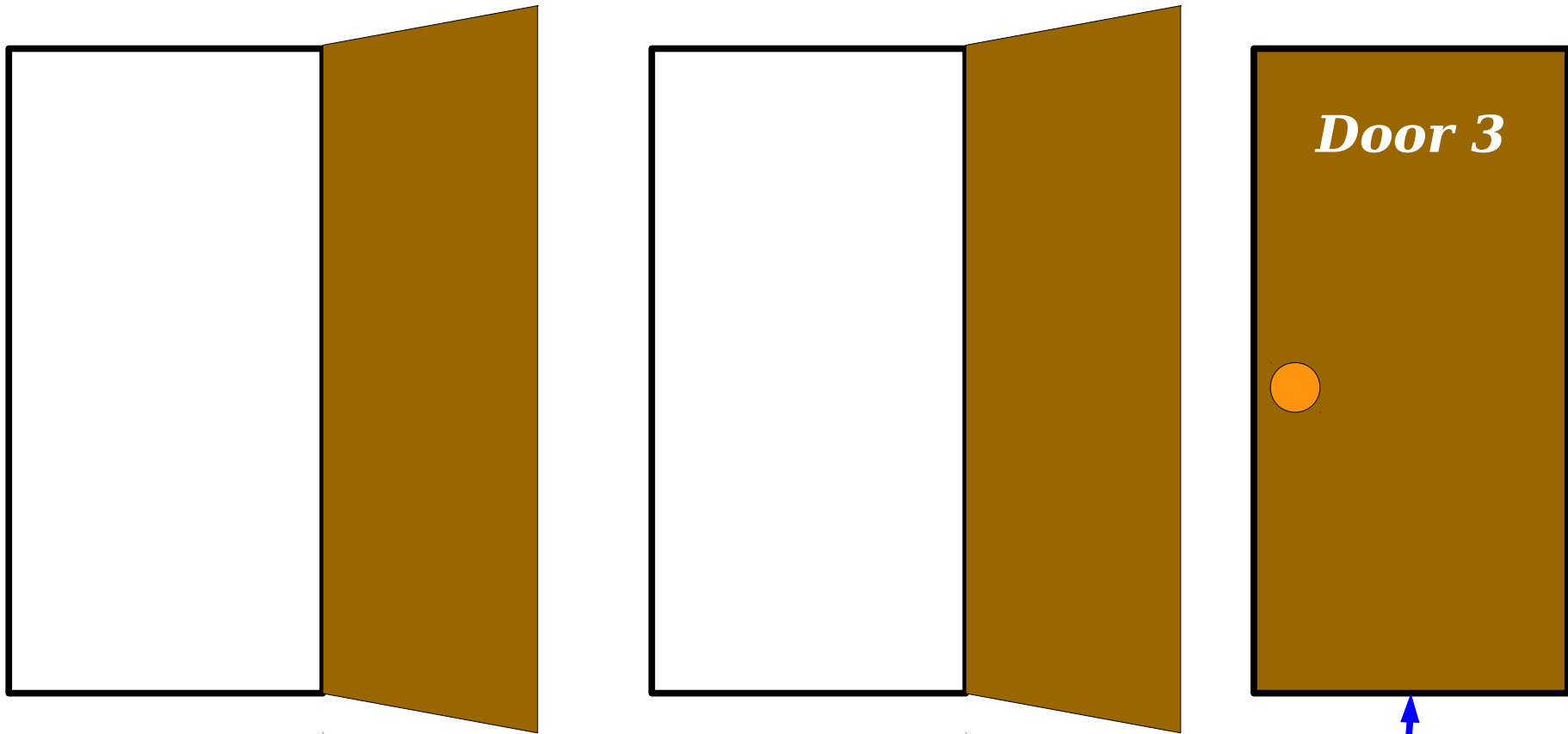
Door 3



*There's something hidden behind one of these doors.
Which door is it hidden behind?*

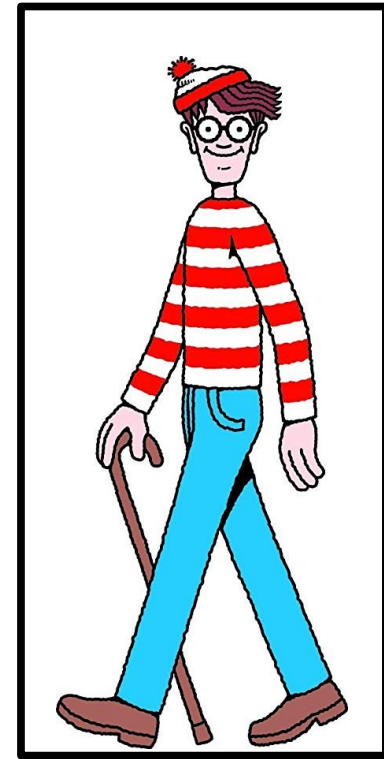
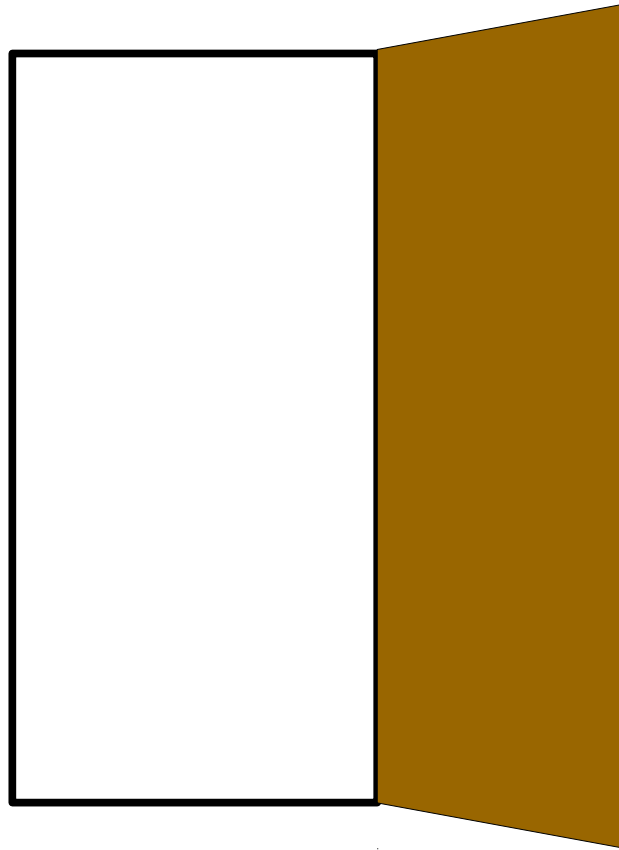
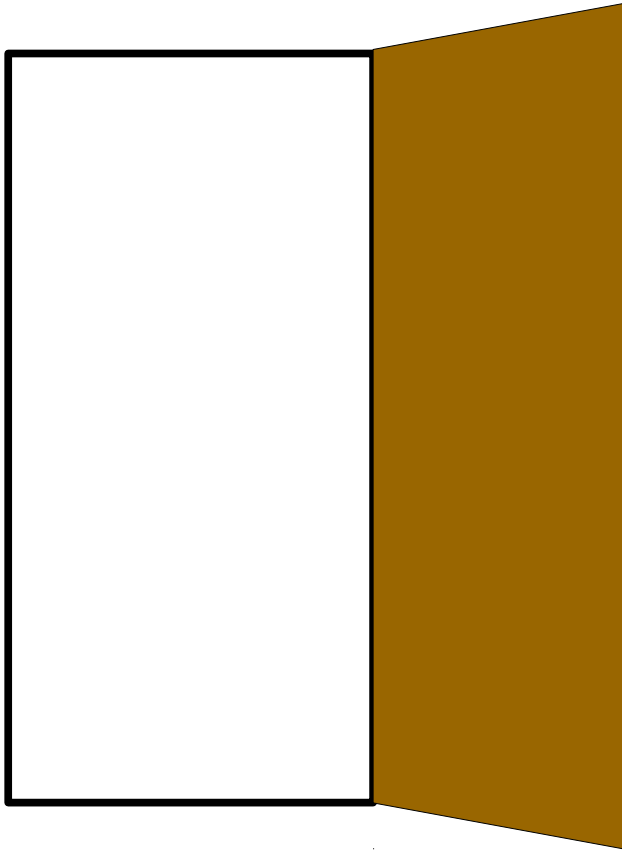


*There's something hidden behind one of these doors.
Which door is it hidden behind?*



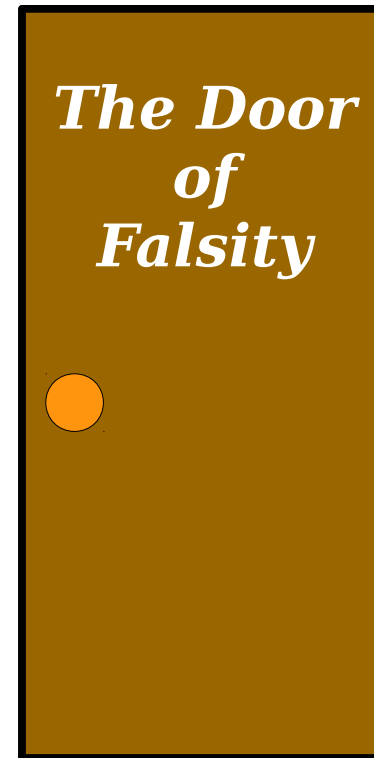
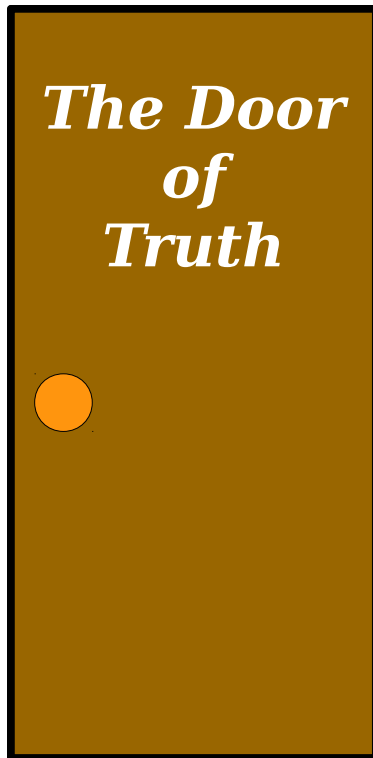
Even without opening this door, we know whatever is hidden has to be here.

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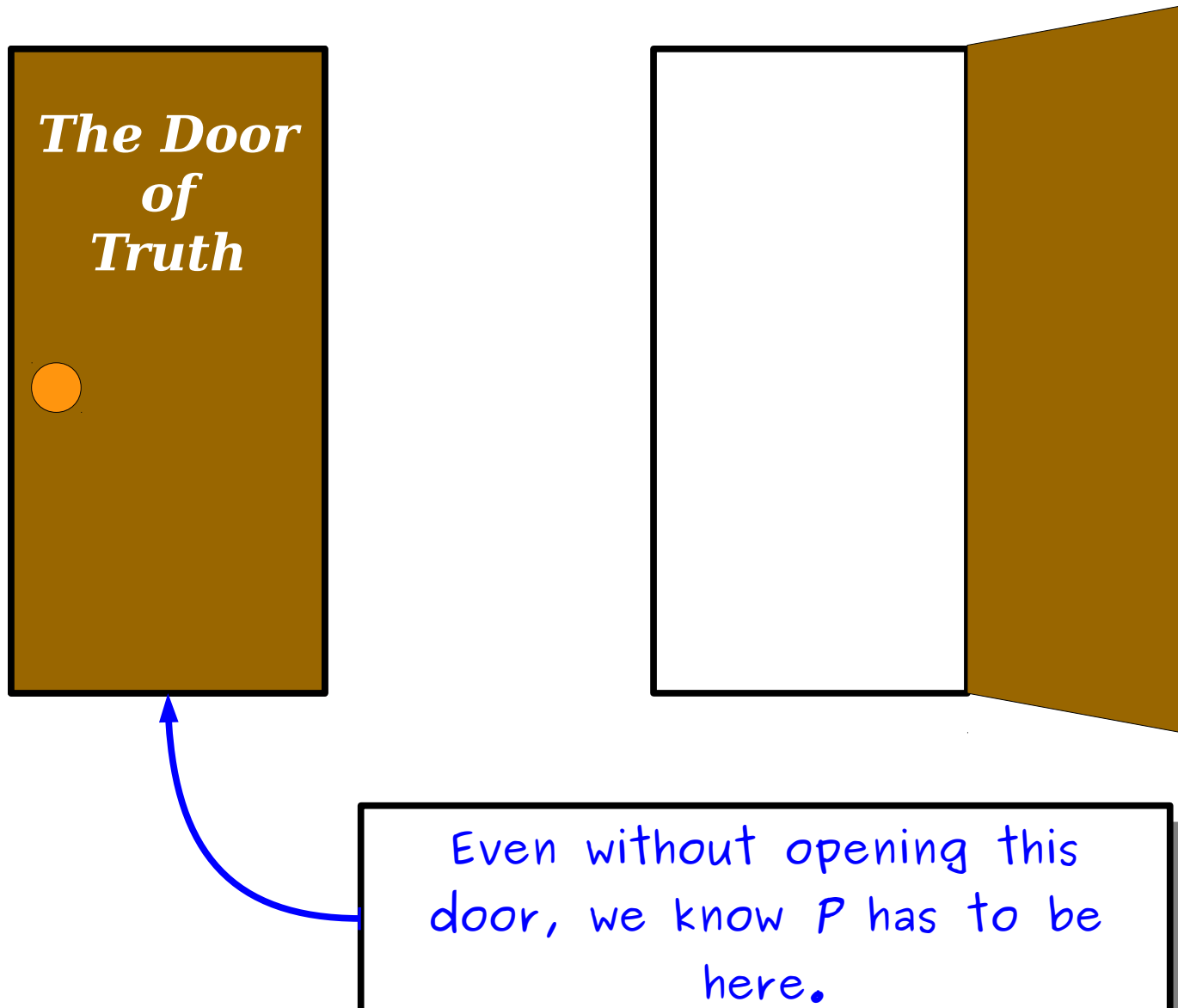


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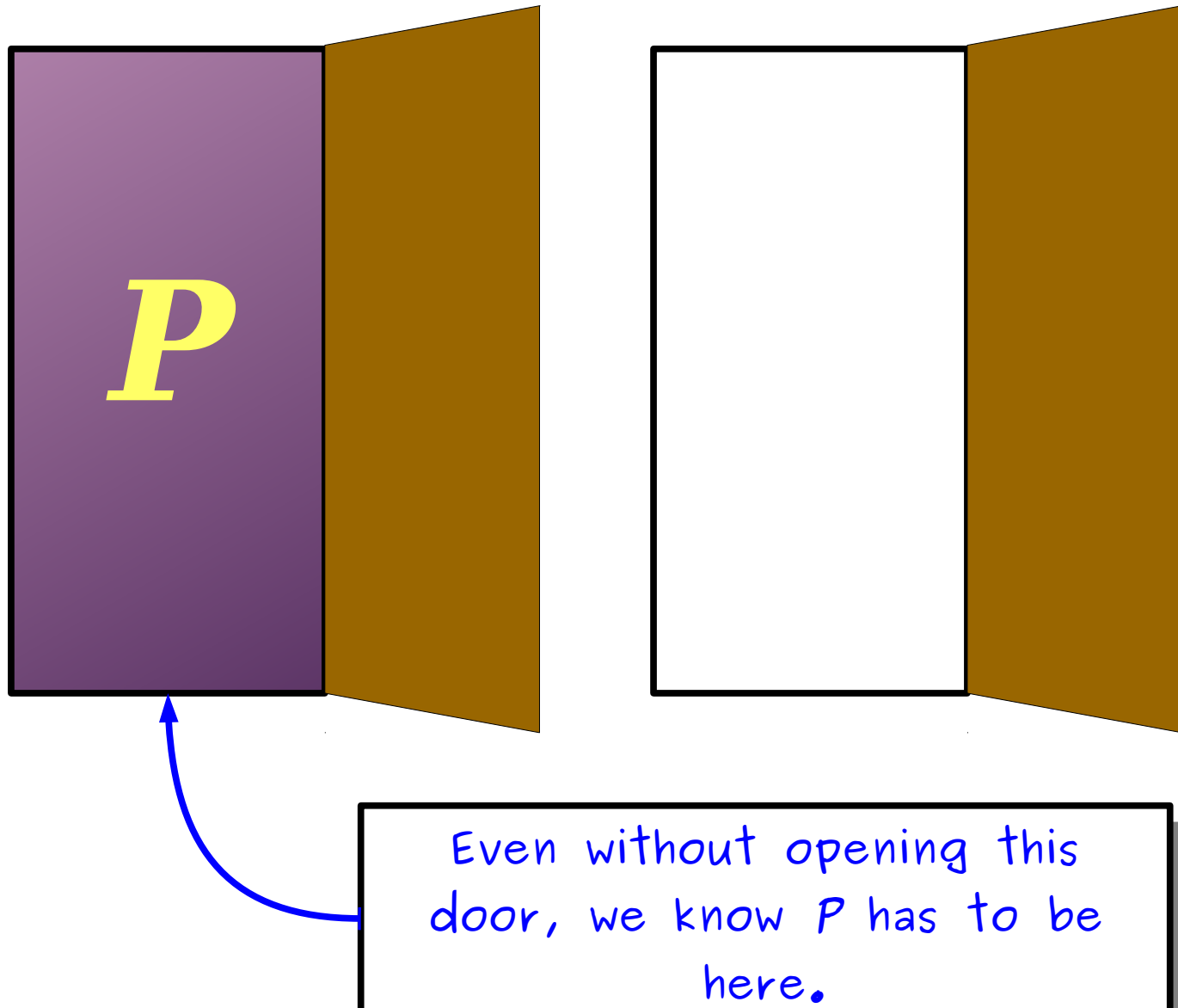
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A ***proof by contradiction*** shows that some statement P is true by showing that P isn't false.

Proof by Contradiction

- **Key Idea:** Prove a statement P is true by showing that it isn't false.
- First, assume that P is false. The goal is to show that this assumption is silly.
- Next, show this leads to an impossible result.
 - For example, we might have that $1 = 0$, that $x \in S$ and $x \notin S$, that a number is both even and odd, etc.
- Finally, conclude that since P can't be false, we know that P must be true.

An Example: ***Set Cardinalities***

Set Cardinalities

- We've seen sets of many different cardinalities:
 - $|\emptyset| = 0$
 - $|\{1, 2, 3\}| = 3$
 - $|\{n \in \mathbb{N} \mid n < 137\}| = 137$
 - $|\mathbb{N}| = \aleph_0$.
- These span from the finite up through the infinite.
- **Question:** Is there a “largest” set? That is, is there a set that's bigger than every other set?

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Proof: Assume for the sake of contradiction that there is a largest set; call it S .

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Notice that we're announcing

1. that this is a proof by contradiction, and
2. what, specifically, we're assuming.

This helps the reader understand where we're going. Remember - proofs are meant to be read by other people!

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The three key pieces:

1. Say that the proof is by contradiction.
2. Say what you are assuming is the negation of the statement to prove.
3. Say you have reached a contradiction and what the contradiction means.

In CS103, please include all these steps in your proofs!

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Proving Implications

- Suppose we want to prove this implication:

If ***P*** is true, then ***Q*** is true.

- We have three options available to us:
 - ***Direct Proof:***
 - ***Proof by Contrapositive.***
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 ... what does this look like?

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Question: What is the negation of this statement?

Respond at pollev.com/cs103

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Question: How do we complete this sentence?

Respond at pollev.com/cs103

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Squaring both sides of equation (1) and simplifying gives the following:

$$n^2 = (2k + 1)^2$$

Question: What would the rest of this proof look like? Remember, we are trying to arrive at some sort of contradiction. What can we say about n^2 ?

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Assume **P is true** and **Q is false**,
then derive a contradiction.

What We Learned

- ***What's an implication?***

- It's a statement of the form “if P , then Q ,” and states that if P is true, then Q is true.

- ***How do you negate formulas?***

- It depends on the formula. There are nice rules for how to negate universal and existential statements and implications.

- ***What is a proof by contrapositive?***

- It's a proof of an implication that instead proves its contrapositive.
- (The contrapositive of “if P , then Q ” is “if not Q , then not P .”)

- ***What's a proof by contradiction?***

- It's a proof of a statement P that works by showing that P cannot be false.

Your Action Items

- ***Read “Guide to Office Hours,” the “Proofwriting Checklist,” and the “Guide to LaTeX.”***
 - There’s a lot of useful information there. In particular, be sure to read the Proofwriting Checklist, as we’ll be working through this checklist when grading your proofs!
- ***Start working on PS1.***
 - At a bare minimum, read over it to see what’s being asked. That’ll give you time to turn things over in your mind this weekend.

Next Time

- ***Mathematical Logic***
 - How do we formalize the reasoning from our proofs?
- ***Propositional Logic***
 - Reasoning about simple statements.
- ***Propositional Equivalences***
 - Simplifying complex statements.