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UC Berkeley CS61C : Machine Structures

Lecture 25 – Representations of Combinational Logic Circuits

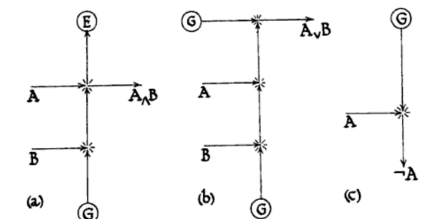
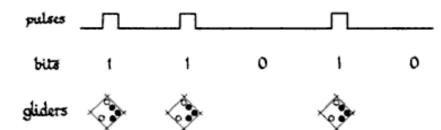


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Conway's Life Logic Gates \Rightarrow

**Berlekamp, Conway and
Guy in their “Winning Ways” series
showed how a glider was a 1, no
glider a 0, & how to build logic gates!**



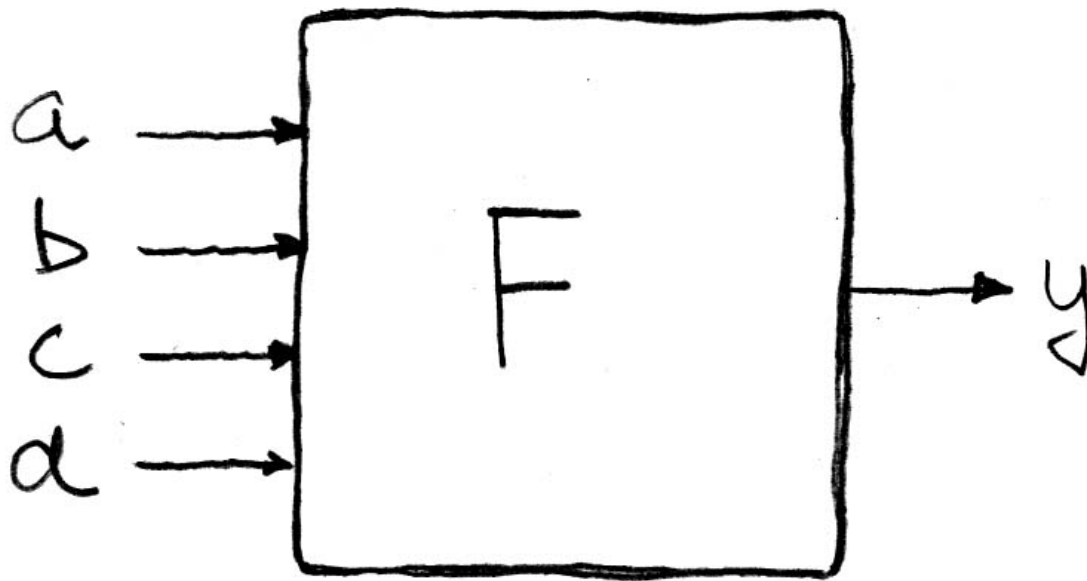
en.wikipedia.org/wiki/Conway%27s_Game_of_Life

Review

- **State elements are used to:**
 - Build memories
 - Control the flow of information between other state elements and combinational logic
- D-flip-flops used to build registers
- Clocks tell us when D-flip-flops change
 - Setup and Hold times important
- We pipeline long-delay CL for faster clock
- Finite State Machines extremely useful
 - Represent states and transitions



Truth Tables



**How many Fs
(4-input devices)
@ Radio Shack?**

a	b	c	d	y
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)
0	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)

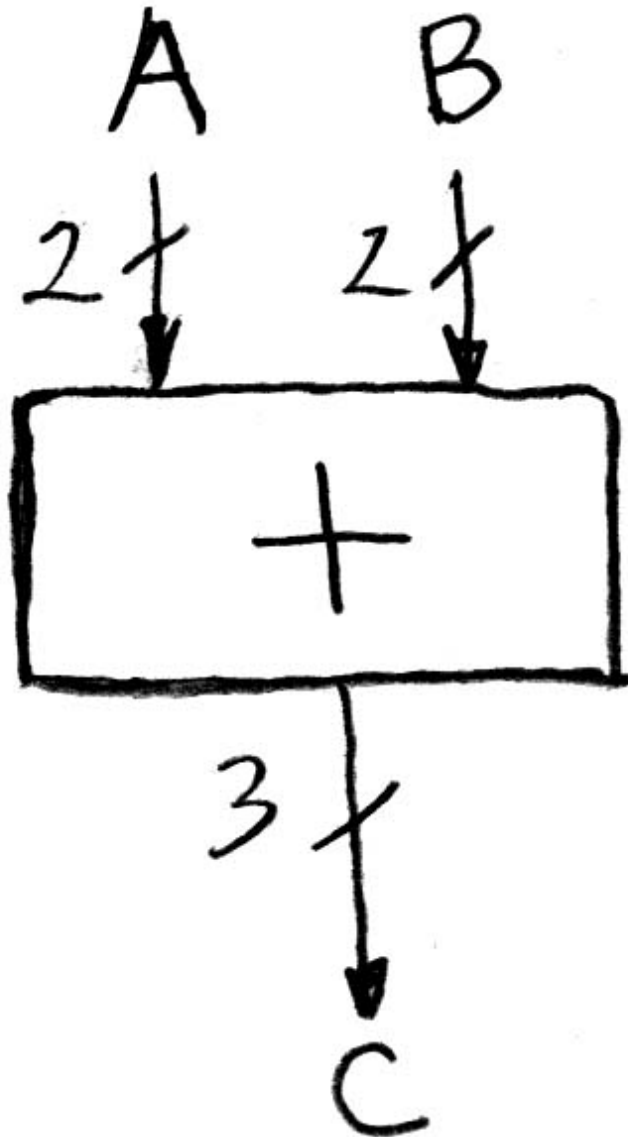


TT Example #1: 1 iff one (not both) $a, b=1$

a	b	y
0	0	0
0	1	1
1	0	1
1	1	0



TT Example #2: 2-bit adder



A	B	C
a_1a_0	b_1b_0	$c_2c_1c_0$
00	00	000
00	01	001
00	10	010
00	11	011
01	00	001
01	01	010
01	10	011
01	11	100
10	00	010
10	01	011
10	10	100
10	11	101
11	00	011
11	01	100
11	10	101
11	11	110

How
Many
Rows?

TT Example #3: 32-bit unsigned adder

A		B		C	
000 ... 0	000 ... 0	000 ... 00			
000 ... 0	000 ... 1	000 ... 01			
.	.	.			
.	.	.			
.	.	.			
111 ... 1	111 ... 1	111 ... 10			

How
Many
Rows?



TT Example #4: 3-input majority circuit

a	b	c	y
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



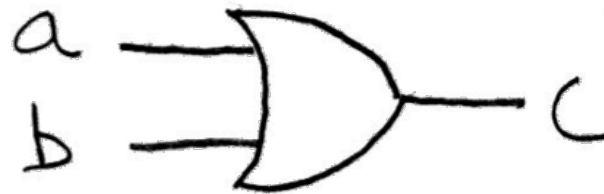
Logic Gates (1/2)

AND



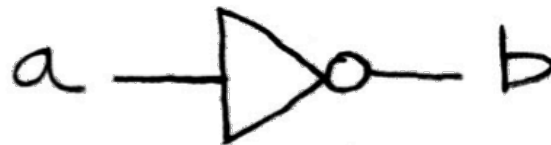
ab	c
00	0
01	0
10	0
11	1

OR



ab	c
00	0
01	1
10	1
11	1

NOT



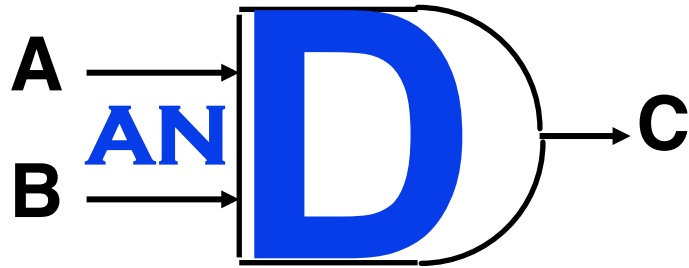
a	b
0	1
1	0



And vs. Or review – Dan's mnemonic

AND Gate

Symbol



Definition

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

Logic Gates (2/2)

XOR



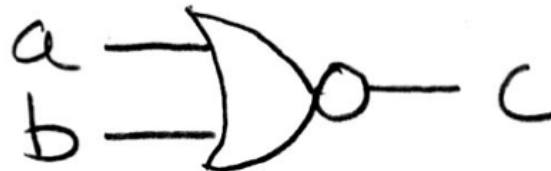
ab	c
00	0
01	1
10	1
11	0

NAND



ab	c
00	1
01	1
10	1
11	0

NOR



ab	c
00	1
01	0
10	0
11	0



2-input gates extend to n-inputs

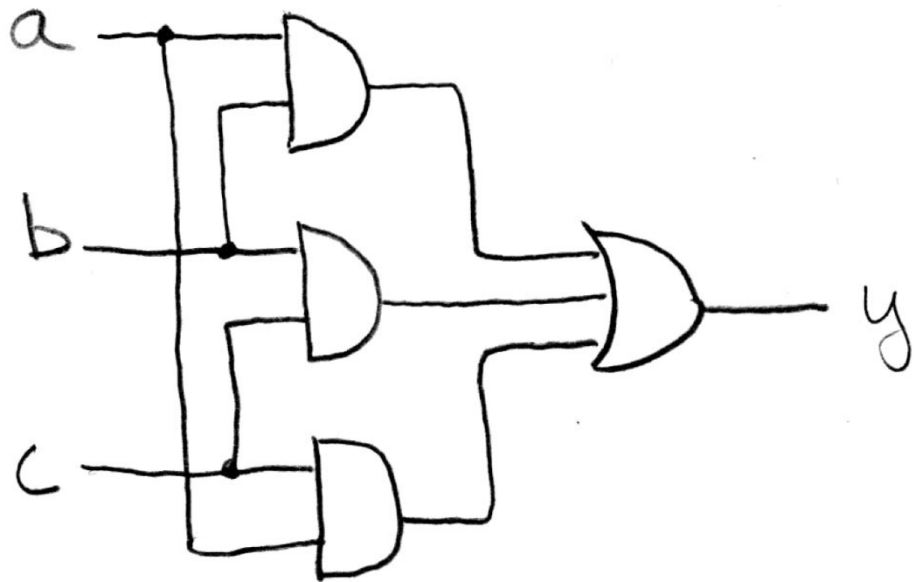
- N-input XOR is the only one which isn't so obvious
- It's simple: XOR is a 1 iff the # of 1s at its input is odd \Rightarrow

a	b	c	y
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1



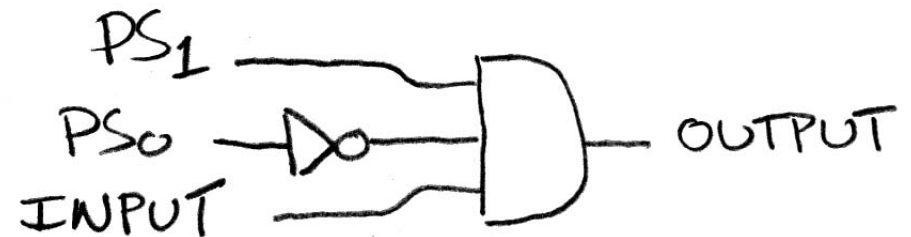
Truth Table \Rightarrow Gates (e.g., majority circ.)

a	b	c	y
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

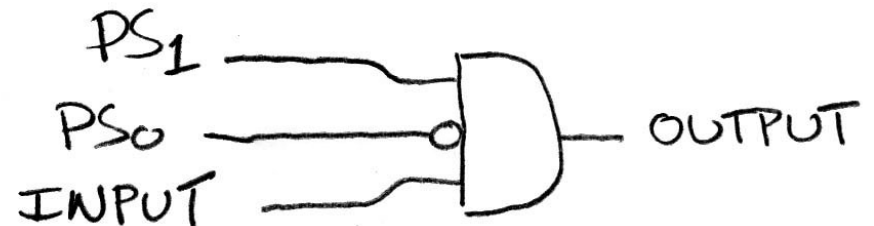


Truth Table \Rightarrow Gates (e.g., FSM circ.)

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1



or equivalently...



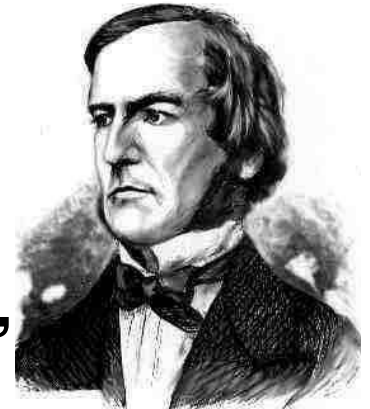
Administrivia

- **How many hours on project 2 so far?**
 - a) 0-10
 - b) 10-20
 - c) 30-40
 - d) 50-60
 - e) 60-70



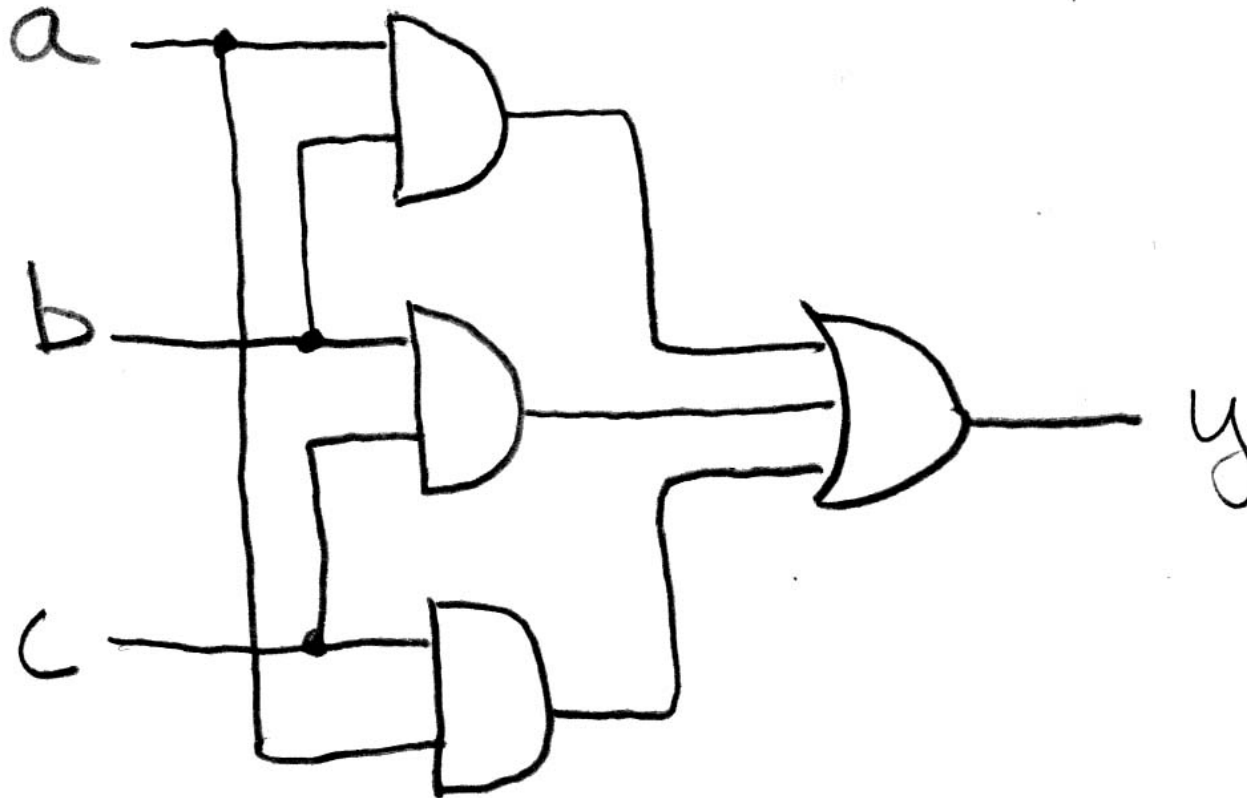
Boolean Algebra

- **George Boole, 19th Century mathematician**
- **Developed a mathematical system (algebra) involving logic**
 - later known as “Boolean Algebra”
- **Primitive functions: AND, OR and NOT**
- **The power of BA is there's a one-to-one correspondence between circuits made up of AND, OR and NOT gates and equations in BA**



+ means OR, \cdot means AND, \bar{x} means NOT

Boolean Algebra (e.g., for majority fun.)

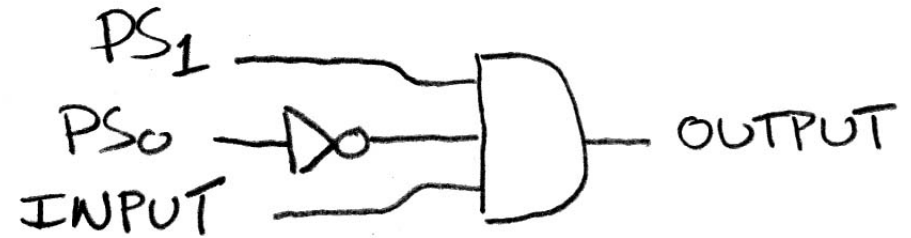


$$y = a \cdot b + a \cdot c + b \cdot c$$

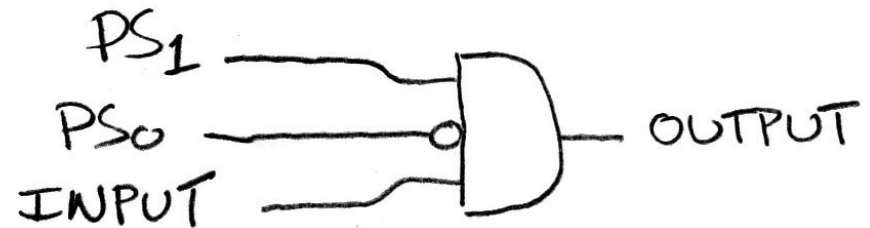
$$y = ab + ac + bc$$

Boolean Algebra (e.g., for FSM)

PS	Input	NS	Output
00	0	00	0
00	1	01	0
01	0	00	0
01	1	10	0
10	0	00	0
10	1	00	1

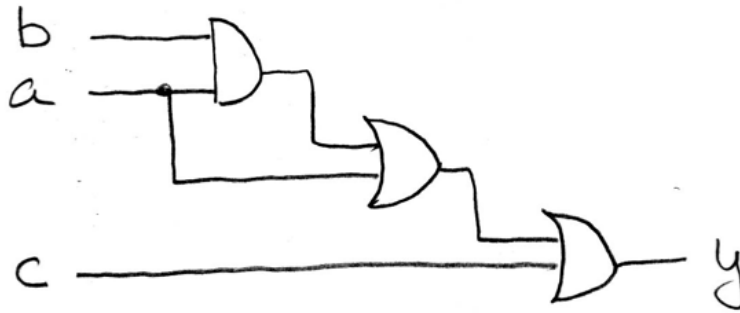


or equivalently...



$$y = PS_1 \cdot \overline{PS_0} \cdot INPUT$$

BA: Circuit & Algebraic Simplification



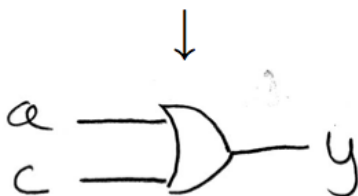
original circuit

$$y = ((ab) + a) + c$$

equation derived from original circuit

$$\begin{aligned} &\downarrow \\ &= ab + a + c \\ &\downarrow \\ &= a(b + 1) + c \\ &= a(1) + c \\ &= a + c \end{aligned}$$

algebraic simplification



simplified circuit

**BA also great for
circuit verification
Circ X = Circ Y?
use BA to prove!**



Laws of Boolean Algebra

$$x \cdot \bar{x} = 0$$

$$x \cdot 0 = 0$$

$$x \cdot 1 = x$$

$$x \cdot x = x$$

$$x \cdot y = y \cdot x$$

$$(xy)z = x(yz)$$

$$x(y + z) = xy + xz$$

$$xy + x = x$$

$$\bar{x}y + x = x + y$$

$$\overline{x \cdot y} = \bar{x} + \bar{y}$$

$$x + \bar{x} = 1$$

$$x + 1 = 1$$

$$x + 0 = x$$

$$x + x = x$$

$$x + y = y + x$$

$$(x + y) + z = x + (y + z)$$

$$x + yz = (x + y)(x + z)$$

$$(x + y)x = x$$

$$(\bar{x} + y)x = xy$$

$$\overline{x + y} = \bar{x} \cdot \bar{y}$$

complementarity

laws of 0's and 1's

identities



idempotent law

commutativity

associativity

distribution

uniting theorem

uniting theorem v.2

DeMorgan's Law




Boolean Algebraic Simplification Example

$$\begin{aligned}y &= ab + a + c \\&= a(b + 1) + c && \text{distribution, identity} \\&= a(1) + c && \text{law of 1's} \\&= a + c && \text{identity}\end{aligned}$$



Canonical forms (1/2)

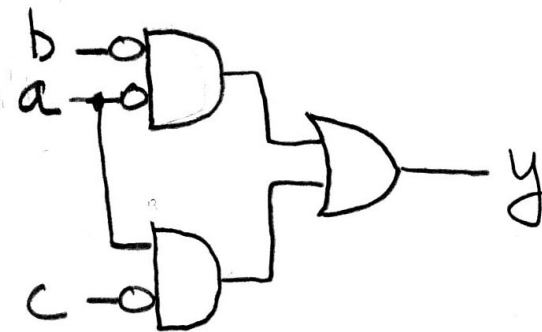
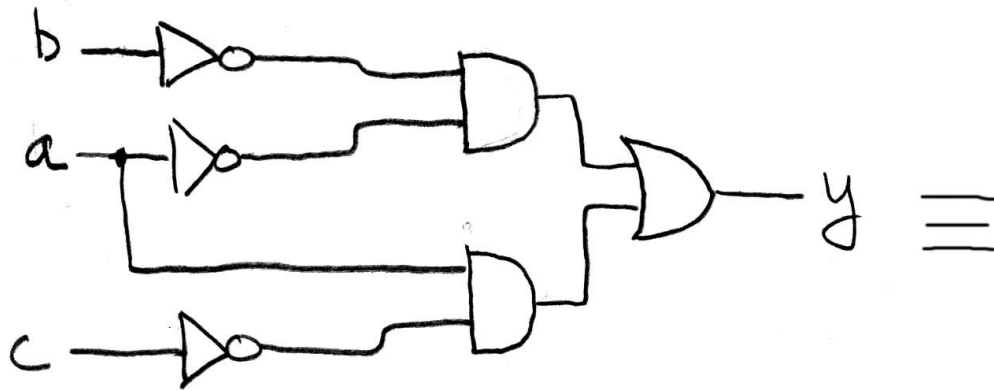
	abc	y		Sum-of-products (ORs of ANDs)
$\bar{a} \cdot \bar{b} \cdot \bar{c}$	000	1		
$\bar{a} \cdot \bar{b} \cdot c$	001	1		
	010	0		
	011	0		
$a \cdot \bar{b} \cdot \bar{c}$	100	1		
	101	0		
$a \cdot b \cdot \bar{c}$	110	1		
	111	0		



Canonical forms (2/2)

$$\begin{aligned}y &= \bar{a}\bar{b}\bar{c} + \bar{a}\bar{b}c + a\bar{b}\bar{c} + ab\bar{c} \\&= \bar{a}\bar{b}(\bar{c} + c) + a\bar{c}(\bar{b} + b) \\&= \bar{a}\bar{b}(1) + a\bar{c}(1) \\&= \bar{a}\bar{b} + a\bar{c}\end{aligned}$$

distribution
complementarity
identity



Peer Instruction

- 1) $(a+b) \cdot (\bar{a}+b) = b$
- 2) N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND
- 3) You can use NOR(s) with clever wiring to simulate AND, OR, & NOT

	1	2	3
a:	F	F	F
a:	F	F	T
b:	F	T	F
b:	F	T	T
c:	T	F	F
d:	T	F	T
d:	T	T	F
e:	T	T	T

Peer Instruction Answer

1) $(a+b) \cdot (\bar{a}+b) = a\bar{a}+ab+b\bar{a}+bb = 0+b(a+\bar{a})+b = b+b = b$ **TRUE**

2) (next slide)

3) You can use NOR(s) with clever wiring to simulate AND, OR, & NOT.

$$\text{NOR}(a,a) = \overline{a+a} = \overline{aa} = \bar{a}$$

Using this NOT, can we make a NOR an OR? An And?

TRUE

1) $(a+b) \cdot (\bar{a}+b) = b$

2) N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND

3) You can use NOR(s) with clever wiring to simulate AND, OR, & NOT

	1	2	3
a:	F	F	F
a:	F	F	T
b:	F	T	F
b:	F	T	T
c:	T	F	F
d:	T	F	T
d:	T	T	F
e:	T	T	T

Peer Instruction Answer (B)

- 2) N-input gates can be thought of cascaded 2-input gates. I.e.,
 $(a \Delta bc \Delta d \Delta e) = a \Delta (bc \Delta (d \Delta e))$
where Δ is one of AND, OR, XOR, NAND... **FALSE**

Let's confirm!

CORRECT 3-input				
XYZ	AND	OR	XOR	NAND
000	0	0	0	1
001	0	1	1	1
010	0	1	1	1
011	0	1	0	1
100	0	1	1	1
101	0	1	0	1
110	0	1	0	1
111	1	1	1	0

CORRECT 2-input				
YZ	AND	OR	XOR	NAND
00	0	0	0	1
01	0	1	1	1
10	0	1	1	1
11	1	1	0	0



“And In conclusion...”

- Pipeline big-delay CL for faster clock
- Finite State Machines extremely useful
 - You’ll see them again in 150, 152 & 164
- Use this table and techniques we learned to transform from 1 to another

