Intro to Digital Design
Combinational Logic

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Teaching Assistants:

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Introducing Your Course Staff

- Your Instructor: just call me Justin
  - CSE Associate Teaching Professor
  - From California (UC Berkeley and the Bay Area)
  - Raising a toddler takes up energy and dictates my schedule

- TAs:

  - Available in labs, support (office) hours, and on Ed
  - An invaluable source of information and help

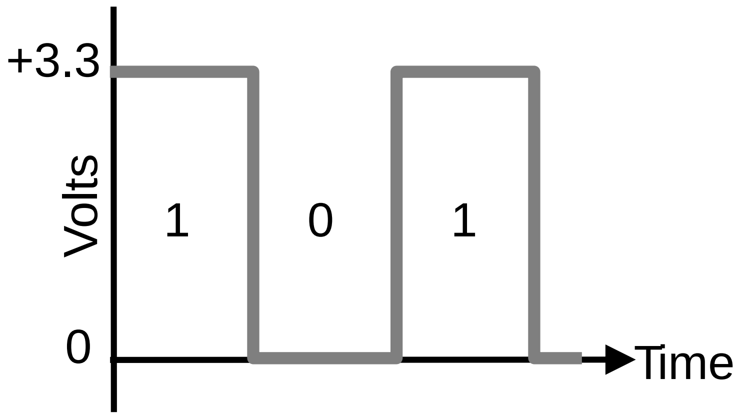
- Get to know us – we are here to help you succeed!

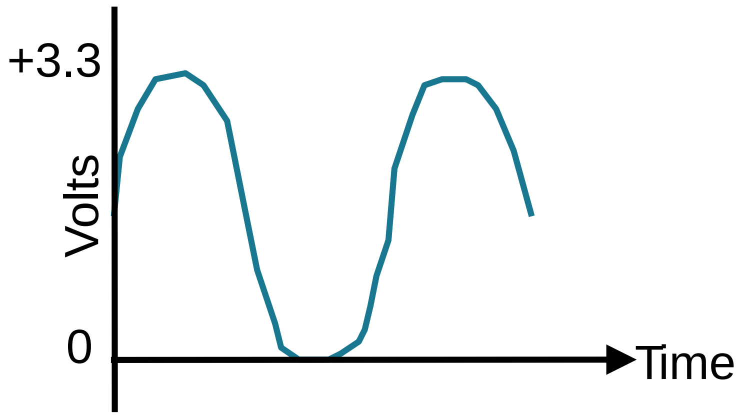
Course Motivation

- Electronics an increasing part of our lives
  - Computers & phones
  - Vehicles (cars, planes)
  - Robots
  - Portable & household electronics

- An *introduction* to digital logic design
  - **Lecture:** How to think about hardware, basic higher-level circuit design techniques – preparation for EE/CSE469
  - **Lab:** Hands-on FPGA programming using Verilog – preparation for EE/CSE371

Digital vs. Analog





Digital:
Discrete set of possible values

Binary (2 values):
On, 3.3 V, high, TRUE, "1"
Off, 0 V, low, FALSE, "0"

Analog:
Values vary over a continuous range

Digital vs. Analog Systems

- Digital systems are more reliable and less error-prone
  - Slight errors can cascade in Analog system
  - Digital systems reject a significant amount of error; easy to cascade
- Computers use digital circuits internally
  - CPU, memory, I/O
- Interface circuits with "real world" often analog
  - Sensors & actuators

This course is about logic design,
not system design (processor architecture),
and not circuit design (transistor level)

Digital Design: What's It All About?

- Come up with an implementation using a set of primitives given a functional description and constraints
- Digital design is in some ways more art than a science
  - The creative spirit is in combining primitive elements and other components in new ways to achieve a desired function
- However, unlike art, we have objective measures of a design (*i.e.*, constraints):
  - Performance
  - Power
  - Cost

Digital Design: What's It All About?

- How do we learn how to do this?
  - Learn about the primitives and how to use them
  - Learn about design representations
  - Learn formal methods and tools to manipulate representations
  - Look at design examples
  - Use trial and error – CAD tools and prototyping (practice!) Lab

Lecture

apply

Lecture Outline

- **Course Logistics**
- Combinational Logic Review
- Combinational Logic in the Lab

Bookmarks

- Website: https://cs.uw.edu/369/
  - Schedule (lecture slides, lab specs), weekly calendar, other useful documents
- Ed Discussion: https://edstem.org/us/courses/50615/
  - Announcements made here
  - Ask and answer questions – staff will monitor and contribute
- Gradescope: https://www.gradescope.com/courses/680677/
  - Lab submissions, Quiz grades, regrade requests
- Canvas: https://canvas.uw.edu/courses/1695952/
  - Grade book, Zoom links, lecture recordings

Grading

- Labs (66%)
  - 6 regular labs – 1 week each
    - Labs 3-4: 60 points each, Labs 1&2, 5-7: 100 points each
  - 1 "final project" – 2 weeks
    - Lab 8 Check-In: 10 points, Lab 8: 150 points
- 3 Quizzes (no final exam)
  - Quiz 1 (10%): 20 min in class on January 30
  - Quiz 2 (10%): 30 min in class on February 20
  - Quiz 3 (14%): 60 min in class on March 5
- This class uses a straight scale (> 95% → 4.0)
  - Extra credit points count the same as regular points

Labs

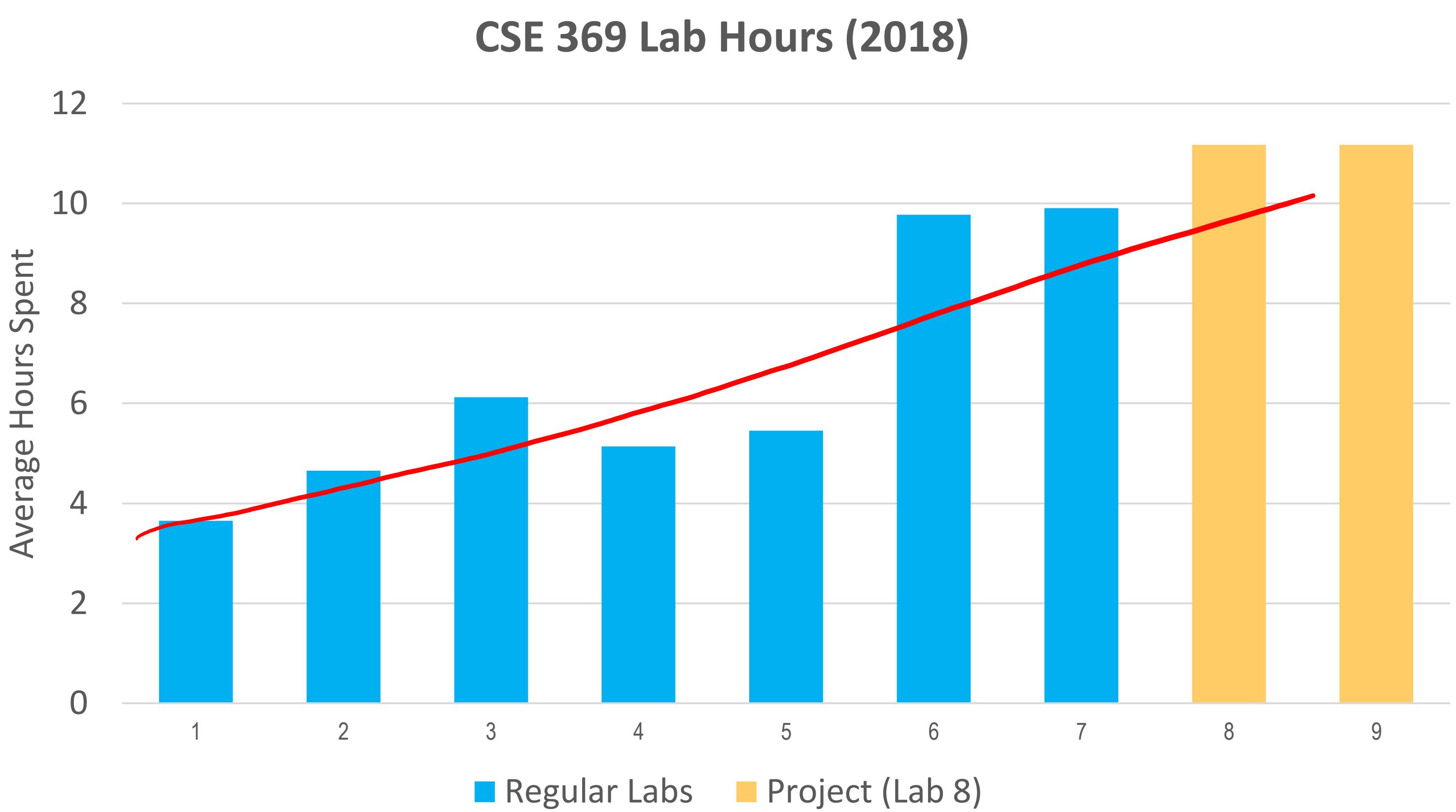
- Lab Hours: Wed & Thu 2:30-5:20 pm (CSE 003)
- Each student will get a lab kit for the quarter
  - Lab kit picked up from CSE 003 during labs/OHs this week
  - Install software on laptop (Windows or VM)
- Labs are combination of report + demo
  - Submit via Gradescope Wednesdays before 2:30 pm
  - 10-minute demos done in lab sections (sign-up process)
- Late penalties:
  - No lab report can be submitted more than two days late
  - 4 late day tokens to prevent penalties, 10%/day after that
  - No penalties on lab demos, but must be done by EOD Friday

Collaboration Policy

- Labs and project are to be completed *individually*
  - Goal is to give every student the hands-on experience
  - Violation of these rules is grounds for failing the class
- **OK:**
  - Discussing lectures and/or readings, studying together
  - *High-level* discussion of general approaches
  - Help with debugging, tools peculiarities, etc.
- **Not OK:**
  - Developing a lab together
  - Giving away solutions or having someone else do your lab for you

Course Workload

- The workload (3 credits) ramps up significantly towards the end of the quarter:

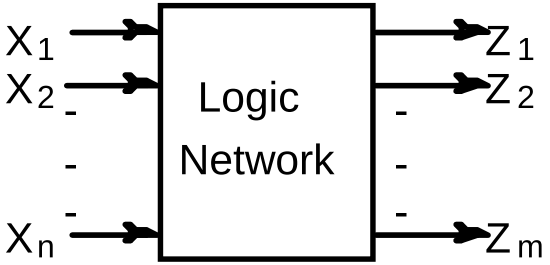


Lecture Outline

- Course Logistics
- **Combinational Logic Review**
- Combinational Logic in the Lab

Combinational vs. Sequential Logic

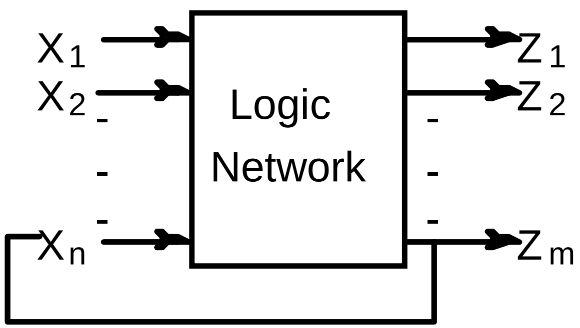
- **Combinational Logic (CL)**



Network of logic gates without feedback.

Outputs are functions only of inputs.

- **Sequential Logic (SL)**



The presence of feedback introduces the notion of "state."

Circuits that can "remember" or store information.

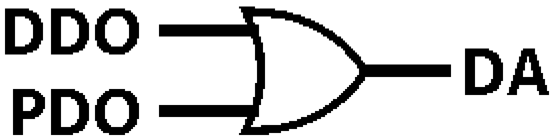
Representations of Combinational Logic

1 - Text Description
2 - Circuit Description
    - ~~Transistors~~ Not covered in 369
    - Logic Gates
3 - Truth Table
4 - Boolean Expression

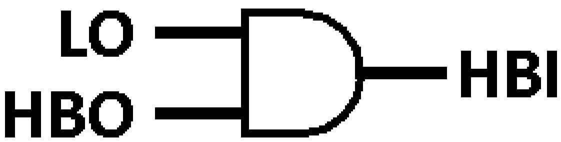
- *All are equivalent!*

Example: Simple Car Electronics

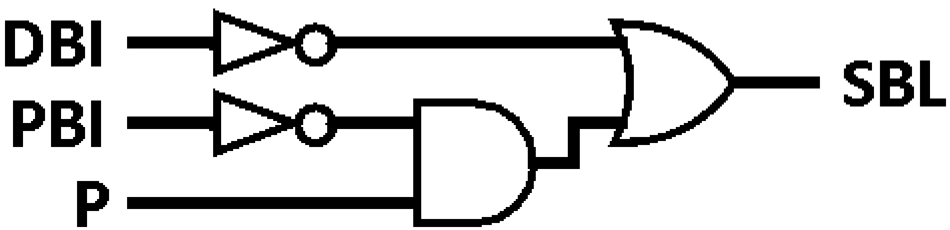
- Door Ajar (DriverDoorOpen, PassengerDoorOpen)
  - $\text{DA} = \text{DDO} + \text{PDO}$



- High Beam Indicator (LightsOn, HighBeamOn)
  - $\text{HBI} = \text{LO} \cdot \text{HBO}$

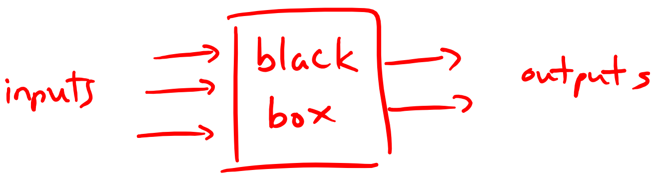


- Seat Belt Light (DriverBeltIn, PassengerBeltIn, Passenger)
  - $\text{SBL} = \overline{\text{DBI}} + (\text{P} \cdot \overline{\text{PBI}})$



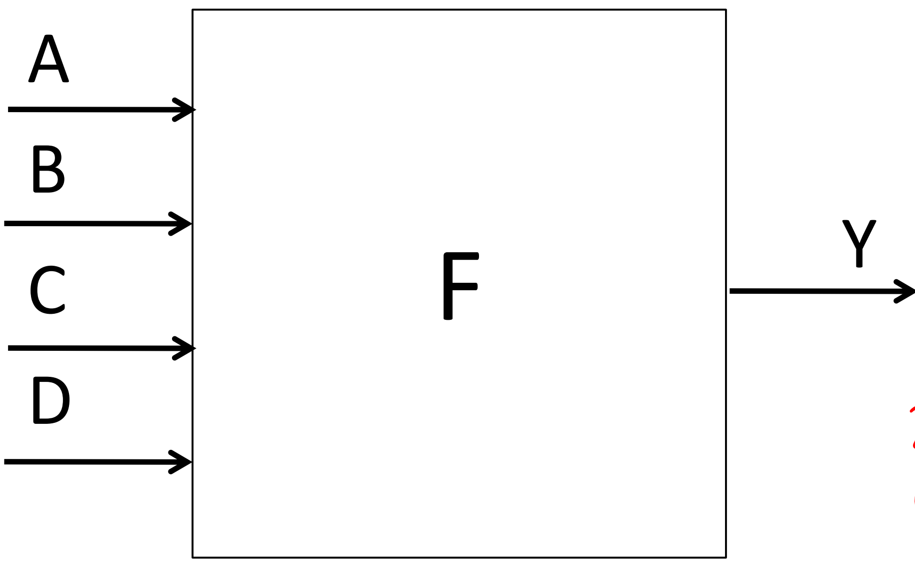
Truth Tables

- Table that relates the inputs to a combinational logic (CL) circuit to its output
  - Output *only* depends on current inputs
  - Use abstraction of 0/1 instead of high/low voltage
  - Shows output for *every* possible combination of inputs ("black box" approach)



- How big is the table?
  - 0 or 1 for each of N inputs, so 2^N rows
  - Each output is a separate function of inputs, so don't need to add rows for additional outputs

CL General Form



If N inputs, how many distinct functions F do we have? 2^N output "positions", each being 0/1

Function maps each row to 0 or 1, so 2^(2^N) possible functions

2^N rows (16)

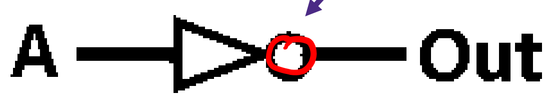
a	b	c	d	y 0/1
0	0	0	0	F(0,0,0,0)
0	0	0	1	F(0,0,0,1)
0	0	1	0	F(0,0,1,0)
0	0	1	1	F(0,0,1,1)
0	1	0	0	F(0,1,0,0)
0	1	0	1	F(0,1,0,1)
0	1	1	0	F(0,1,1,0)
1	1	1	1	F(0,1,1,1)
1	0	0	0	F(1,0,0,0)
1	0	0	1	F(1,0,0,1)
1	0	1	0	F(1,0,1,0)
1	0	1	1	F(1,0,1,1)
1	1	0	0	F(1,1,0,0)
1	1	0	1	F(1,1,0,1)
1	1	1	0	F(1,1,1,0)
1	1	1	1	F(1,1,1,1)

Logic Gates (1/2)

- Special names and symbols:

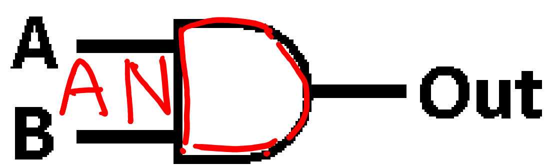
Circle indicates NOT

NOT



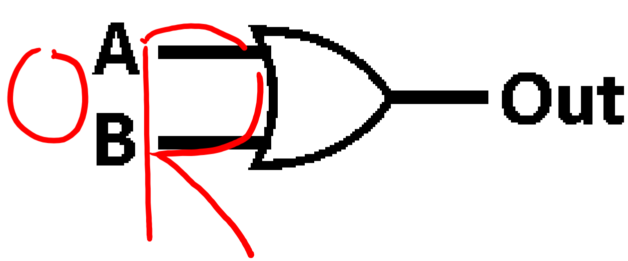
A	Out
0	1
1	0

AND



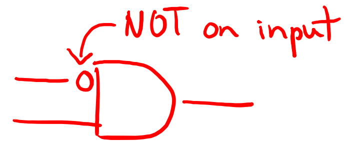
A	B	Out
0	0	0
0	1	0
1	0	0
1	1	1

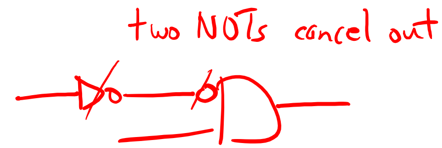
OR



A	B	Out
0	0	0
0	1	1
1	0	1
1	1	1

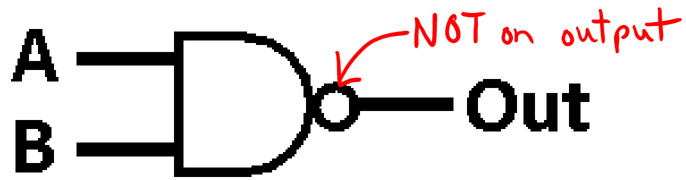
Logic Gates (2/2)





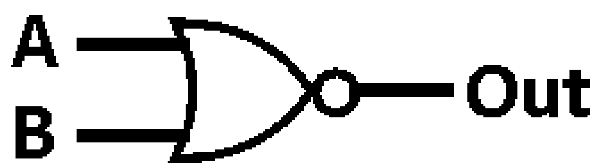
- Special names and symbols:

NAND



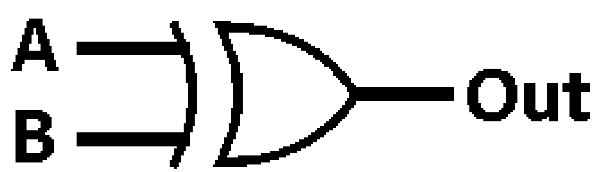
A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

NOR



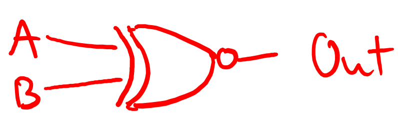
A	B	Out
0	0	1
0	1	0
1	0	0
1	1	0

XOR



A	B	Out
0	0	0
0	1	1
1	0	1
1	1	0

XNOR



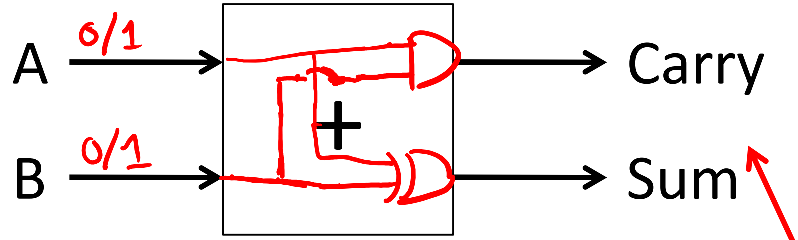
More Complicated Truth Tables

3-Input Majority

How many rows? $2^3 = 8$ rows

A	B	C	Out
0	0	0	0
0	0	1	0
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-bit Adder



2 separate functions (columns)

A	B	Carry	Sum
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

$A \cdot B$ $\quad A \oplus B$

Boolean Algebra

- Represent inputs and outputs as variables
  - Each variable can only take on the value 0 or 1

$\neg$
- Overbar is NOT: "logical complement"
  - If A is 0, then $\overline{\mathrm{A}}$ is 1 and vice-versa

$\vee$
- Plus ($+$) is 2-input OR: "logical sum"

$\wedge$
- Product ($\cdot$) is 2-input AND: "logical product"

- All other gates and logical expressions can be built from combinations of these
  - *e.g.,* $\mathrm{A\ XOR\ B} = \mathrm{A} \oplus \mathrm{B} = \overline{\mathrm{A}}\mathrm{B} + \overline{\mathrm{B}}\mathrm{A}$

Truth Table to Boolean Expression

- Read off of table
  - For 1, write variable name
  - For 0, write complement of variable
- *Sum of Products (SoP)*
  - Take rows with 1's in output column, sum products of inputs
    sets to 1 when input combination matches
  - row 2, row 3
    $C = \overline{A}B + \overline{B}A$
- *Product of Sums (PoS)*
  - Take rows with 0's in output column, product the sum of the *complements of the inputs*
    sets to 0 when input combination matched
  - row 1, row 4
    $C = (A + B) \cdot (\overline{A} + \overline{B})$

We can show that these are equivalent!

a	b	c	row
0	0	0	1
0	1	1	2
1	0	1	3
1	1	0	4

Basic Boolean Identities

- $X + 0 = X$
- $X \cdot 1 = X$
- $X + 1 = 1$
- $X \cdot 0 = 0$
- $X + X = X$
- $X \cdot X = X$
- $X + \overline{X} = 1$
- $X \cdot \overline{X} = 0$
- $\overline{\overline{X}} = X$

Basic Boolean Algebra Laws

- **Commutative Law:**

  $X + Y = Y + X$ $\qquad$ $X \cdot Y = Y \cdot X$

- **Associative Law:**

  $X+(Y+Z) = (X+Y)+Z$ $\qquad$ $X \cdot (Y \cdot Z) = (X \cdot Y) \cdot Z$

- **Distributive Law:**

  $X \cdot (Y+Z) = X \cdot Y + X \cdot Z$ $\qquad$ $X+YZ = (X+Y) \cdot (X+Z)$

Advanced Laws (Absorption)

- $X + XY = X$
- $XY + X\overline{Y} = X$
- $X + \overline{X}Y = X + Y$
- $X(X + Y) = X$
- $(X + Y)(X + \overline{Y}) = X$
- $X(\overline{X} + Y) = XY$

$X + \overline{X}Y = X \cdot 1 + \overline{X}Y = X \cdot (1 + Y) + \overline{X}Y$
$= X + XY + \overline{X}Y$
$= X + Y$ ☑

$Y = \overline{X}Y + XY = Y(\overline{X} + X)$

Practice Problem

- Boolean Function: $F = \overline{X}YZ + XZ$

Truth Table:

X	Y	Z	F
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

Simplification:

$= \overline{X}YZ + X\overline{Y}Z + XYZ$

$= \overline{X}YZ + XZ$

distribution

$= (\overline{X}Y + X)Z$

absorption

$= (X + Y)Z$

distribute

$= XZ + YZ$

2 gates (1 OR, 1 AND)

3 gates (2 AND, 1 OR)

Which of these is "simpler"?

Technology Break

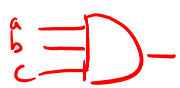
Lecture Outline

- Course Logistics
- Combinational Logic Review
- **Combinational Logic in the Lab**

Why Is This Useful?

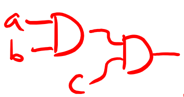
- Logic minimization: reduce complexity at gate level
  - Allows us to build smaller and faster hardware
  - Care about both # of gates, # of literals (gate inputs), # of gate levels, and types of logic gates

literals:



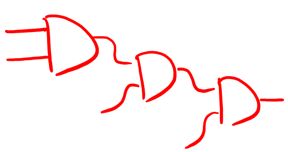
1, 3-input gate

⟺



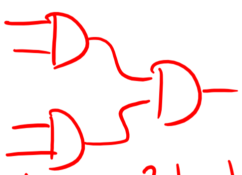
2, 2-input gates

levels:



3 gates in 3 levels

vs.



3 gates in 2 levels (faster)

types: speed of NOT gate vs. AND gate?

Why Is This Useful?

- Logic minimization: reduce complexity at gate level
  - Allows us to build smaller and faster hardware
  - Care about both # of gates, # of literals (gate inputs), # of gate levels, and types of logic gates
- Faster hardware?
  - Fewer inputs implies faster gates in some technologies
  - Fan-ins (# of gate inputs) are limited in some technologies
  - Fewer levels of gates implies reduced signal propagation delays
  - # of gates (or gate packages) influences manufacturing costs
  - Simpler Boolean expressions → smaller transistor networks → smaller circuit delays → faster hardware

Are Logic Gates Created Equal?

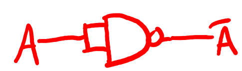
- No!

2-Input Gate Type	# of CMOS transistors
NOT	2
AND	6
OR	6
NAND	4
NOR	4
XOR	8
XNOR	8

← simplest, but not too useful

useful, and simpler than alternatives

- Can recreate all other gates using only NAND or only NOR gates
  - Called "universal" gates
  - *e.g.*, A NAND A = $\overline{\text{A}}$, B NOR B = $\overline{\text{B}}$
  - DeMorgan's Law helps us here!

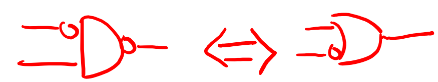


X	Y	NAND	
0	0	1	0→1
0	1	1	
1	0	1	
1	1	0	1→0

DeMorgan's Law

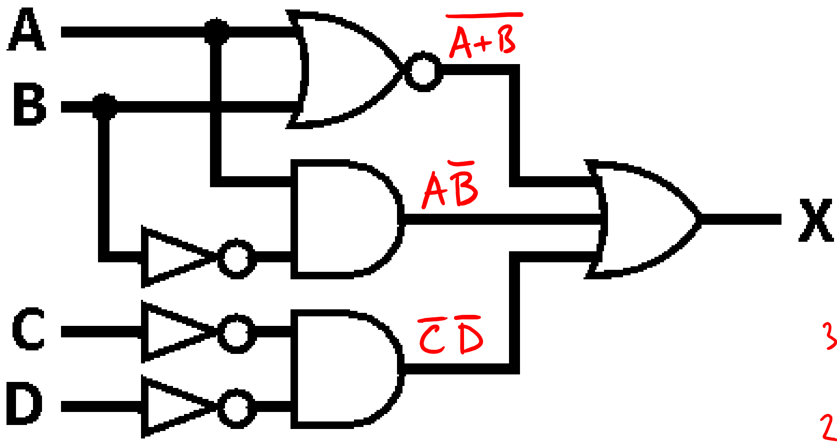
- $\overline{X+Y} = \overline{X} \cdot \overline{Y}$
- $\overline{X \cdot Y} = \overline{X} + \overline{Y}$

				NOR		NAND	
X	Y	$\overline{X}$	$\overline{Y}$	$\overline{X+Y}$	$\overline{X} \cdot \overline{Y}$	$\overline{X \cdot Y}$	$\overline{X} + \overline{Y}$
0	0	1	1	1	1	1	1
0	1	1	0	0	0	1	1
1	0	0	1	0	0	1	1
1	1	0	0	0	0	0	0

- In Boolean Algebra, converts between AND-OR and OR-AND expressions
  - $Z = \overline{A}\overline{B}C + \overline{A}BC + A\overline{B}C$
  - $\overline{Z} = (A + B + \overline{C}) \cdot (A + \overline{B} + \overline{C}) \cdot (\overline{A} + B + \overline{C})$
- At gate level, can convert from AND/OR to NAND/NOR gates
  - "Flip" all input/output bubbles and "switch" gate 

DeMorgan's Law Practice Problem

- Simplify the following diagram:



$$X = \overline{A+B} + A\overline{B} + \overline{C}\,\overline{D}$$

DeMorgan's

$$X = \overline{A}\,\overline{B} + A\overline{B} + \overline{C}\,\overline{D}$$

5 gates $X = \overline{B} + \overline{C}\,\overline{D}$

DeMorgan's

3-4 gates $X = \overline{B} + \overline{C + D}$

DeMorgan's

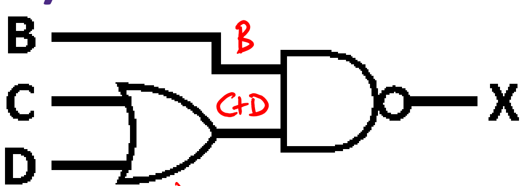
2-3 gates $X = \overline{B(C + D)}$

let $E = C+D$, so $X = \overline{B} + \overline{E}$

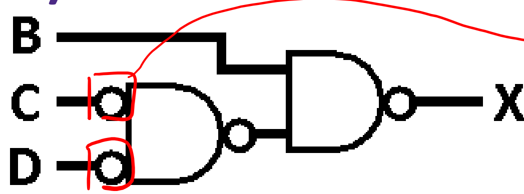
$X = \overline{BE}$

- Then implement with only NAND gates:

1)



2)



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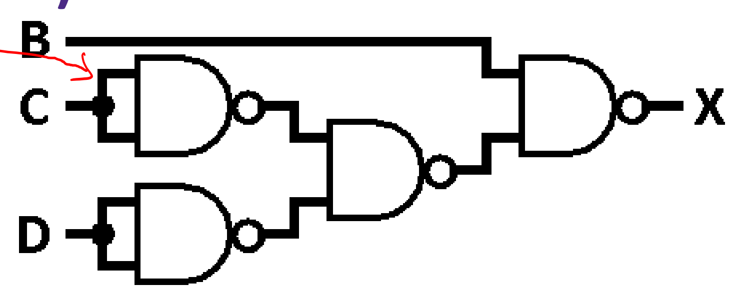
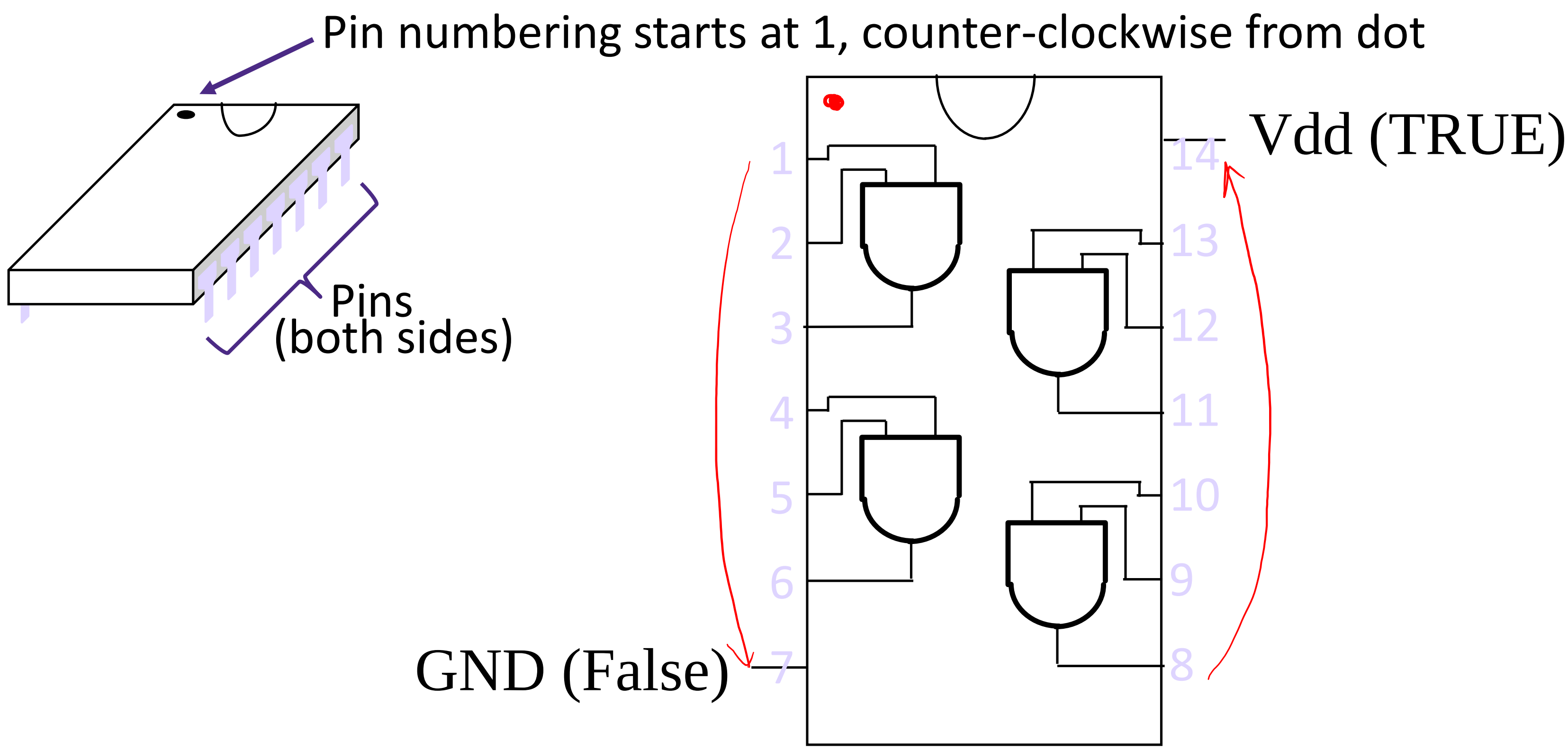


DeMorgan's

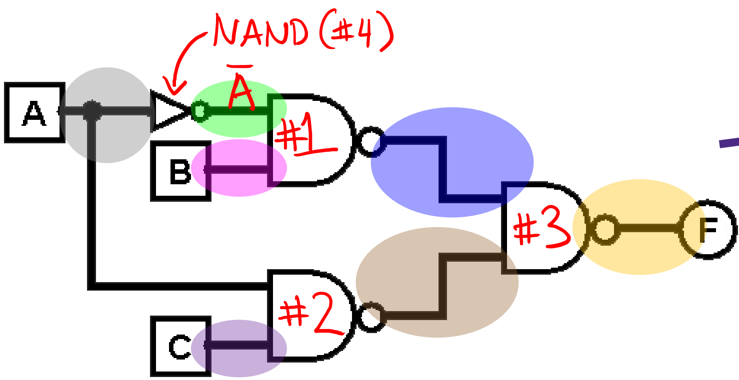
Transistor-Transistor Logic (TTL) Packages



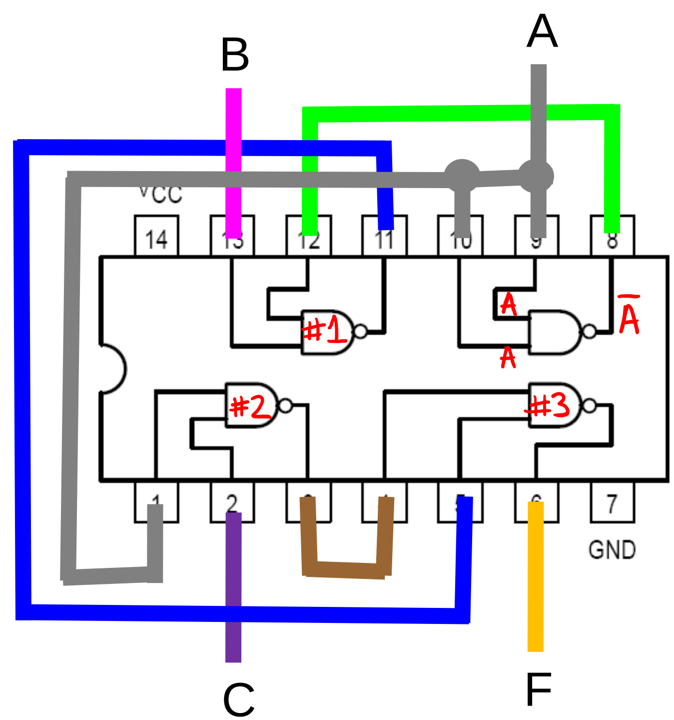
- Diagrams like these and other useful/helpful information can be found on part data sheets
  - It's really useful to learn how to read these

Mapping truth tables to logic gates

- Given a truth table:
  1) Write the Boolean expression
  2) Minimize the Boolean expression
  3) Draw as gates
  4) Map to available gates
  5) Determine # of packages
     and their connections

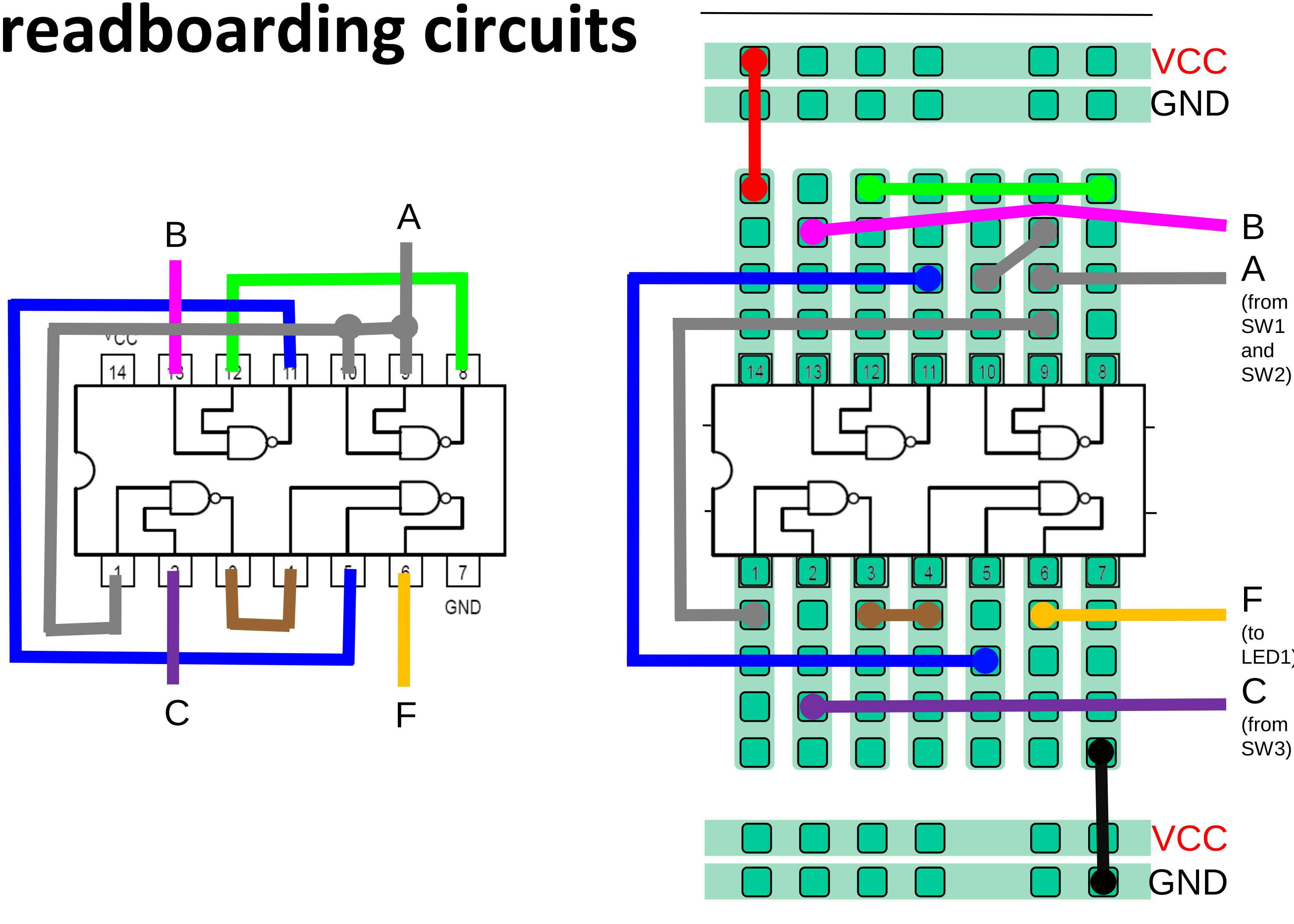


(4)



7 nets (wires) in this design

Breadboarding circuits



Summary

- Digital systems are constructed from Combinational and Sequential Logic
- Logic minimization to create smaller and faster hardware
- Gates come in TTL packages that require careful wiring