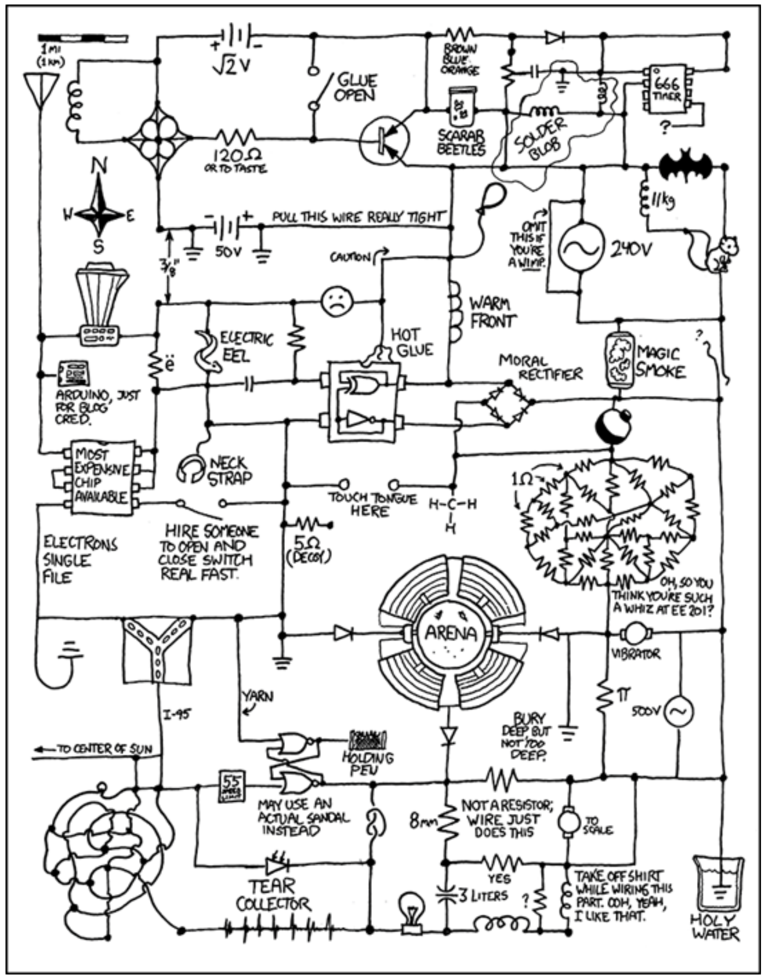
CSE 311: Foundations of Computing

Lecture 5: DNF, CNF and Predicate Logic



Administrivia

HW1 due tonight

HW2 posted tomorrow

- some tools available for testing equivalence chains
  - http://homes.cs.washington.edu/~kevinz/equiv-test/
  - another mentioned in the HW, preloaded with HW1 problems
- both are optional
  - also “beta” software

Last Time: Building Circuits

Turn-the-Crank Process:

1. write down a table showing desired 0/1 outputs
2. construct a Boolean algebra expression
   – term for each 1 in the column
   – sum (or) them to get all 1s
3. simplify the expression using equivalences
4. translate Boolean algebra to a circuit

(Since it's turn-the-crank, software can do this for you.)

1-bit Binary Adder

A	$0 + 0 = 0$ (with $C_{OUT} = 0$)
$\underline{+ \ B}$	$0 + 1 = 1$ (with $C_{OUT} = 0$)
S	$1 + 0 = 1$ (with $C_{OUT} = 0$)
(C_{OUT})	$1 + 1 = 0$ (with $C_{OUT} = 1$)

1-bit Binary Adder

A	$0 + 0 = 0$ (with $C_{OUT} = 0$)
+ B	$0 + 1 = 1$ (with $C_{OUT} = 0$)
S	$1 + 0 = 1$ (with $C_{OUT} = 0$)
(C_{OUT})	$1 + 1 = 0$ (with $C_{OUT} = 1$)

Idea: To chain these together, let's add a carry-in

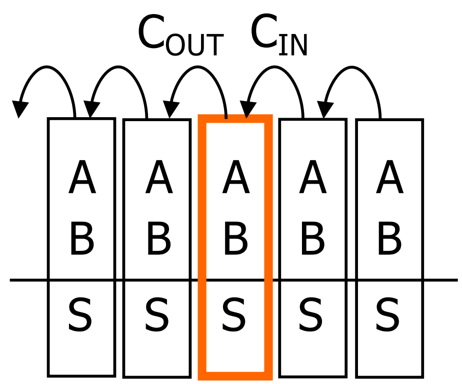
1-bit Binary Adder

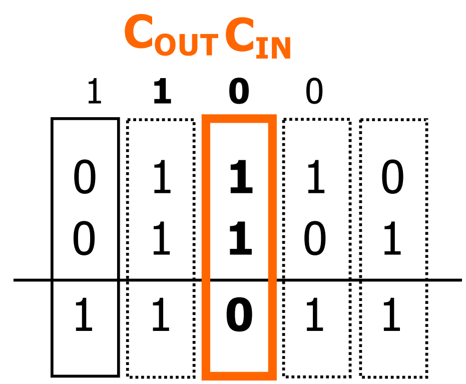
A
+ B
S
(C_{OUT})

$0 + 0 = 0$ (with $C_{OUT} = 0$)
$0 + 1 = 1$ (with $C_{OUT} = 0$)
$1 + 0 = 1$ (with $C_{OUT} = 0$)
$1 + 1 = 0$ (with $C_{OUT} = 1$)

Idea: These are chained together, with a carry-in

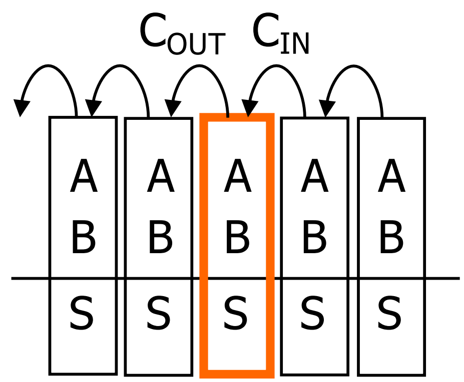
(C_{IN})
A
+ B
S
(C_{OUT})





1-bit Binary Adder

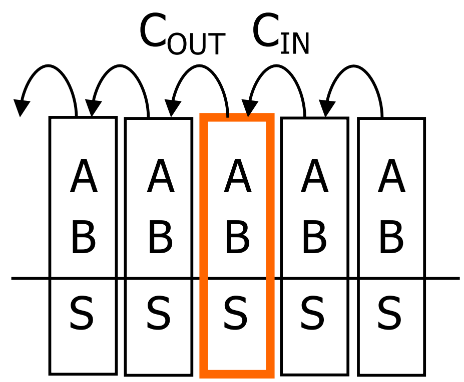
- **Inputs:** A, B, Carry-in
- **Outputs:** Sum, Carry-out



A	B	C_{IN}	C_{OUT}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

1-bit Binary Adder

- **Inputs:** A, B, Carry-in
- **Outputs:** Sum, Carry-out



A	B	C_{IN}	C_{OUT}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Derive an expression for S

$A' \cdot B' \cdot C_{IN}$

$A' \cdot B \cdot C_{IN}'$

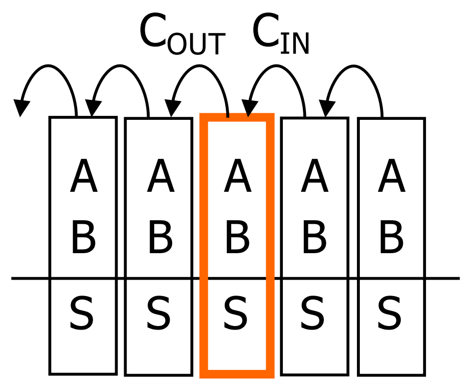
$A \cdot B' \cdot C_{IN}'$

$A \cdot B \cdot C_{IN}$

$$S = A' \cdot B' \cdot C_{IN} + A' \cdot B \cdot C_{IN}' + A \cdot B' \cdot C_{IN}' + A \cdot B \cdot C_{IN}$$

1-bit Binary Adder

- **Inputs:** A, B, Carry-in
- **Outputs:** Sum, Carry-out



A	B	C_{IN}	C_{OUT}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Derive an expression for C_{OUT}

$A' \cdot B \cdot C_{IN}$

$A \cdot B' \cdot C_{IN}$

$A \cdot B \cdot C_{IN}'$

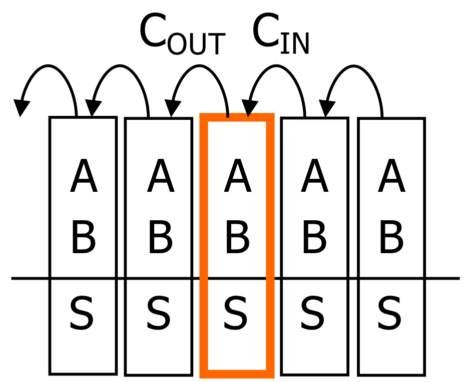
$A \cdot B \cdot C_{IN}$

$$C_{OUT} = A' \cdot B \cdot C_{IN} + A \cdot B' \cdot C_{IN} + A \cdot B \cdot C_{IN}' + A \cdot B \cdot C_{IN}$$

$$S = A' \cdot B' \cdot C_{IN} + A' \cdot B \cdot C_{IN}' + A \cdot B' \cdot C_{IN}' + A \cdot B \cdot C_{IN}$$

1-bit Binary Adder

- **Inputs:** A, B, Carry-in
- **Outputs:** Sum, Carry-out



A	B	C_{IN}	C_{OUT}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

$$S = A' \cdot B' \cdot C_{IN} + A' \cdot B \cdot C_{IN}' + A \cdot B' \cdot C_{IN}' + A \cdot B \cdot C_{IN}$$

$$C_{OUT} = A' \cdot B \cdot C_{IN} + A \cdot B' \cdot C_{IN} + A \cdot B \cdot C_{IN}' + A \cdot B \cdot C_{IN}$$

Apply Theorems to Simplify Expressions

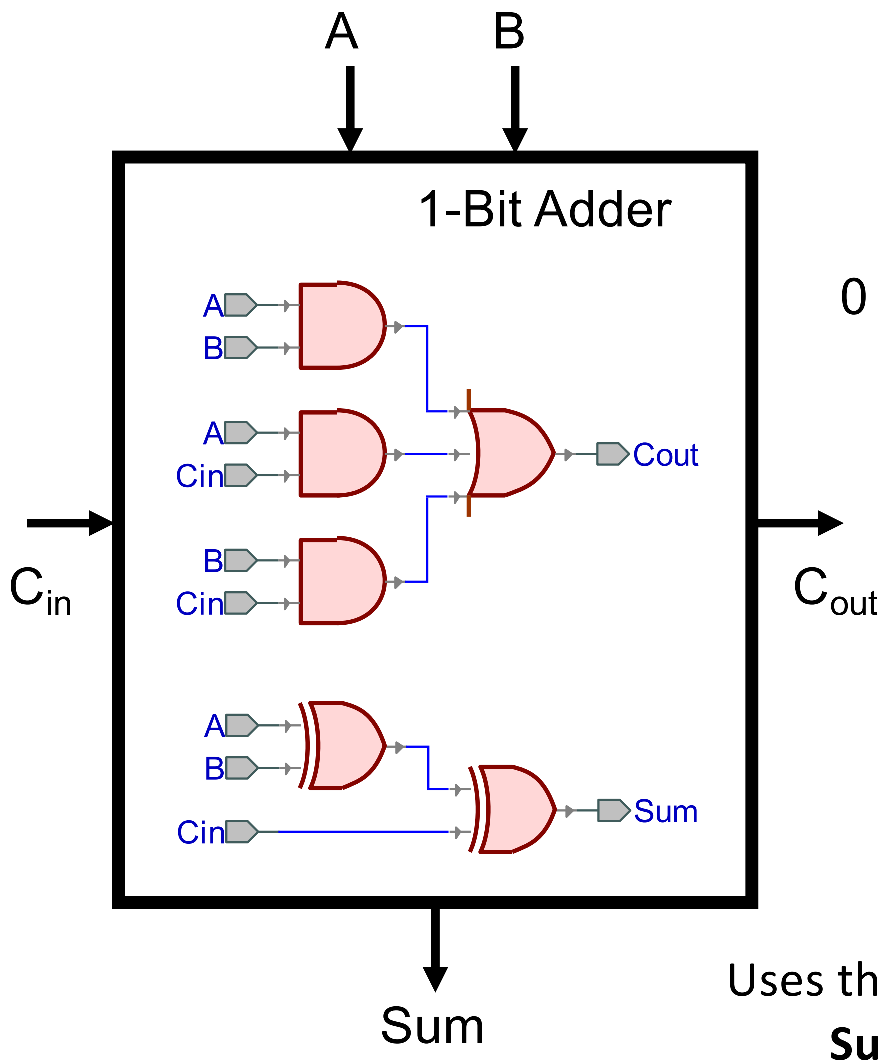
The theorems of Boolean algebra can simplify expressions

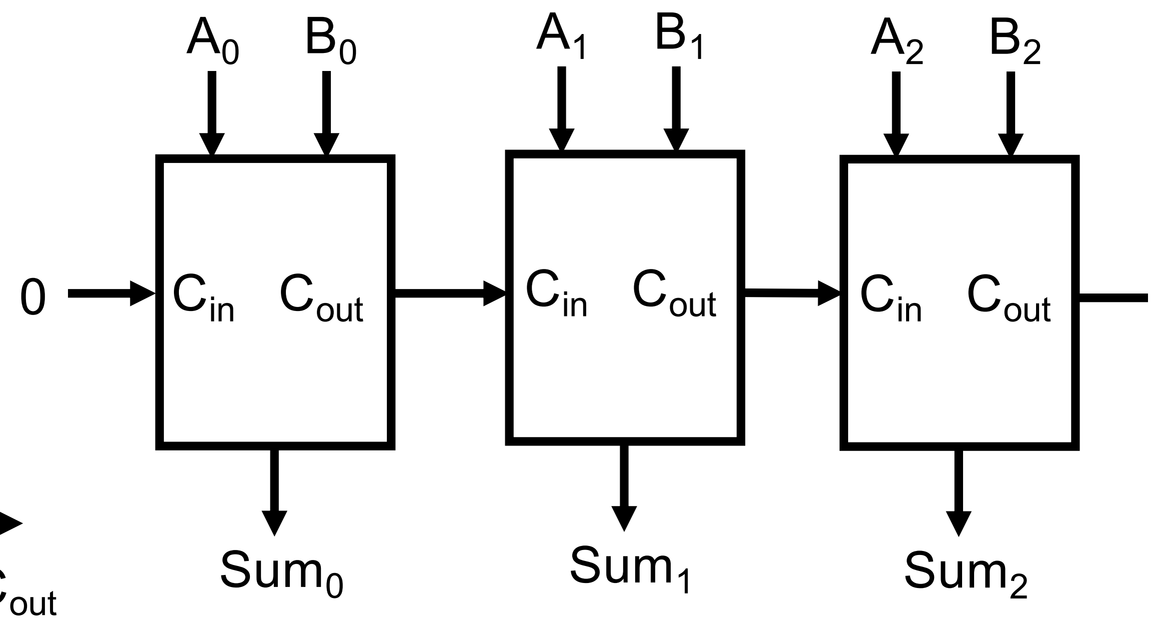
– **e.g., full adder's carry-out function**

$$
\begin{aligned}
\text{Cout} &= A'\,B\,Cin + A\,B'\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= A'\,B\,Cin + A\,B'\,Cin + A\,B\,Cin' + \boxed{A\,B\,Cin + A\,B\,Cin} \\
&= A'\,B\,Cin + A\,B\,Cin + A\,B'\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= (A' + A)\,B\,Cin + A\,B'\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= (1)\,B\,Cin + A\,B'\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= B\,Cin + A\,B'\,Cin + A\,B\,Cin' + \boxed{A\,B\,Cin + A\,B\,Cin} \\
&= B\,Cin + A\,B'\,Cin + A\,B\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= B\,Cin + A\,(B' + B)\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= B\,Cin + A\,(1)\,Cin + A\,B\,Cin' + A\,B\,Cin \\
&= B\,Cin + A\,Cin + A\,B\,(Cin' + Cin) \\
&= B\,Cin + A\,Cin + A\,B\,(1) \\
&= B\,Cin + A\,Cin + A\,B
\end{aligned}
$$

adding extra terms creates new factoring opportunities

A 2-bit Ripple-Carry Adder





Uses the fact that

Sum = $A' \bullet B' \bullet C_{IN} + A' \bullet B \bullet C_{IN}' + A \bullet B' \bullet C_{IN}' + A \bullet B \bullet C_{IN}$

is equivalent to **Sum = $(A \oplus B) \oplus C_{IN}$**

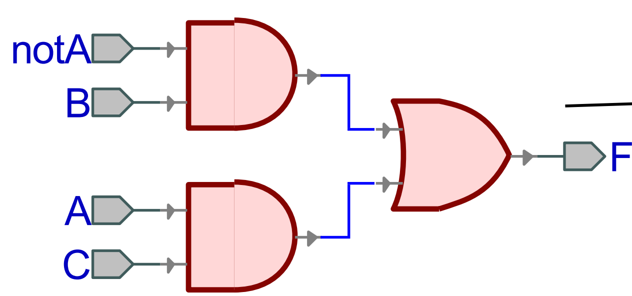
Mapping Truth Tables to Logic Gates

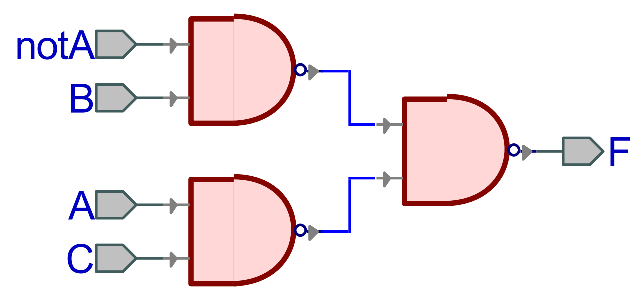
Given a truth table:

1. Write the output in a table
2. Write the Boolean expression
3. Minimize the Boolean expression
4. Draw as gates
5. Map to available gates

A	B	C	F
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

$$\begin{aligned} F &= A'BC' + A'BC + AB'C + ABC \\ &= A'B(C' + C) + AC(B' + B) \\ &= A'B + AC \end{aligned}$$





Canonical Forms

- Truth table is the **unique signature** of a 0/1 function

- The same truth table can have many gate realizations
  - We've seen this already
  - Depends on how good we are at Boolean simplification

- Canonical forms
  - Standard forms for a Boolean expression
  - We all come up with the same expression

Sum-of-Products Canonical Form

- AKA **Disjunctive Normal Form (DNF)**
- AKA **Minterm Expansion**

A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

1 Read T rows off truth table

2 Convert to Boolean Algebra

001 → A'B'C

011 → A'BC

101 → AB'C

110 → ABC'

111 → ABC

F

3 Add the minterms together

F= A'B'C + A'BC + AB'C + ABC' + ABC'

Sum-of-Products Canonical Form

Product term (or minterm)

- ANDed product of literals – input combination for which output is true
- each variable appears exactly once, true or inverted (but not both)

A	B	C	minterms
0	0	0	A′B′C′
0	0	1	A′B′C
0	1	0	A′BC′
0	1	1	A′BC
1	0	0	AB′C′
1	0	1	AB′C
1	1	0	ABC′
1	1	1	ABC

F in canonical form:

$$F(A, B, C) = A'B'C + A'BC + AB'C + ABC' + ABC$$

canonical form ≠ minimal form

$$\begin{aligned} F(A, B, C) &= A'B'C + A'BC + AB'C + ABC + ABC' \\ &= (A'B' + A'B + AB' + AB)C + ABC' \\ &= ((A' + A)(B' + B))C + ABC' \\ &= C + ABC' \\ &= ABC' + C \\ &= AB + C \end{aligned}$$

Product-of-Sums Canonical Form

- AKA Conjunctive Normal Form (CNF)
- AKA Maxterm Expansion

4 Multiply the maxterms together

F =

A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

1 Read F rows off truth table

2 Negate all bits

3 Convert to Boolean Algebra

F

Product-of-Sums Canonical Form

- AKA **Conjunctive Normal Form (CNF)**
- AKA **Maxterm Expansion**

A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

1 Read F rows off truth table

2 Negate all bits

3 Convert to Boolean Algebra

$000 \rightarrow 111 \rightarrow A + B + C$

$010 \rightarrow 101 \rightarrow A + B' + C$

$100 \rightarrow 011 \rightarrow A' + B + C$

F

4 Multiply the maxterms together

$F = (A + B + C)(A + B' + C)(A' + B + C)$

Product-of-Sums: Why does this procedure work?

Useful Facts:

- We know (F')' = F
- We know how to get a **minterm** expansion for F'

A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

$$F' = A'B'C' + A'BC' + AB'C'$$

Product-of-Sums: Why does this procedure work?

Useful Facts:

- We know (F')' = F
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A	B	C	F
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

$$F' = A'B'C' + A'BC' + AB'C'$$

Taking the complement of both sides…

$$(F')' = (A'B'C' + A'BC' + AB'C')'$$

And using DeMorgan/Comp….

$$F = (A'B'C')' \; (A'BC')' \; (AB'C')'$$

$$F = (A + B + C)(A + B' + C)(A' + B + C)$$

Product-of-Sums Canonical Form

Sum term (or maxterm)

- ORed sum of literals – input combination for which output is false
- each variable appears exactly once, true or inverted (but not both)

A	B	C	maxterms
0	0	0	$A+B+C$
0	0	1	$A+B+C'$
0	1	0	$A+B'+C$
0	1	1	$A+B'+C'$
1	0	0	$A'+B+C$
1	0	1	$A'+B+C'$
1	1	0	$A'+B'+C$
1	1	1	$A'+B'+C'$

F in canonical form:

$$F(A, B, C) = (A + B + C)\,(A + B' + C)\,(A' + B + C)$$

canonical form ≠ minimal form

$$\begin{aligned} F(A, B, C) &= (A + B + C)\,(A + B' + C)\,(A' + B + C) \\ &= (A + B + C)\,(A + B' + C) \\ &\quad\ (A + B + C)\,(A' + B + C) \\ &= (A + C)\,(B + C) \end{aligned}$$

Predicate Logic

Predicate Logic

- **Propositional Logic**

  "If you take the high road and I take the low road then I'll arrive in Scotland before you."

- **Predicate Logic**

  "All positive integers x, y, and z satisfy $x^3 + y^3 \neq z^3$."

Predicate Logic

- Propositional Logic
  – Allows us to analyze complex propositions in terms of their simpler constituent parts (a.k.a. atomic propositions) joined by connectives

- Predicate Logic
  – Lets us analyze them at a deeper level by expressing how those propositions depend on the objects they are talking about

Predicate Logic

Adds two key notions to propositional logic

- Predicates

- Quantifiers

Predicates

Predicate

– **A function that returns a truth value, e.g.,**

Cat(x) ::= "x is a cat"

Prime(x) ::= "x is prime"

HasTaken(x, y) ::= "student x has taken course y"

LessThan(x, y) ::= "$x < y$"

Sum(x, y, z) ::= "$x + y = z$"

GreaterThan5(x) ::= "$x > 5$"

HasNChars(s, n) ::= "string s has length n"

Predicates can have varying numbers of arguments and input types.

Domain of Discourse

For ease of use, we define one “type”/“domain” that we work over. This non-empty set of objects is called the “**domain of discourse**”.

For each of the following, what might the domain be?

(1) “x is a cat”, “x barks”, “x ruined my couch”

“mammals” or “sentient beings” or “cats and dogs” or …

(2) “x is prime”, “$x = 0$”, “$x < 0$”, “x is a power of two”

“numbers” or “integers” or “integers greater than 5” or …

(3) “student x has taken course y” “x is a pre-req for z”

“students and courses” or “university entities” or …

Quantifiers

We use *quantifiers* to talk about collections of objects.

$\forall x\ P(x)$

$P(x)$ **is true for every** x **in the domain**

read as "for all x, P of x"

$\exists x\ P(x)$

There is an x **in the domain for which** $P(x)$ **is true**

read as "there exists x, P of x"

Quantifiers

We use ***quantifiers*** to talk about collections of objects.

Universal Quantifier ("for all"): $\forall x\ P(x)$

$P(x)$ **is true for every** x **in the domain**

read as "for all x, P of x"

Examples: Are these true?

- $\forall$x **Odd(x)**
- $\forall$x **LessThan4(x)**

Quantifiers

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Universal Quantifier ("for all"): $\forall x\ P(x)$

$P(x)$ **is true for every** x **in the domain**

read as "for all x, P of x"

Examples: **Are these true? It depends on the domain. For example:**

	{1, 3, -1, -27}	Integers	Odd Integers
• $\forall$x Odd(x)	True	False	True
• $\forall$x LessThan4(x)	True	False	False

Quantifiers

We use ***quantifiers*** to talk about collections of objects.

Existential Quantifier ("exists"): $\exists x\, P(x)$

There is an x in the domain for which P(x) is true

read as "there exists x, P of x"

Examples: Are these true?

- $\exists x$ Odd(x)
- $\exists x$ LessThan4(x)

Quantifiers

We use *quantifiers* to talk about collections of objects.

Existential Quantifier ("exists"): $\exists x\ P(x)$

There is an x in the domain for which $P(x)$ is true

read as "there exists x, P of x"

Examples: **Are these true? It depends on the domain. For example:**

	{1, 3, -1, -27}	Integers	Positive Multiples of 5
• $\exists x$ Odd(x)	True	True	True
• $\exists x$ LessThan4(x)	True	True	False