

## 70: Discrete Math and Probability Theory

Programming + Microprocessors  $\equiv$  Superpower!

What are your super powerful programs/processors doing?

Logic and Proofs!

Induction  $\equiv$  Recursion.

What can computers do?

Work with discrete objects.

**Discrete Math**  $\implies$  immense application.

Computers learn and interact with the world?

E.g. machine learning, data analysis, robotics, ...

**Probability!**

See Professor Sahai's note under Resources, for more discussion.

## Why I use Slides and some Advice.

Lots of arguments are demonstrated well by examples or verbal explanations, but sometimes painful to write down, which works for me with slides.

(1) Is there value for you to watch me write on screen or paper?

(2) You have them!

Use the slides to guide you.

Handout Version: for getting landscape.

Slide Version: for detailed understanding.

**It is easier to present more.**

"More" is overview, connections, insights, some jokes (breaks), the details.

Risk: Students get frustrated at not understanding everything.

The truth: Students don't understand everything.

I certainly don't in real time or sometimes ever.

It is ok: many levels to grok. Lecture is one pass.

Notes are sufficient.

## The Truth about CS70

...according to me.

It's transformative.

Programming is a superpower.

Reasoning is perhaps even better.

Each Topic:

Define, understand, and build.

Clearly and correctly.

Rate of Change + Newton  $\rightarrow$  Calculus.

## Admin

Course Webpage: <http://www.eecs70.org/>

Explains policies, has office hours, homework, midterm dates, etc.

One midterm, final.

midterm.

Questions  $\implies$  piazza:

**Logistics, etc.**

**Content Support: other students!**

**Plus Piazza hours.**

**Weekly Post.**

It's **weekly**.

Read it!!!!

Announcements, logistics, critical advice.

## Satish Rao

21st year at Berkeley.

PhD: Long time ago, far far away.

Research: Theory (Algorithms)

Taught in CS: 70, 170, 174, 188, 270, 273, 294, 375, ...

Other: Three adult kids. **One Cal Grad!**

Lecturing Style: I have used slides.

## Wason's experiment:1

Suppose we have four cards on a table:

- ▶ 1st about Alice, 2nd about Bob, 3rd Charlie, 4th Donna.
- ▶ Card contains person's **destination** on one side, and **mode of travel**.
- ▶ Consider the theory:  
"If a person travels to Chicago, he/she flies."
- ▶ Suppose you see that Alice went to Baltimore, Bob drove, Charlie went to Chicago, and Donna flew.

Alice	Bob	Charlie	Donna
Baltimore	drove	Chicago	flew

- ▶ Which cards must you flip to test the theory?

Answer: Later.

## CS70: Lecture 1. Outline.

Today: Note 1. Note 0 is background. Do read it.

The language of proofs!

1. Propositions.
2. Propositional Forms.
3. Implication.
4. Truth Tables
5. Quantifiers
6. More De Morgan's Laws

## Propositions: Statements that are true or false.

$\sqrt{2}$ is irrational	<b>Proposition</b>	True
$2+2 = 4$	<b>Proposition</b>	True
$2+2 = 3$	<b>Proposition</b>	False
826th digit of pi is 4	<b>Proposition</b>	False
Johnny Depp is a good actor	<b>Not Proposition</b>	
Any even $> 2$ is sum of 2 primes	<b>Proposition</b>	False
$4 + 5$	<b>Not Proposition.</b>	
$x + x$	<b>Not a Proposition.</b>	
Alice travelled to Chicago	<b>Proposition.</b>	False
I love you.	<b>Hmmm.</b>	Its complicated.

Again: "value" of a proposition is ... True or False

## Propositional Forms.

Put propositions together to make another...

Conjunction ("and"):  $P \wedge Q$

" $P \wedge Q$ " is True when both  $P$  and  $Q$  are True . Else False .

Disjunction ("or"):  $P \vee Q$

" $P \vee Q$ " is True when at least one  $P$  or  $Q$  is True . Else False .

Negation ("not"):  $\neg P$

" $\neg P$ " is True when  $P$  is False . Else False .

Examples:

$\neg "(2+2 = 4)"$  – a proposition that is ... False

" $2+2 = 3$ "  $\wedge$  " $2+2 = 4$ " – a proposition that is ... False

" $2+2 = 3$ "  $\vee$  " $2+2 = 4$ " – a proposition that is ... True

## Propositional Forms: quick check!

$P = "\sqrt{2}$  is rational"

$Q = "826$ th digit of pi is 2"

$P$  is ...False .

$Q$  is ...True .

$P \wedge Q$  ... False  $\wedge$  True  $\rightarrow$  False

$P \vee Q$  ... False  $\vee$  True  $\rightarrow$  True

$\neg P$  ...  $\neg$ False  $\rightarrow$  True

## Put them together..

Propositions:

$P_1$  - Person 1 rides the bus.

$P_2$  - Person 2 rides the bus.

....

But we can't have either of the following happen; That either person 1 or person 2 ride the bus and person 3 or 4 ride the bus. Or that person 2 or person 3 ride the bus and that either person 4 rides the bus or person 5 doesn't.

Propositional Form:

$\neg(((P_1 \vee P_2) \wedge (P_3 \vee P_4)) \vee ((P_2 \vee P_3) \wedge (P_4 \vee \neg P_5)))$

Can person 3 ride the bus?

Can person 3 and person 4 ride the bus together?

This seems ...complicated.

We can program!!!!

We need a way to keep track!

## Truth Tables for Propositional Forms.

" $P \wedge Q$ " is True when both  $P$  and  $Q$  are True .

" $P \vee Q$ " is True when  $\geq$  one of  $P$  or  $Q$  is True .

$P$	$Q$	$P \wedge Q$
T	T	T
T	F	F
F	T	F
F	F	F

$P$	$Q$	$P \vee Q$
T	T	T
T	F	T
F	T	T
F	F	F

Check:  $\wedge$  and  $\vee$  are commutative.

One use for truth tables: Logical Equivalence of propositional forms!

Example:  $\neg(P \wedge Q)$  logically equivalent to  $\neg P \vee \neg Q$ . Same Truth Table!

$P$	$Q$	$\neg(P \vee Q)$	$\neg P \wedge \neg Q$
T	T	F	F
T	F	F	F
F	T	F	F
F	F	T	T

DeMorgan's Law's for Negation: distribute and flip!

$\neg(P \wedge Q) \equiv \neg P \vee \neg Q$        $\neg(P \vee Q) \equiv \neg P \wedge \neg Q$

## Quick Questions

P	Q	$P \wedge Q$
T	T	T
T	F	F
F	T	F
F	F	F

P	Q	$P \vee Q$
T	T	T
T	F	T
F	T	T
F	F	F

Is  $(T \wedge Q) \equiv Q$ ? Yes? No?

Yes! Look at rows in truth table for  $P = T$ .

What is  $(F \wedge Q)$ ? F or False.

What is  $(T \vee Q)$ ? T

What is  $(F \vee Q)$ ? Q

## Non-Consequences/consequences of Implication

The statement " $P \implies Q$ "

only is **False** if  $P$  is **True** and  $Q$  is **False**.

False implies nothing

$P$  **False** means  $Q$  can be **True** or **False**

Anything implies true.

$P$  can be **True** or **False** when  $Q$  is **True**

If chemical plant pollutes river, fish die.

If fish die, did chemical plant pollute river?

Not necessarily.

$P \implies Q$  and  $Q$  are **True** does not mean  $P$  is **True**

Be careful!

Instead we have:

$P \implies Q$  and  $P$  are **True** does mean  $Q$  is **True**.

The chemical plant pollutes river. Can we conclude fish die?

Some Fun: use propositional formulas to describe implication?

$((P \implies Q) \wedge P) \implies Q$ .

## Distributive?

$P \wedge (Q \vee R) \equiv (P \wedge Q) \vee (P \wedge R)$ ?

Simplify:  $(T \wedge Q) \equiv Q, (F \wedge Q) \equiv F$ .

Cases:

$P$  is **True**.

LHS:  $T \wedge (Q \vee R) \equiv (Q \vee R)$ .

RHS:  $(T \wedge Q) \vee (T \wedge R) \equiv (Q \vee R)$ .

$P$  is **False**.

LHS:  $F \wedge (Q \vee R) \equiv F$ .

RHS:  $(F \wedge Q) \vee (F \wedge R) \equiv (F \vee F) \equiv F$ .

$P \vee (Q \wedge R) \equiv (P \vee Q) \wedge (P \vee R)$ ?

Simplify:  $T \vee Q \equiv T, F \vee Q \equiv Q$ . ...

Foil 1:

$(A \vee B) \wedge (C \vee D) \equiv (A \wedge C) \vee (A \wedge D) \vee (B \wedge C) \vee (B \wedge D)$ ?

Foil 2:

$(A \wedge B) \vee (C \wedge D) \equiv (A \vee C) \wedge (A \vee D) \wedge (B \vee C) \wedge (B \vee D)$ ?

## Implication.

$P \implies Q$  interpreted as

If  $P$ , then  $Q$ .

True Statements:  $P, P \implies Q$ .

Conclude:  $Q$  is true.

Examples:

Statement: If you stand in the rain, then you'll get wet.

$P$  = "you stand in the rain"

$Q$  = "you will get wet"

Statement: "Stand in the rain"

Can conclude: "you'll get wet."

Statement:

If a right triangle has sidelengths  $a \leq b \leq c$ , then  $a^2 + b^2 = c^2$ .

$P$  = "a right triangle has sidelengths  $a \leq b \leq c$ ".

$Q$  = " $a^2 + b^2 = c^2$ ".

## Implication and English.

$P \implies Q$

▶ If  $P$ , then  $Q$ .

▶  $Q$  if  $P$ .

Just reversing the order.

▶  $P$  only if  $Q$ .

Remember if  $P$  is true then  $Q$  must be true.

this suggests that  $P$  can only be true if  $Q$  is true.

since if  $Q$  is false  $P$  must have been false.

▶  $P$  is sufficient for  $Q$ .

This means that proving  $P$  allows you

to conclude that  $Q$  is true.

Example: Showing  $n > 4$  is sufficient for showing  $n > 3$ .

▶  $Q$  is necessary for  $P$ .

For  $P$  to be true it is necessary that  $Q$  is true.

Or if  $Q$  is false then we know that  $P$  is false.

Example: It is necessary that  $n > 3$  for  $n > 4$ .

## Truth Table: implication.

P	Q	$P \implies Q$
T	T	T
T	F	F
F	T	T
F	F	T

P	Q	$\neg P \vee Q$
T	T	T
T	F	F
F	T	T
F	F	T

$\neg P \vee Q \equiv P \implies Q$ .

These two propositional forms are logically equivalent!

## Contrapositive, Converse

▶ **Contrapositive** of  $P \implies Q$  is  $\neg Q \implies \neg P$ .

- ▶ If the plant pollutes, fish die.
- ▶ If the fish don't die, the plant does not pollute.  
(contrapositive)
- ▶ If you stand in the rain, you get wet.
- ▶ If you did not stand in the rain, you did not get wet.  
(not contrapositive!) converse!
- ▶ If you did not get wet, you did not stand in the rain.  
(contrapositive.)

Logically equivalent! Notation:  $\equiv$ .

$$P \implies Q \equiv \neg P \vee Q \equiv \neg(\neg Q) \vee \neg P \equiv \neg Q \implies \neg P.$$

▶ **Converse** of  $P \implies Q$  is  $Q \implies P$ .

If fish die the plant pollutes.

Not logically equivalent!

▶ **Definition:** If  $P \implies Q$  and  $Q \implies P$  is  $P$  if and only if  $Q$  or  $P \iff Q$ .

(Logically Equivalent:  $\iff$  .)

## Quantifiers: universes.

**Proposition:** "For all natural numbers  $n$ ,  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$ ."

Proposition has **universe:** "the natural numbers".

Universe examples include..

- ▶  $\mathbb{N} = \{0, 1, \dots\}$  (natural numbers).
- ▶  $\mathbb{Z} = \{\dots, -1, 0, \dots\}$  (integers)
- ▶  $\mathbb{Z}^+$  (positive integers)
- ▶  $\mathbb{R}$  (real numbers)
- ▶ Any set:  $S = \{Alice, Bob, Charlie, Donna\}$ .
- ▶ See note 0 for more!

## Variables.

Propositions?

- ▶  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$ .
- ▶  $x > 2$
- ▶  $n$  is even and the sum of two primes

No. They have a free variable.

We call them **predicates**, e.g.,  $Q(x) = "x \text{ is even}"$   
Same as boolean valued functions from 61A!

- ▶  $P(n) = "\sum_{i=1}^n i = \frac{n(n+1)}{2}"$ .
- ▶  $R(x) = "x > 2"$
- ▶  $G(n) = "n \text{ is even and the sum of two primes}"$
- ▶ Remember Wason's experiment!  
 $F(x) = "Person x \text{ flew}"$   
 $C(x) = "Person x \text{ went to Chicago}"$
- ▶  $C(x) \implies F(x)$ . Theory from Wason's.  
If person  $x$  goes to Chicago then person  $x$  flew.

Next: Statements about boolean valued functions!!

## Back to: Wason's experiment:1

Theory: "If a person travels to Chicago, he/she flies."

Alice to Baltimore, Bob drove, Charlie to Chicago, and Donna flew.

Which cards do you need to flip to test the theory?

$Chicago(x) = "x \text{ went to Chicago}"$     $Flew(x) = "x \text{ flew}"$

Statement/theory:  $\forall x \in \{A, B, C, D\}, Chicago(x) \implies Flew(x)$

$Chicago(A) = \text{False}$ . Do we care about  $Flew(A)$ ?

No.  $Chicago(A) \implies Flew(A)$ , when  $Chicago(A)$  is **False**,  $Flew(A)$  can be anything.

$Flew(B) = \text{False}$ . Do we care about  $Chicago(B)$ ?

Yes.  $Chicago(B) \implies Flew(B) \equiv \neg Flew(B) \implies \neg Chicago(B)$ .  
So  $Chicago(Bob)$  must be **False**.

$Chicago(C) = \text{True}$ . Do we care about  $Flew(C)$ ?

Yes.  $Chicago(C) \implies Flew(C)$  means  $Flew(C)$  must be true.

$Flew(D) = \text{True}$ . Do we care about  $Chicago(D)$ ?

No.  $Chicago(D) \implies Flew(D)$  holds whatever  $Chicago(D)$  is when  $Flew(D)$  is true.

Only have to turn over cards for Bob and Charlie.

## Quantifiers..

**There exists quantifier:**

$(\exists x \in S)(P(x))$  means "There exists an  $x$  in  $S$  where  $P(x)$  is true."

For example:

$$(\exists x \in \mathbb{N})(x = x^2)$$

Equivalent to " $(0 = 0) \vee (1 = 1) \vee (2 = 4) \vee \dots$ "

Much shorter to use a quantifier!

**For all quantifier;**

$(\forall x \in S)(P(x))$ . means "For all  $x$  in  $S$ ,  $P(x)$  is **True**."

Examples:

"Adding 1 makes a bigger number."

$$(\forall x \in \mathbb{N})(x + 1 > x)$$

"the square of a number is always non-negative"

$$(\forall x \in \mathbb{N})(x^2 \geq 0)$$

Wait! What is  $\mathbb{N}$ ?

## More for all quantifiers examples.

- ▶ "doubling a number always makes it larger"

$$(\forall x \in \mathbb{N})(2x > x) \quad \text{False} \quad \text{Consider } x = 0$$

Can fix statement...

$$(\forall x \in \mathbb{N})(2x \geq x) \quad \text{True}$$

- ▶ "Square of any natural number greater than 5 is greater than 25."

$$(\forall x \in \mathbb{N})(x > 5 \implies x^2 > 25).$$

Idea alert: Restrict domain using implication.

Later we may omit universe if clear from context.

## Quantifiers..not commutative.

- ▶ In English: "there is a natural number that is the square of every natural number".

$$(\exists y \in \mathbb{N}) (\forall x \in \mathbb{N}) (y = x^2) \quad \text{False}$$

- ▶ In English: "the square of every natural number is a natural number."

$$(\forall x \in \mathbb{N}) (\exists y \in \mathbb{N}) (y = x^2) \quad \text{True}$$

## Which Theorem?

Theorem:  $(\forall n \in \mathbb{N}) \neg(\exists a, b, c \in \mathbb{N}) (n \geq 3 \implies a^n + b^n = c^n)$

Which Theorem?

Fermat's Last Theorem!

Remember Special Triangles: for  $n = 2$ , we have 3,4,5 and 5,7, 12 and ...

1637: Proof doesn't fit in the margins.

1993: Wiles ...(based in part on Ribet's Theorem)

DeMorgan Restatement:

Theorem:  $\neg(\exists n \in \mathbb{N}) (\exists a, b, c \in \mathbb{N}) (n \geq 3 \implies a^n + b^n = c^n)$

## Quantifiers....negation...DeMorgan again.

Consider

$$\neg(\forall x \in S)(P(x)),$$

English: there is an  $x$  in  $S$  where  $P(x)$  does not hold.

That is,

$$\neg(\forall x \in S)(P(x)) \iff \exists(x \in S)(\neg P(x)).$$

What we do in this course! We consider claims.

**Claim:**  $(\forall x) P(x)$  "For all inputs  $x$  the program works."  
For **False**, find  $x$ , where  $\neg P(x)$ .

Counterexample.

Bad input.

Case that illustrates bug.

For **True**: prove claim. Next lectures...

## Negation of exists.

Consider

$$\neg(\exists x \in S)(P(x))$$

English: means that there is no  $x \in S$  where  $P(x)$  is true. English: means that for all  $x \in S$ ,  $P(x)$  does not hold.

That is,

$$\neg(\exists x \in S)(P(x)) \iff \forall(x \in S)\neg P(x).$$

## Summary.

Propositions are statements that are true or false.

Propositional forms use  $\wedge, \vee, \neg$ .

Propositional forms correspond to truth tables.

Logical equivalence of forms means same truth tables.

Implication:  $P \implies Q \iff \neg P \vee Q$ .

Contrapositive:  $\neg Q \implies \neg P$

Converse:  $Q \implies P$

Predicates: Statements with "free" variables.

Quantifiers:  $\forall x P(x), \exists y Q(y)$

Now can state theorems! And disprove false ones!

DeMorgans Laws: "Flip and Distribute negation"

$$\neg(P \vee Q) \iff (\neg P \wedge \neg Q)$$

$$\neg \forall x P(x) \iff \exists x \neg P(x).$$

Next Time: proofs!