

# Propositional Logic

# ***Logistics:*** Lecture Participation

# Lecture Participation

- Starting today, we will be using the website PolleEV to ask questions in lecture for attendance credit.
- If you answer these questions in lecture you'll get attendance credit for the day.
  - You don't need to have the right answers – you just need to respond to the questions.
- If you don't attend lecture in person, no worries! You can alternatively answer questions about the lecture on Gradescope before the start of the next lecture to earn participation credit.
  - You do have to get the answers right, though you get unlimited resubmit attempts.
- If you don't do either, that's fine too! We'll count your final exam score in place of your participation grade.

# Lecture Participation

- We'll dry-run PolLEV questions today.
- Let's start with the following warm-up:
  - 👉 ***Make a music recommendation!*** 👈
- Answer online by visiting
  - <https://pollev.com/cs103>**
- Here's two of my own:
  - *Expert in a Dying Field* by The Beths
  - *Manchester* by Kishi Bashi

***Question:*** How do we formalize the definitions and reasoning we use in our proofs?

# Where We're Going

- ***Propositional Logic*** (Today)
  - Reasoning about Boolean values.
- ***First-Order Logic*** (Wednesday/Friday)
  - Reasoning about properties of multiple objects.

# Outline for Today

- ***Propositional Variables***
  - Booleans, math edition!
- ***Propositional Connectives***
  - Linking things together.
- ***Truth Tables***
  - Rigorously defining connectives.
- ***Simplifying Negations***
  - Mechanically computing negations.

# Propositional Logic

*TakeMath51*  $\vee$  *TakeCME100*

$\neg$ *FirstSucceed*  $\rightarrow$  *TryAgain*

*IsCardinal*  $\wedge$  *IsWhite*

$TakeMath51 \vee TakeCME100$

$\neg FirstSucceed \rightarrow TryAgain$

$IsCardinal \wedge IsWhite$

These are **propositional variables**. Each propositional variable stands for a **proposition**, something that is either true or false.

*TakeMath51*  $\vee$  *TakeCME100*

$\neg$ *FirstSucceed*  $\rightarrow$  *TryAgain*

*IsCardinal*  $\wedge$  *IsWhite*

These are **propositional connectives**, which link propositions into larger propositions

# Propositional Variables

- In propositional logic, individual propositions are represented by ***propositional variables***.
- In a move that contravenes programming style conventions, propositional variables are usually represented as lower-case letters, such as *p*, *q*, *r*, *s*, etc.
  - That said, there's nothing stopping you from using multiletter names!
- Each variable can take on one of two values: true or false. You can think of them as **bool** values.

# Propositional Connectives

- There are seven propositional connectives, five of which will be familiar from programming.
- First, there's the logical "NOT" operation:

$\neg p$

- You'd read this out loud as "not  $p$ ."
- The fancy name for this operation is ***logical negation***.

# Propositional Connectives

- There are seven propositional connectives, five of which will be familiar from programming.
- Next, there's the logical "AND" operation:

$$p \wedge q$$

- You'd read this out loud as " $p$  and  $q$ ."
- The fancy name for this operation is ***logical conjunction***.

# Propositional Connectives

- There are seven propositional connectives, five of which will be familiar from programming.
- Then, there's the logical "OR" operation:

$$p \vee q$$

- You'd read this out loud as "*p* or *q*."
- The fancy name for this operation is **logical disjunction**. This is an *inclusive* or.

# Propositional Connectives

- There are seven propositional connectives, five of which will be familiar from programming.
- There's also the "truth" connective:

T

- You'd read this out loud as "true."
- Although this is technically considered a connective, it "connects" zero things and behaves like a variable that's always true.

# Propositional Connectives

- There are seven propositional connectives, five of which will be familiar from programming.
- Finally, there's the “false” connective.

⊥

- You'd read this out loud as “false.”
- Like  $\top$ , this is technically a connective, but acts like a variable that's always false.

# Truth Tables

- A ***truth table*** is a table showing the truth value of a propositional logic formula as a function of its inputs.
- Let's go look at the truth tables for the connectives we've seen so far:

$\neg$        $\wedge$        $\vee$        $\top$        $\perp$

# Summary of Important Points

- The  $\vee$  connective is an *inclusive* “or.” It's true if at least one of the operands is true.
  - Similar to the `||` operator in C, C++, Java, etc. and the `or` operator in Python.
- If we need an exclusive “or” operator, we can build it out of what we already have.
- Try this yourself! Take a minute to combine these operators together to form an expression that represents the exclusive or of  $p$  and  $q$  (something that's true if and only if exactly one of  $p$  and  $q$  are true.)

## *Quick Question:*

What would I have to show you to convince you that the statement  $p \wedge q$  is false?

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What would I have to show you to convince you that the statement  $p \vee q$  is false?

# de Morgan's Laws

$\neg(p \wedge q)$  *is equivalent to*  $\neg p \vee \neg q$

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# de Morgan's Laws in Code

- **Pro tip:** Don't write this:

```
if (!(p() && q())) {  
    /* ... */  
}
```

- Write this instead:

```
if (!p() || !q()) {  
    /* ... */  
}
```

- (This even short-circuits correctly: if `p()` returns false, `q()` is never evaluated.)

# Mathematical Implication

# Implication

- We can represent implications using this connective:

$$p \rightarrow q$$

- You'd read this out loud as “ $p$  implies  $q$ .”
  - The fancy name for this is the ***material conditional***.
- ***Question:*** What should the truth table for  $p \rightarrow q$  look like?
- Pull out a sheet of paper, make a guess, and talk things over with your neighbors!

$p$	$q$	$p \rightarrow q$
F	F	T
F	T	T
T	F	F
T	T	T

An implication is false only when the antecedent is true and the consequent is false.

Every formula is either true or false, so these other entries have to be true.

$p$	$q$	$p \rightarrow q$
F	F	T
F	T	T
T	F	F
T	T	T

***Important observation:***

The statement  $p \rightarrow q$  is true whenever  $p \wedge \neg q$  is false.

$p$	$q$	$p \rightarrow q$
F	F	T
F	T	T
T	F	F
T	T	T

An implication with a false antecedent is called ***vacuously true***.

An implication with a true consequent is called ***trivially true***.

$p$	$q$	$p \rightarrow q$
F	F	T
F	T	T
T	F	F
T	T	T

***Please commit this table to memory.*** We're going to need it, extensively, over the next couple of weeks.

# Fun Fact 1: The Contrapositive Revisited

Fun Fact 2: Proof by Contradiction

Fun Fact 3: Implies, Another Way

# An Important Equivalence

- Earlier, we talked about the truth table for  $p \rightarrow q$ . We chose it so that

**$p \rightarrow q$  is equivalent to  $\neg(p \wedge \neg q)$**

- Later on, this equivalence will be incredibly useful:

**$\neg(p \rightarrow q)$  is equivalent to  $p \wedge \neg q$**

# Another Important Equivalence

- Here's a useful equivalence. Start with

$$**p \rightarrow q** \text{ is equivalent to } \neg(\mathbf{p \wedge \neg q})$$

- By de Morgan's laws:

$$**p \rightarrow q** \text{ is equivalent to } \neg(\mathbf{p \wedge \neg q})$$

$$\text{is equivalent to } \neg\mathbf{p \vee \neg\neg q}$$

$$\text{is equivalent to } \neg\mathbf{p \vee q}$$

- Thus **p \rightarrow q** is equivalent to **\neg p \vee q**

# The Biconditional Connective

# The Biconditional Connective

- Last week, we saw that “ $p$  if and only if  $q$ ” means both that  $p \rightarrow q$  and  $q \rightarrow p$ .
- We can write this in propositional logic using the ***biconditional*** connective:

$$p \leftrightarrow q$$

- This connective’s truth table has the same meaning as “ $p$  implies  $q$  and  $q$  implies  $p$ .”
- Based on that, what should its truth table look like?
- Take a guess, and talk it over with your neighbor!

# Biconditionals

- The ***biconditional*** connective  $p \leftrightarrow q$  is read “ $p$  if and only if  $q$ .”
- Here's its truth table:

$p$	$q$	$p \leftrightarrow q$
F	F	T
F	T	F
T	F	F
T	T	T

One interpretation of  $\leftrightarrow$  is to think of it as equality: the two propositions must have equal truth values.

# Negating a Biconditional

- How do we simplify

$$\neg(p \leftrightarrow q)$$

using the tools we've seen so far?

- There are many options, but here are our two favorites:

$$p \leftrightarrow \neg q$$

$$\neg p \leftrightarrow q$$

# Operator Precedence

- How do we parse this statement?

$$\neg x \rightarrow y \vee z \rightarrow x \vee y \wedge z$$

- Operator precedence for propositional logic:

$\neg$

$\wedge$

$\vee$

$\rightarrow$

$\leftrightarrow$

- All operators are right-associative.
- We can use parentheses to disambiguate.

# Operator Precedence

- How do we parse this statement?

$$(\neg x) \rightarrow ((y \vee z) \rightarrow (x \vee (y \wedge z)))$$

- Operator precedence for propositional logic:

$\neg$

$\wedge$

$\vee$

$\rightarrow$

$\leftrightarrow$

- All operators are right-associative.
- We can use parentheses to disambiguate.

# Operator Precedence

- The main points to remember:
  - $\neg$  binds to whatever immediately follows it.
  - $\wedge$  and  $\vee$  bind more tightly than  $\rightarrow$ .
- We will commonly write expressions like  $p \wedge q \rightarrow r$  without adding parentheses.
- For more complex expressions, we'll try to add parentheses.
- Confused? ***Please ask!***

# The Big Table

Connective	Read Aloud As	C++ Version	Fancy Name
$\neg$	“not”	!	Negation
$\wedge$	“and”	&&	Conjunction
$\vee$	“or”		Disjunction
$\top$	“true”	<b>true</b>	Truth
$\perp$	“false”	<b>false</b>	Falsity
$\rightarrow$	“implies”	<i>see PS2!</i>	Implication
$\leftrightarrow$	“if and only if”	<i>see PS2!</i>	Biconditional

**Time-Out for Announcements!**

# Ask Me Anything

- Between lectures, I'll make a post on EdStem soliciting your questions.
- This is a chance to ask questions about any topic: course material, life advice, music recommendations, etc.
  - Just keep things civil and only ask questions if you really want to hear the answer.
- Feel free to ♥ questions you like. I'll take some of the more popular questions in lecture.

# Office Hours

- Office hours start today. Think of them as “drop-in help hours” where you can ask questions on problem sets, lecture topics, etc.
  - Check the Guide to Office Hours on the course website for the schedule.
- Most office hours are held in person in the Huang basement. A few are purely online. Mine are in my office, Durand 317.
- Once you arrive, sign up on QueueStatus so that we can help people in the order they arrived:  
**<https://questatus.com/queues/782>**
- Office hours are much less crowded earlier in the week than later.

Back to CS103!

# Recap So Far

- A ***propositional variable*** is a variable that is either true or false.
- The ***propositional connectives*** are
  - Negation:  $\neg p$
  - Conjunction:  $p \wedge q$
  - Disjunction:  $p \vee q$
  - Truth:  $\top$
  - Falsity:  $\perp$
  - Implication:  $p \rightarrow q$
  - Biconditional:  $p \leftrightarrow q$

# Negation Practice

- Here's a propositional formula that contains some negations. Simplify it as much as possible:

$$\neg(p \wedge q \rightarrow r \vee s)$$

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- Here's a propositional formula that contains some negations. Simplify it as much as possible:

$$p \wedge q \wedge \neg r \wedge \neg s$$

# Negation Practice

- Here's a propositional formula that contains some negations. Simplify it as much as possible:

$$\neg((p \vee (q \wedge r)) \leftrightarrow (a \wedge b \wedge c \rightarrow d))$$

# Negation Practice

- Here's a propositional formula that contains some negations. Simplify it as much as possible:

$$(p \vee (q \wedge r)) \leftrightarrow (a \wedge b \wedge c \wedge \neg d)$$

Why All This Matters

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- Suppose we want to prove the following statement:

“If  $x + y = 16$ , then  $x \geq 8$  or  $y \geq 8$ ”

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“If  $x + y = 16$ , then  $x \geq 8$  or  $y \geq 8$ ”

$$x + y = 16 \rightarrow x \geq 8 \vee y \geq 8$$

# Why All This Matters

- Suppose we want to prove the following statement:

“If  $x + y = 16$ , then  $x \geq 8$  or  $y \geq 8$ ”

$$x < 8 \wedge y < 8 \rightarrow x + y \neq 16$$

# Why All This Matters

- Suppose we want to prove the following statement:

“If  $x + y = 16$ , then  $x \geq 8$  or  $y \geq 8$ ”

$$x < 8 \wedge y < 8 \rightarrow x + y \neq 16$$

“If  $x < 8$  and  $y < 8$ , then  $x + y \neq 16$ ”

**Theorem:** If  $x + y = 16$ , then  $x \geq 8$  or  $y \geq 8$ .

**Proof:** We will prove the contrapositive, namely, that if  $x < 8$  and  $y < 8$ , then  $x + y \neq 16$ .

Pick  $x$  and  $y$  where  $x < 8$  and  $y < 8$ . We want to show that  $x + y \neq 16$ . To see this, note that

$$\begin{aligned}x + y &< 8 + y \\ &< 8 + 8 \\ &= 16.\end{aligned}$$

This means that  $x + y < 16$ , so  $x + y \neq 16$ , which is what we needed to show. ■

# Why This Matters

- Propositional logic is a tool for reasoning about how various statements affect one another.
- To better understand how to prove a result, it often helps to translate what you're trying to prove into propositional logic first.
- That said, propositional logic isn't expressive enough to capture all statements. For that, we need something more powerful.

# Next Time

- ***First-Order Logic***
  - Reasoning about groups of objects.
- ***First-Order Translations***
  - Expressing yourself in symbolic math!