

CSC 252: Computer Organization

Spring 2019: Lecture 3

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Department of Computer Science
University of Rochester

Action Items:

- **Trivia 1 is due tomorrow, midnight**
- **Main assignment due Feb. 1, midnight**

Announcement

- Programming Assignment 1 is out
 - Details: <http://cs.rochester.edu/courses/252/spring2019/labs/assignment1.html>
 - Due on Feb 1, 11:59 PM
 - Trivia due Friday, 1/25, 11:59 PM
 - You have 3 slip days (not for trivia)

20	21	22	23	24	25	26
				Today	Trivia	
27	28	29	30	31	Feb 1	2
					Due	

Announcement

- TA review sessions schedule is posted

Review Session Schedule

Two 1-hour review sessions are offered each week. Review sessions are not mandatory. During review sessions, TAs might review course materials from the past week, go over problem sets and past exams, provide an overview of programming assignments, etc. They will be interactive and you are encouraged to ask questions. It is up to the TAs to decide how to run it.

Tuesday 6 PM - 7 PM, in WH 2506 (Rotating across Olivia, Jessica, Max, Sam, Yawo)

Thursday 7:30 PM - 8:30 PM, in WH 2506 (Rotating across Amir, Minh, Yiyang, Yu)

Announcement

- Check the course website before asking
 - <http://www.cs.rochester.edu/courses/252/spring2019/>

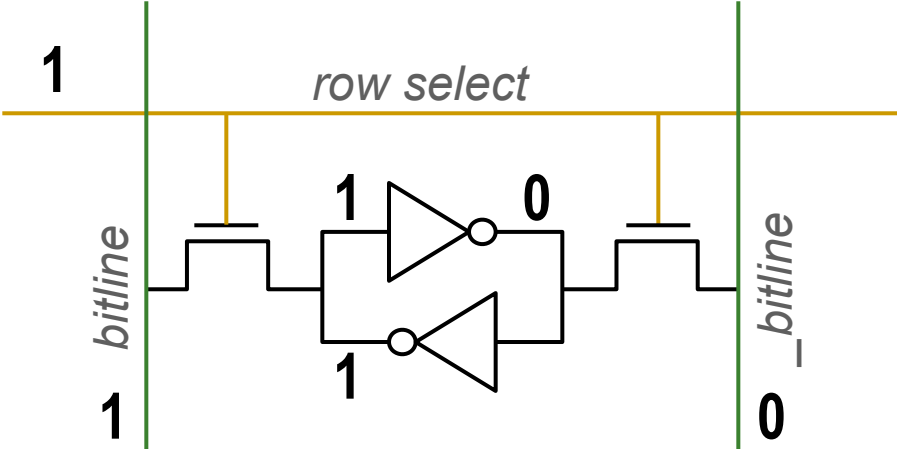
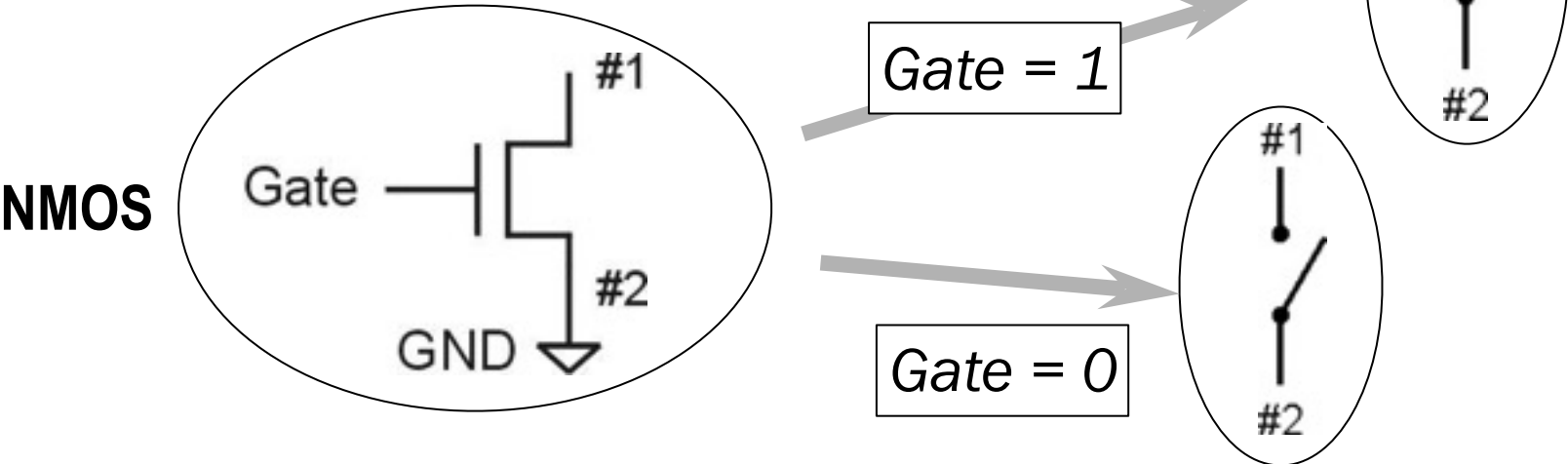
Announcement

- Check the course website before asking
 - <http://www.cs.rochester.edu/courses/252/spring2019/>
- Direct ALL questions regarding assignments to the TAs
 - They have done them. They have debugged them. They know them inside out.
 - If one doesn't know, ask another.
 - If all don't know, ask me.

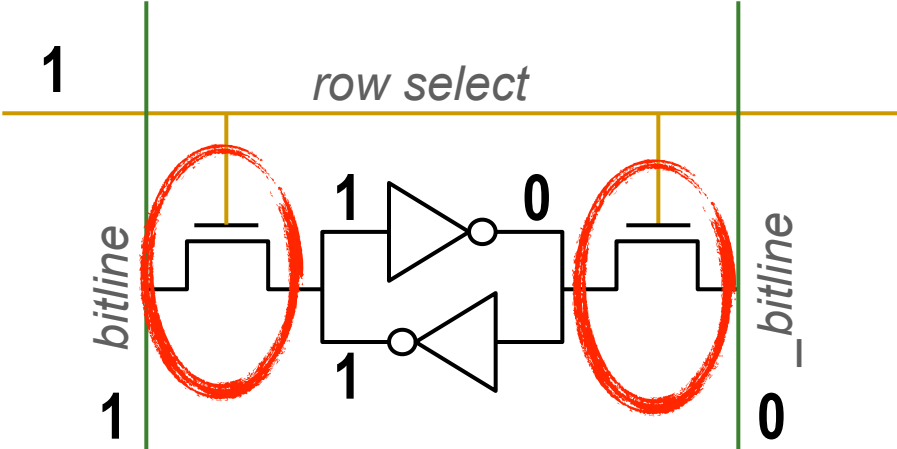
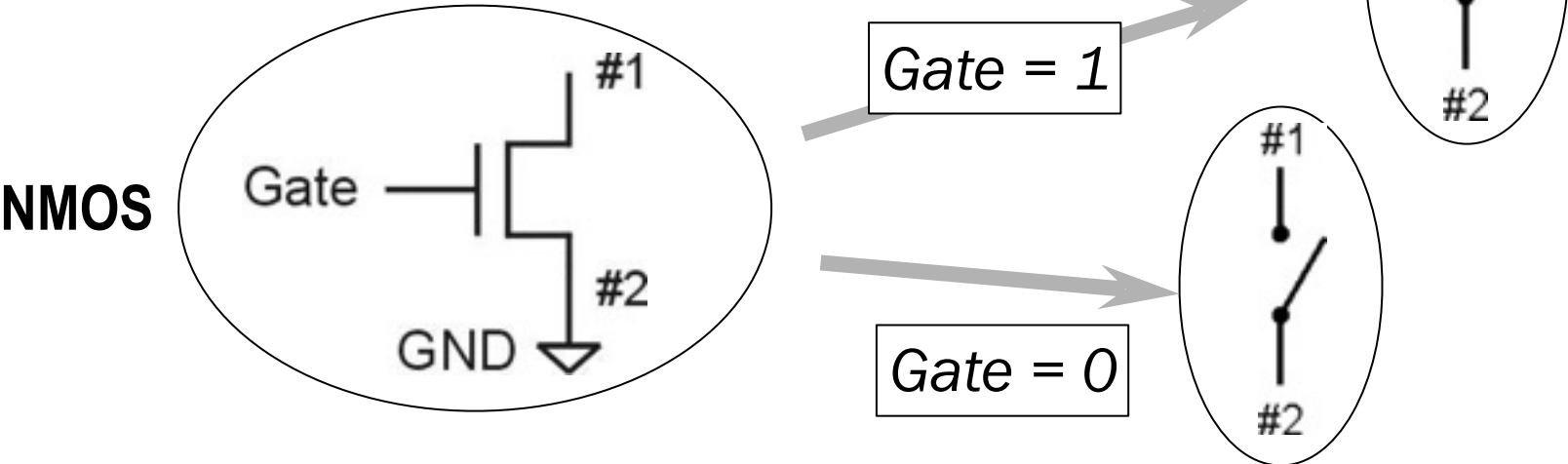
Previously in 252...

- Computers are built to understand bits: 0 and 1
 - 0: low (no) voltage; 1: high voltage
- Integer representations (Fixed-point really)

Store/Access Data



Store/Access Data

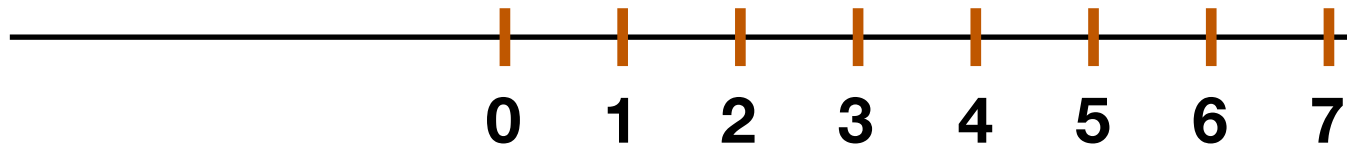


Encoding Negative Numbers

- Two's Complement

Encoding Negative Numbers

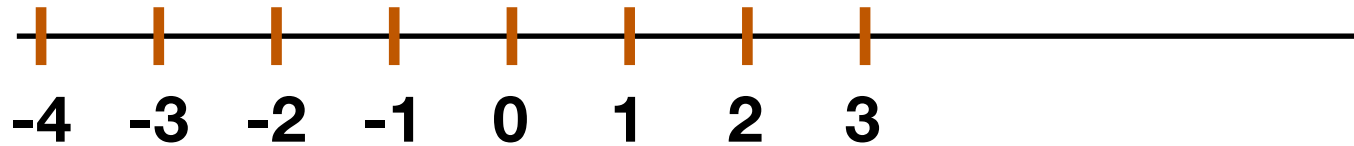
- Two's Complement



Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
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7	111

Encoding Negative Numbers

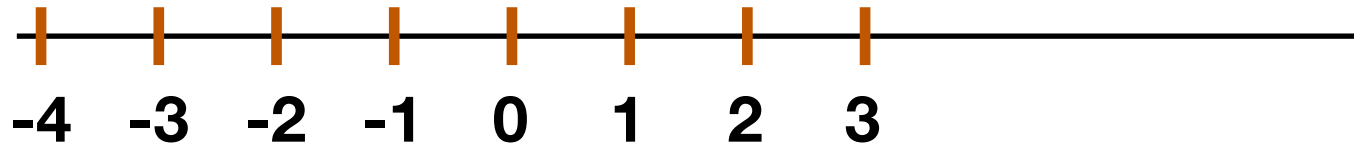
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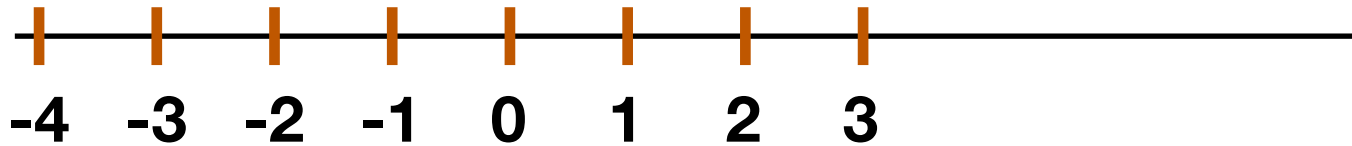
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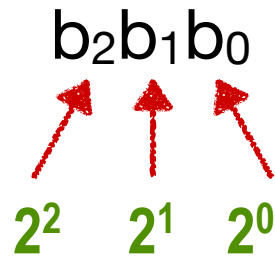
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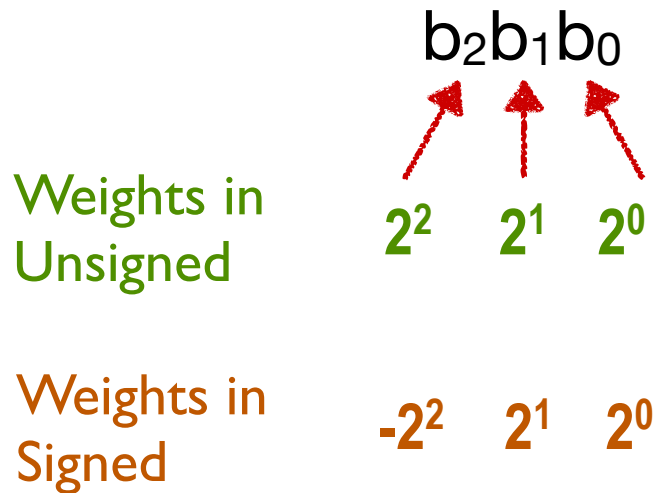
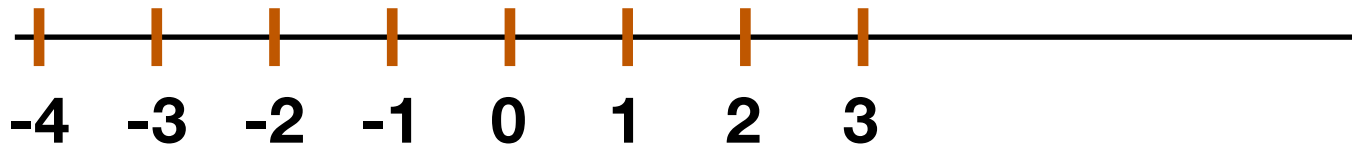
Weights in
Unsigned



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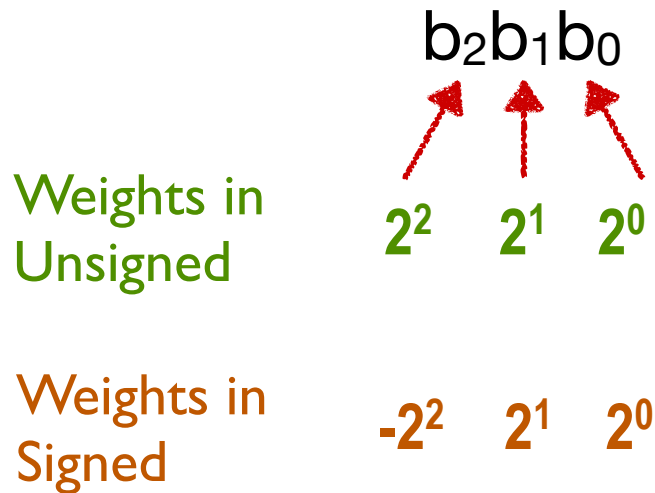
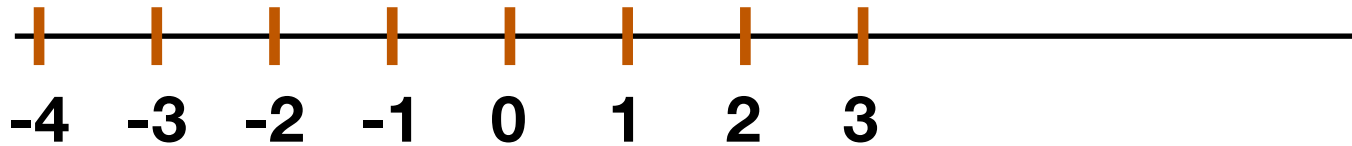
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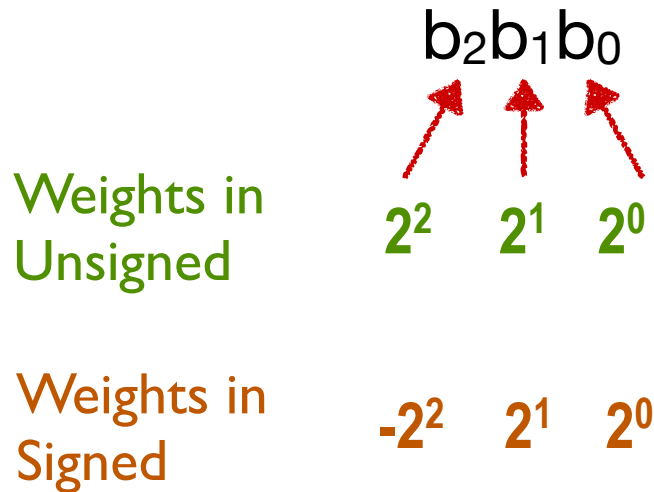
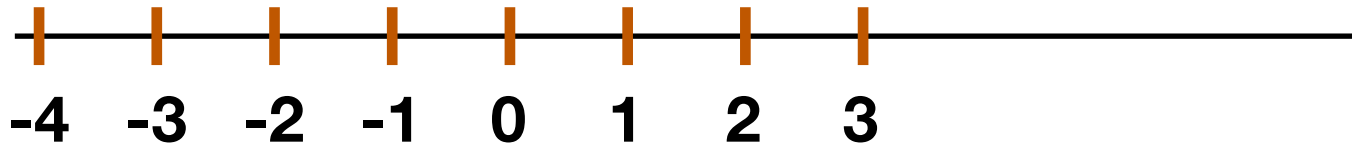


$$101_2 = 1 \cdot 2^0 + 0 \cdot 2^1 + (-1 \cdot 2^2) = -3_{10}$$

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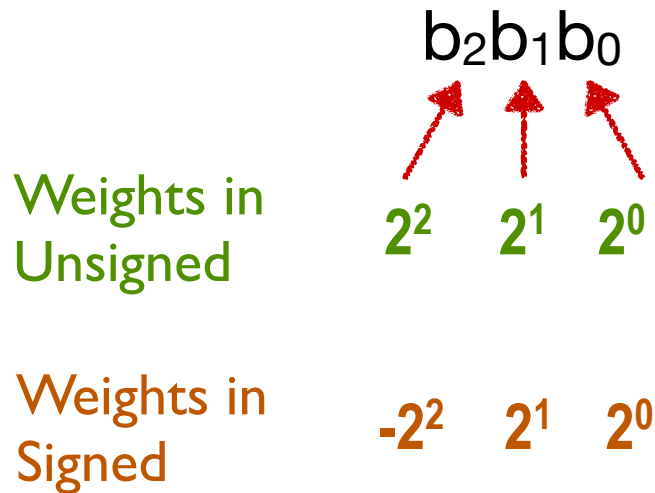
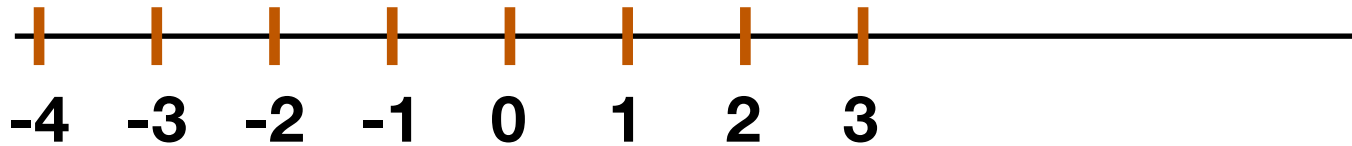


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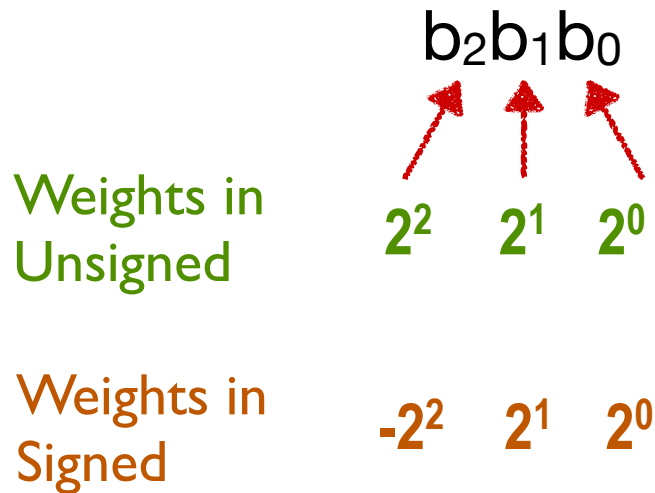
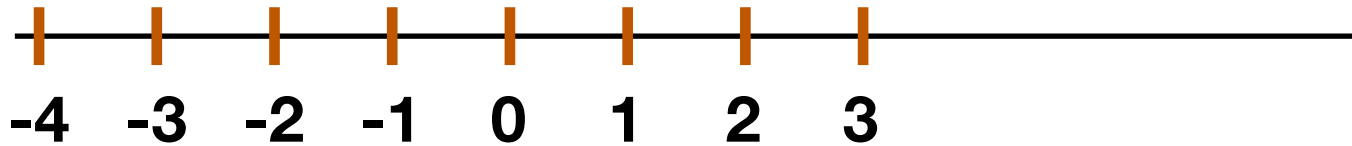
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Two-Complement Implications

- Only 1 zero
- There is (still) a bit that represents sign!
- Unsigned arithmetic still works

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$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$

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- 3 + 1 becomes -4 (called **overflow**. More on it later.)

Data Types (in C)

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`unsigned char` in C
 - Internally, an **unsigned char** variable is represented as a 8-bit, non-negative, binary number

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 - The C language designers chose two's complement
 - This is where math meets computer science

Data Types (in C)

C Data Type	32-bit	64-bit
(unsigned) char	1	1
(unsigned) short	2	2
(unsigned) int	4	4
(unsigned) long	4	8

Data Types (in C)

	W			
	8	16	32	64
UMax	255	65,535	4,294,967,295	18,446,744,073,709,551,615
TMax	127	32,767	2,147,483,647	9,223,372,036,854,775,807
TMin	-128	-32,768	-2,147,483,648	-9,223,372,036,854,775,808

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- C Language
 - `#include <limits.h>`
 - Declares constants, e.g.,
 - `ULONG_MAX`
 - `LONG_MAX`
 - `LONG_MIN`
 - Values platform specific

Today: Representing Information in Binary

- Why Binary (bits)?
- Bit-level manipulations
- **Integers**
 - Representation: unsigned and signed
 - **Conversion, casting**
 - Expanding, truncating
 - Addition, negation, multiplication, shifting
 - Summary
- Representations in memory, pointers, strings

One Bit Sequence, Two Interpretations

- A sequence of bits can be interpreted as either a signed integer or an unsigned integer

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0	0	000
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Signed vs. Unsigned Conversion in C

- What happens when we convert between signed and unsigned numbers?
- Casting (In C terminology)
 - Explicit casting between signed & unsigned

```
int tx, ty = -4;
unsigned ux = 7, uy;
tx = (int) ux; // U2T
uy = (unsigned) ty; // T2U
```

- Implicit casting
 - e.g., assignments, function calls
- ```
tx = ux;
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```



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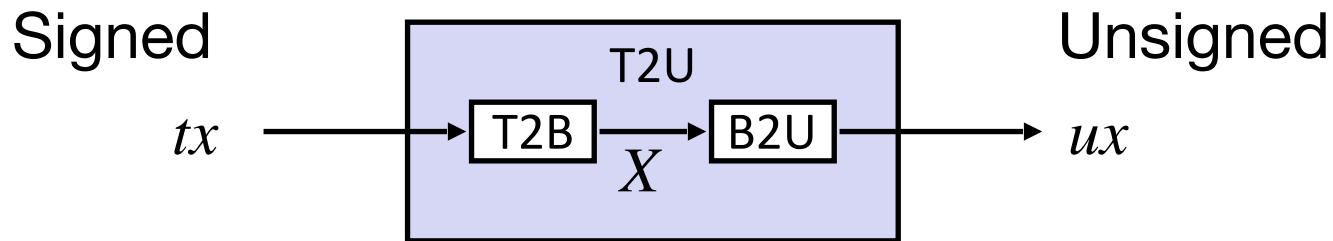
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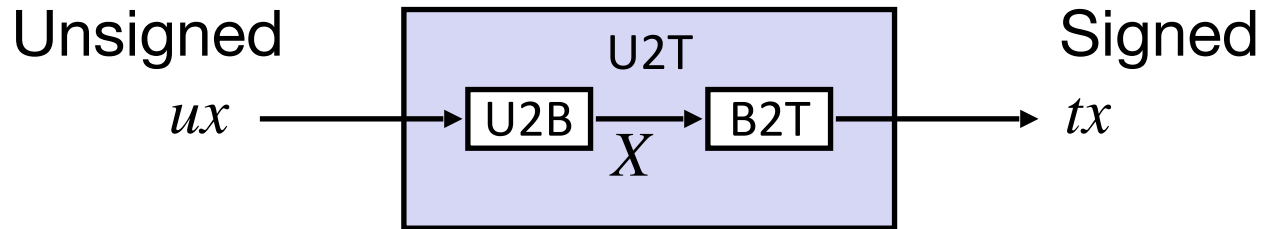
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Mapping Between Signed & Unsigned

- Mappings between unsigned and two's complement numbers: **Keep bit representations and reinterpret**



Maintain Same Bit Pattern



Maintain Same Bit Pattern

Mapping Signed \leftrightarrow Unsigned

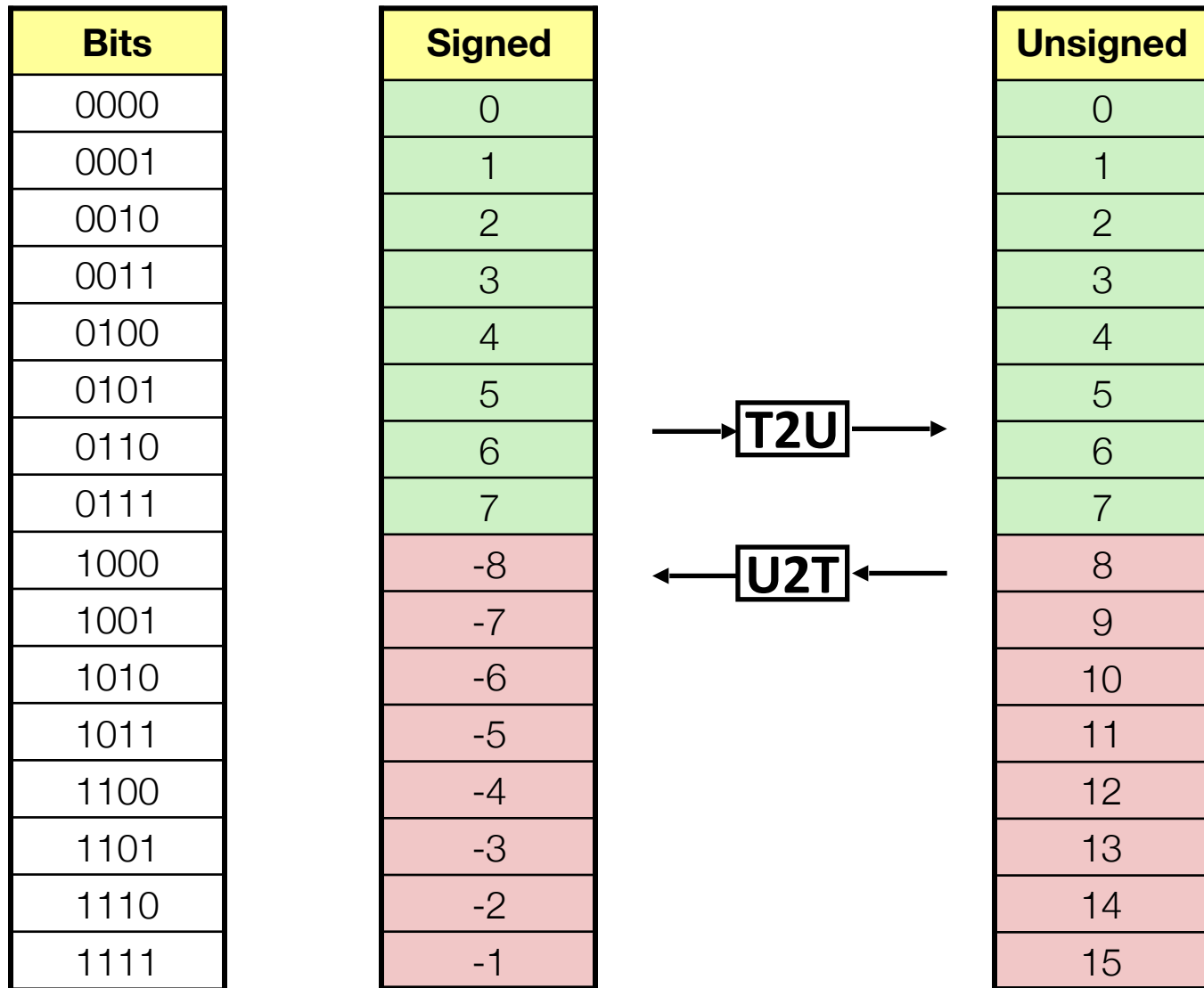
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0101	5	5
0110	6	6
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1000	-8	8
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1010	-6	10
1011	-5	11
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→ **T2U** →

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=

+/- 16

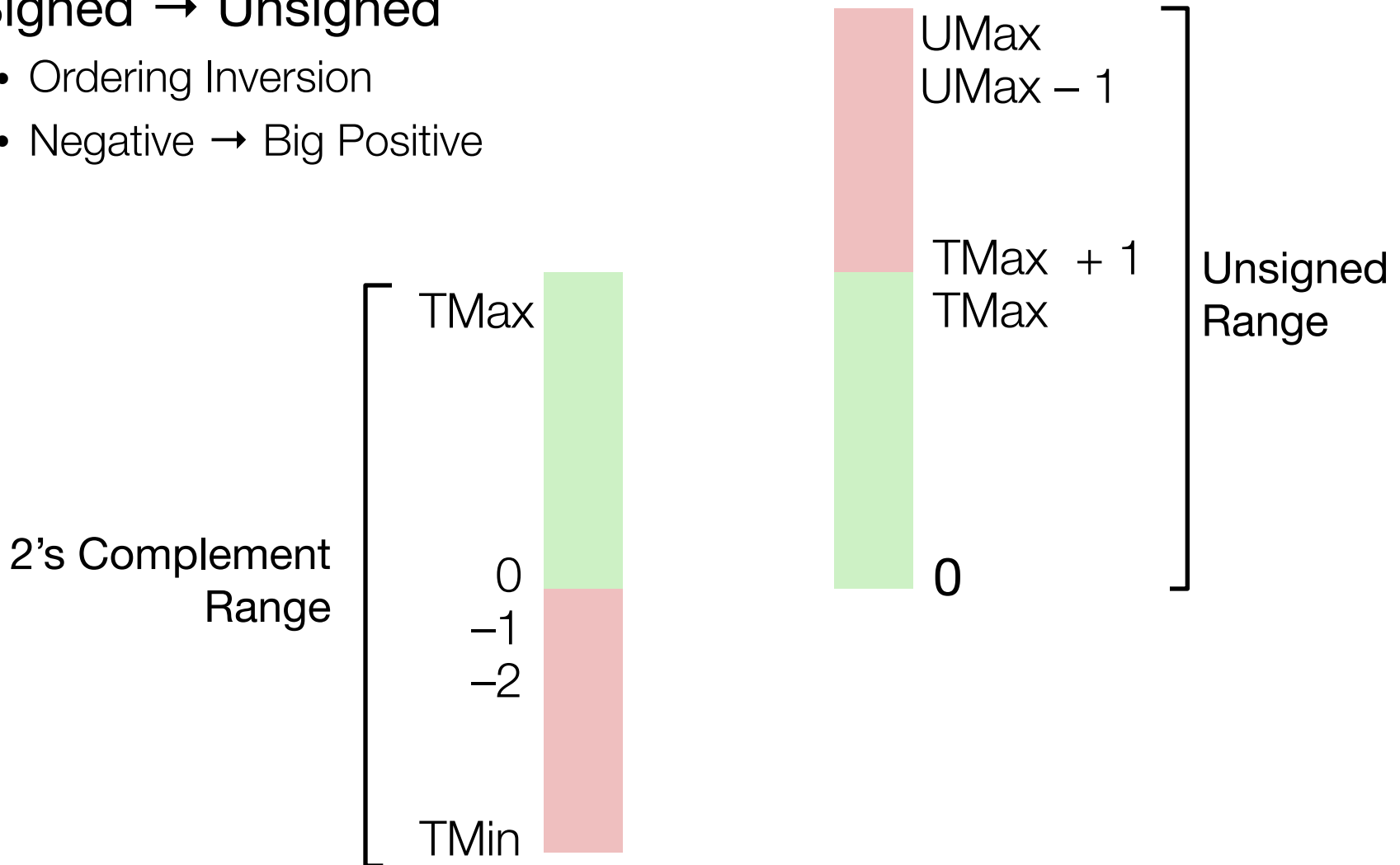
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The mapping shows that for bits 0000 to 0111, the signed and unsigned values are identical. For bits 1000 to 1111, the signed values are 8 less than the unsigned values. A double-headed arrow with an equals sign ($=$) is positioned between the Signed and Unsigned columns for the first seven rows. A double-headed arrow with ± 16 is positioned between the Signed and Unsigned columns for the last seven rows. An orange box highlights the rows for bits 1000 and 1001.

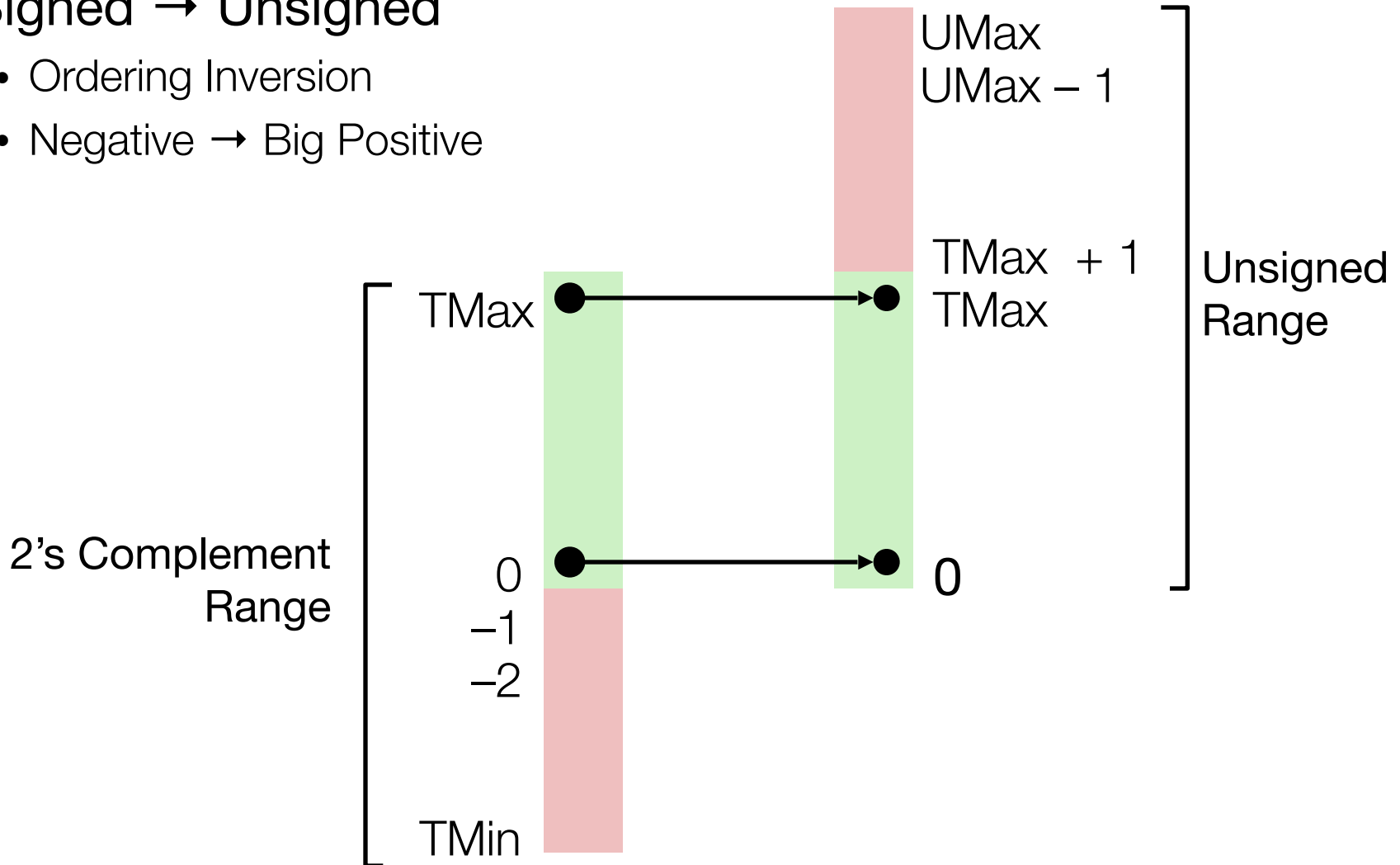
Conversion Visualized

- Signed \rightarrow Unsigned
 - Ordering Inversion
 - Negative \rightarrow Big Positive



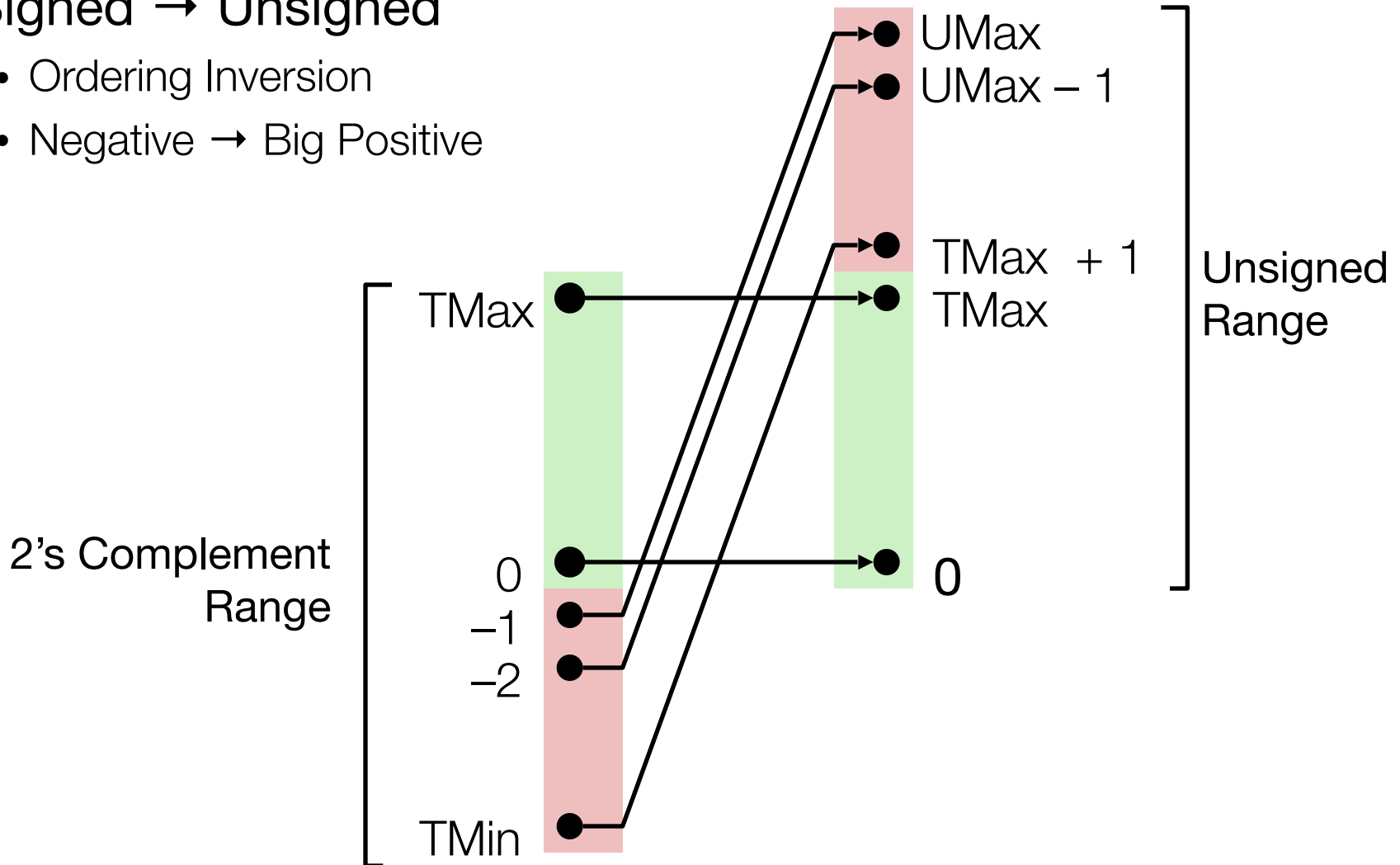
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The Problem

```
short int x = 15213;  
int      ix = (int) x;  
short int y = -15213;  
int      iy = (int) y;
```

C Data Type	64-bit
char	1
short	2
int	4
long	8

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- Should always be able to preserve the value, but how?

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	Decimal	Hex	Binary
x	15213	3B 6D	00111011 01101101
ix	15213	00 00 3B 6D	00000000 00000000 00111011 01101101
y	-15213	C4 93	11000100 10010011
iy	-15213	FF FF C4 93	11111111 11111111 11000100 10010011

Signed Extension

- Task:
 - Given w -bit signed integer x
 - Convert it to $(w+k)$ -bit integer with same value

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- Convert it to $(w+k)$ -bit integer with same value

- Rule:

- Make k copies of sign bit:
- $X' = \underbrace{x_{w-1}, \dots, x_{w-1}}_{k \text{ copies of MSB}}, x_{w-1}, x_{w-2}, \dots, x_0$

k copies of MSB

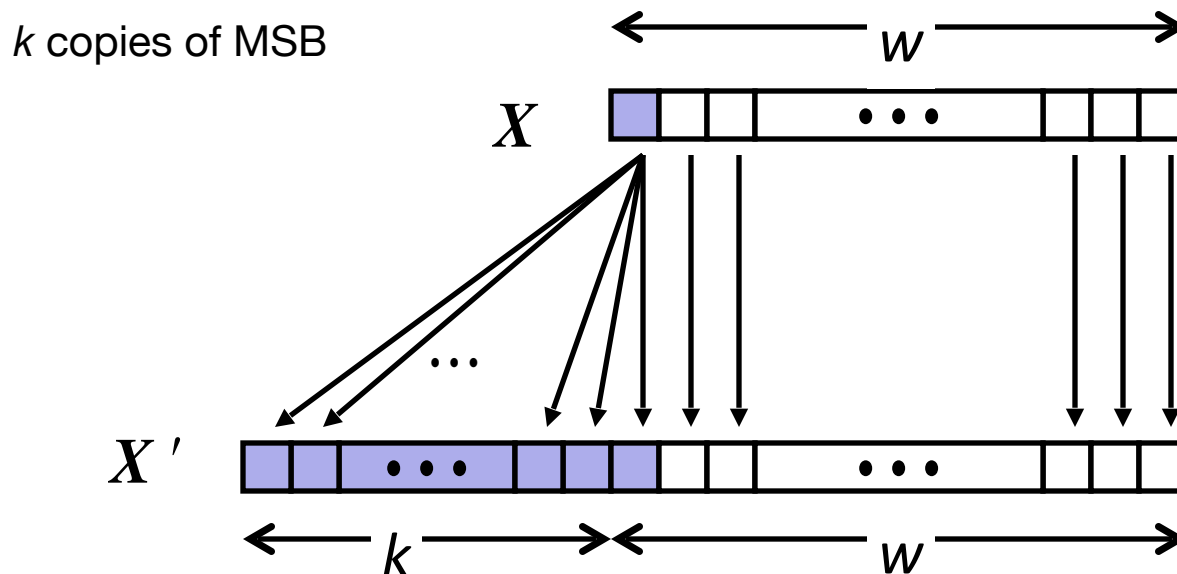
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Another Problem

```
unsigned short x = 47981;  
unsigned int   ux = x;
```

	Decimal	Hex	Binary
x	47981	BB 6D	10111011 01101101
ux	47981	00 00 BB 6D	00000000 00000000 10111011 01101101

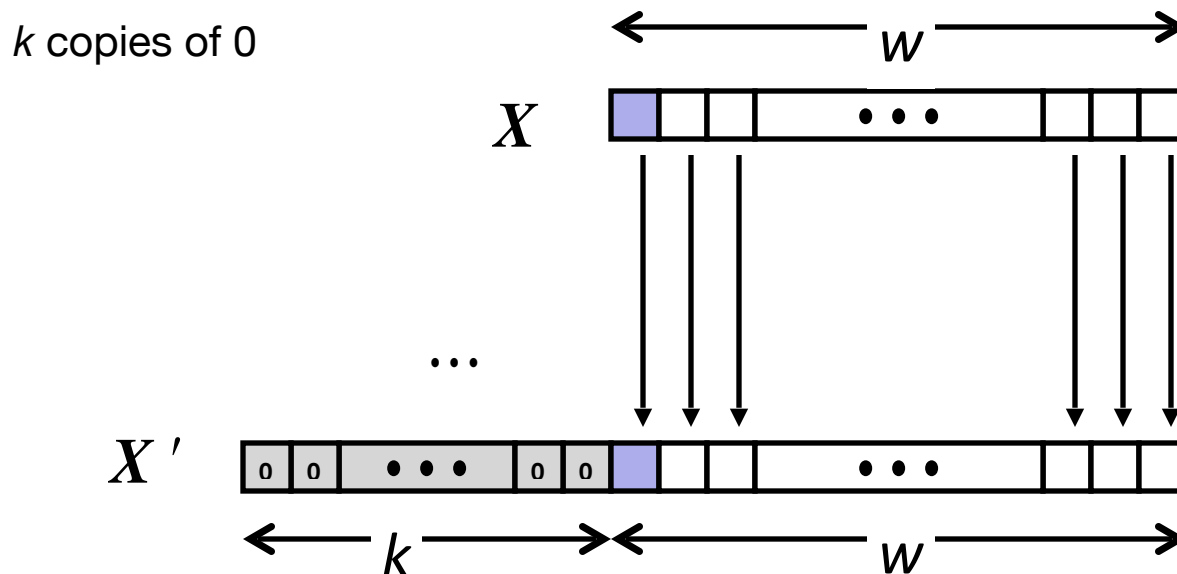
Unsigned (Zero) Extension

- Task:

- Given w -bit unsigned integer x
- Convert it to $(w+k)$ -bit integer with same value

- Rule:

- Simply pad zeros:
- $X' = \underbrace{0, \dots, 0}_{k \text{ copies of } 0}, x_{w-1}, x_{w-2}, \dots, x_0$



Yet Another Problem

```
int    x = 53191;  
short sx = (short) x;
```

	Decimal	Hex	Binary
x	53191	00 00 CF C7	00000000 00000000 11001111 11000111
sx	-12345	CF C7	11001111 11000111

Yet Another Problem

```
int    x = 53191;
short sx = (short) x;
```

	Decimal	Hex	Binary
x	53191	00 00 CF C7	00000000 00000000 11001111 11000111
sx	-12345	CF C7	11001111 11000111

- Truncating (e.g., int to short)
 - Can't always preserve the numerical value
 - C's implementation: leading bits are truncated, results reinterpreted

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sx	-12345	CF C7	11001111 11000111

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Questions?

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- Check the course website before asking
 - <http://www.cs.rochester.edu/courses/252/spring2019/>
- Direct ALL questions regarding assignments to the TAs
 - They have done them. They have debugged them. They know them inside out.
 - If one doesn't know, ask another.
 - If all don't know, ask me.

Today: Representing Information in Binary

- Why Binary (bits)?
- Bit-level manipulations
- **Integers**
 - Representation: unsigned and signed
 - Conversion, casting
 - Expanding, truncating
 - **Addition, negation, multiplication, shifting**
 - Summary
- Representations in memory, pointers, strings

Unsigned Addition

Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Unsigned Addition

- Similar to Decimal Addition

Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Unsigned Addition

- Similar to Decimal Addition
- Suppose we have a new data type that is 3-bit wide (c.f., **short** has 16 bits)

Normal
Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array} \qquad \begin{array}{r} 2 \\ +) 5 \\ \hline 7 \end{array}$$

Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Unsigned Addition

- Similar to Decimal Addition
- Suppose we have a new data type that is 3-bit wide (c.f., **short** has 16 bits)
- Might **overflow**: result can't be represented within the size of the data type

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array} \qquad \begin{array}{r} 2 \\ +) 5 \\ \hline 7 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \end{array} \qquad \begin{array}{r} 6 \\ +) 5 \\ \hline 11 \end{array}$$

Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Unsigned Addition

- Similar to Decimal Addition
- Suppose we have a new data type that is 3-bit wide (c.f., **short** has 16 bits)
- Might **overflow**: result can't be represented within the size of the data type

Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array} \qquad \begin{array}{r} 2 \\ +) 5 \\ \hline 7 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \end{array} \qquad \begin{array}{r} 6 \\ +) 5 \\ \hline 11 \end{array}$$

← True Sum

Unsigned Addition

- Similar to Decimal Addition
- Suppose we have a new data type that is 3-bit wide (c.f., **short** has 16 bits)
- Might **overflow**: result can't be represented within the size of the data type

Unsigned	Binary
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array} \qquad \begin{array}{r} 2 \\ +) 5 \\ \hline 7 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \\ 011 \end{array} \qquad \begin{array}{r} 6 \\ +) 5 \\ \hline 11 \\ 3 \end{array}$$



True Sum



Sum with same bits

Unsigned Addition in C

Operands: w bits



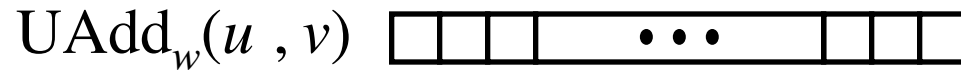
+ v



True Sum: $w+1$ bits



Discard Carry: w bits



Two's Complement Addition

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$
$$\begin{array}{r} 2 \\ +) -3 \\ \hline -1 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)
- Overflow can also occur

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$
$$\begin{array}{r} 2 \\ +) -3 \\ \hline -1 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \end{array}$$
$$\begin{array}{r} -2 \\ +) -3 \\ \hline -5 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)
- Overflow can also occur

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$
$$\begin{array}{r} 2 \\ +) -3 \\ \hline -1 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \\ 011 \end{array}$$
$$\begin{array}{r} -2 \\ +) -3 \\ \hline -5 \\ 3 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)
- Overflow can also occur

Normal Case	010	2
	+) 101	+) -3
	111	-1

Overflow Case	110	-2
	+) 101	+) -3
	1011	-5
	011	3

Min →

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Negative Overflow

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)
- Overflow can also occur

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Min 

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$

$$\begin{array}{r} 2 \\ +) -3 \\ \hline -1 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \\ 011 \end{array}$$

$$\begin{array}{r} -2 \\ +) -3 \\ \hline -5 \\ 3 \end{array}$$

$$\begin{array}{r} 011 \\ +) 001 \\ \hline 0100 \end{array}$$

$$\begin{array}{r} 3 \\ +) 1 \\ \hline 4 \end{array}$$

Negative Overflow

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)
- Overflow can also occur

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Min →

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$

$$\begin{array}{r} 2 \\ +) -3 \\ \hline -1 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \\ 011 \end{array}$$

$$\begin{array}{r} -2 \\ +) -3 \\ \hline -5 \\ 3 \end{array}$$

$$\begin{array}{r} 011 \\ +) 001 \\ \hline 0100 \\ 100 \end{array}$$

$$\begin{array}{r} 3 \\ +) 1 \\ \hline 4 \\ -4 \end{array}$$

Negative Overflow

Two's Complement Addition

- Has identical bit-level behavior as unsigned addition (a big advantage over sign-magnitude)
- Overflow can also occur

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Max 
 Min 

Normal Case

$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$

$$\begin{array}{r} 2 \\ +) -3 \\ \hline -1 \end{array}$$

Overflow Case

$$\begin{array}{r} 110 \\ +) 101 \\ \hline 1011 \\ 011 \end{array}$$

$$\begin{array}{r} -2 \\ +) -3 \\ \hline -5 \\ 3 \end{array}$$

$$\begin{array}{r} 011 \\ +) 001 \\ \hline 0100 \\ 100 \end{array}$$

$$\begin{array}{r} 3 \\ +) 1 \\ \hline 4 \\ -4 \end{array}$$

Negative Overflow

Positive Overflow

Two's Complement Addition in C

Operands: w bits

u



+ v



True Sum: $w+1$ bits

$u + v$



Discard Carry: w bits

$\text{TAdd}_w(u, v)$



Is This Signed Addition an Overflow?

$$\begin{array}{r} 111 \\ +) 110 \\ \hline 1101 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Is This Signed Addition an Overflow?

$$\begin{array}{r} 111 \\ +) 110 \\ \hline \boxed{1}101 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Is This Signed Addition an Overflow?

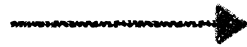
$$\begin{array}{r} 111 \\ +) 110 \\ \hline \boxed{1}101 \end{array}$$

→
Truncate

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Is This Signed Addition an Overflow?

$$\begin{array}{r} 111 \\ +) 110 \\ \hline \boxed{1}101 \end{array}$$



Truncate

$$\begin{array}{r} -1 \\ +) -2 \\ \hline -3 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

Is This Signed Addition an Overflow?

$$\begin{array}{r} 111 \\ +) 110 \\ \hline \boxed{1}101 \end{array} \quad \xrightarrow{\text{Truncate}} \quad \begin{array}{r} -1 \\ +) -2 \\ \hline -3 \end{array}$$

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

- This is not an overflow by definition

Is This Signed Addition an Overflow?

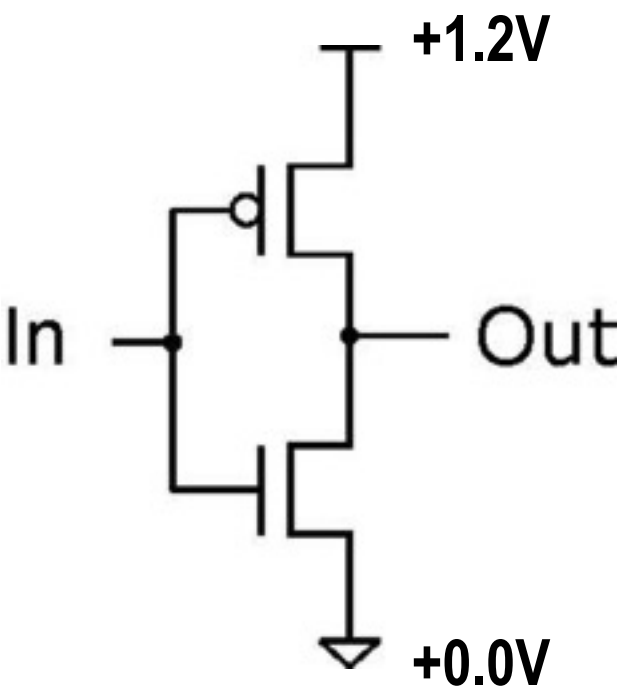
$$\begin{array}{r} 111 \\ +) 110 \\ \hline \boxed{1}101 \end{array} \quad \longrightarrow \quad \begin{array}{r} -1 \\ +) -2 \\ \hline -3 \end{array}$$

Truncate

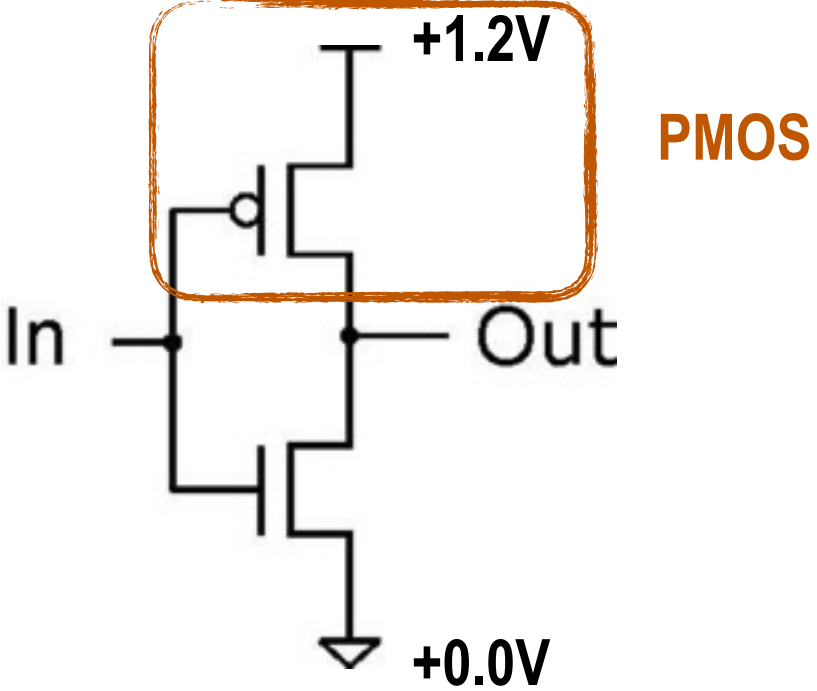
Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

- This is not an overflow by definition
- Because the actual result can be represented by the bit width of the datatype (3 bits here)

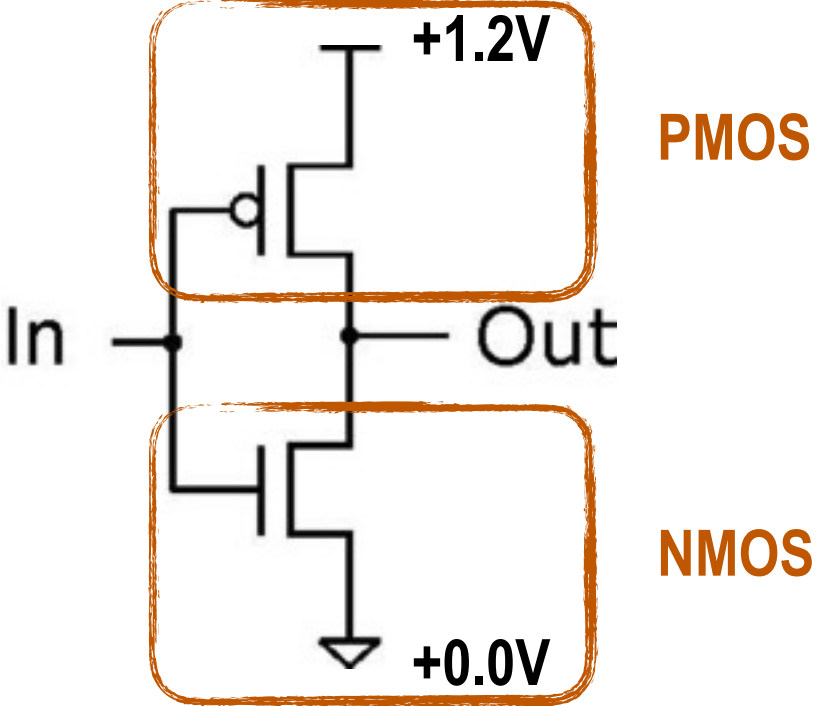
Inverter (NOT Gate)



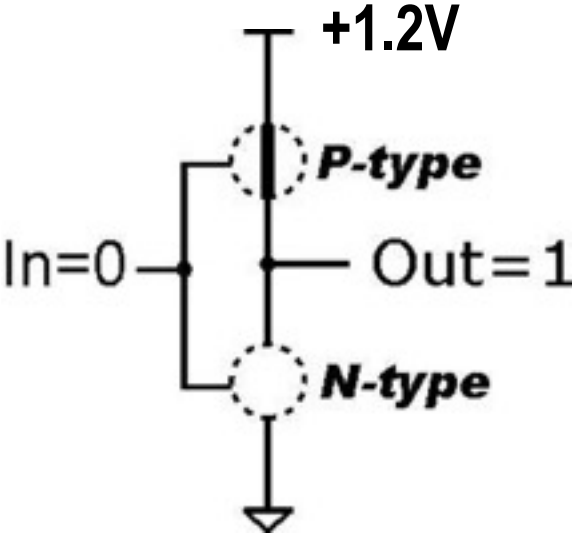
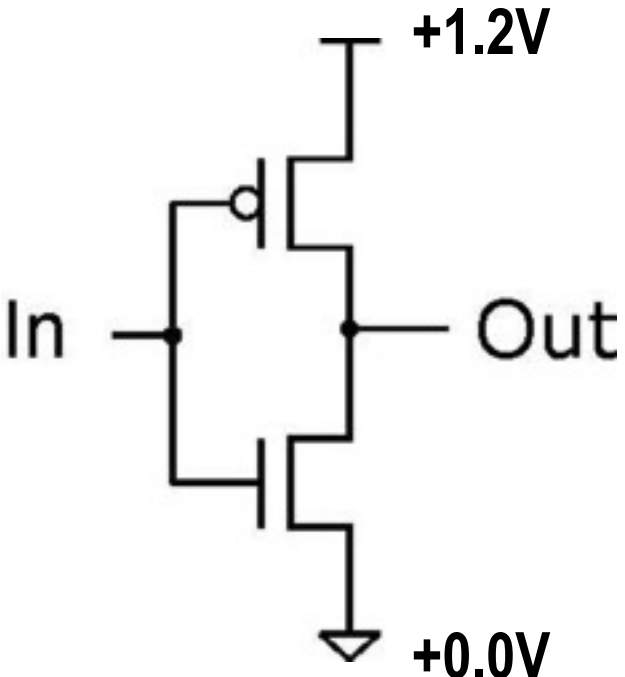
Inverter (NOT Gate)



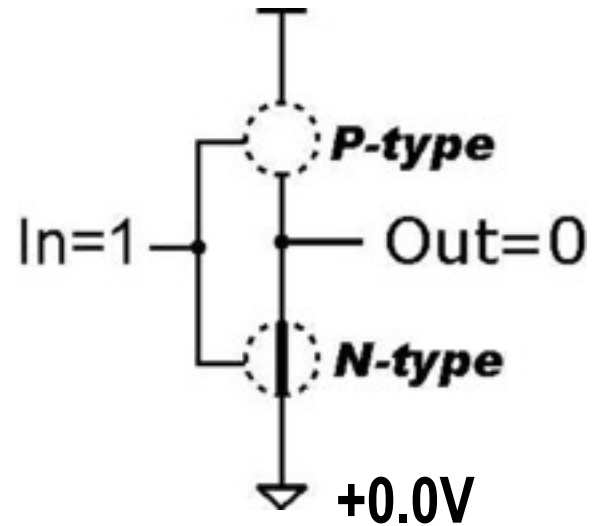
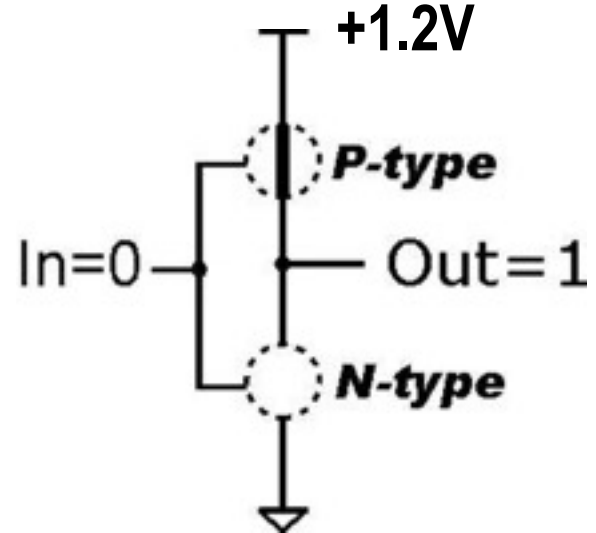
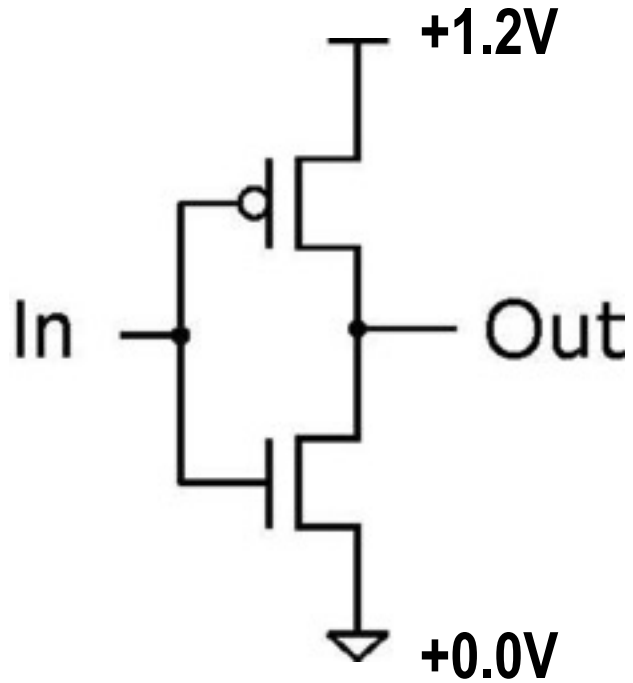
Inverter (NOT Gate)



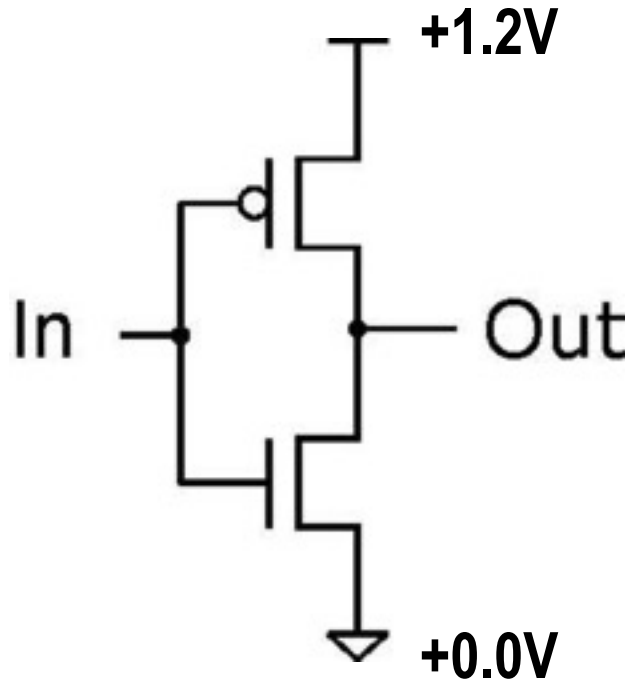
Inverter (NOT Gate)



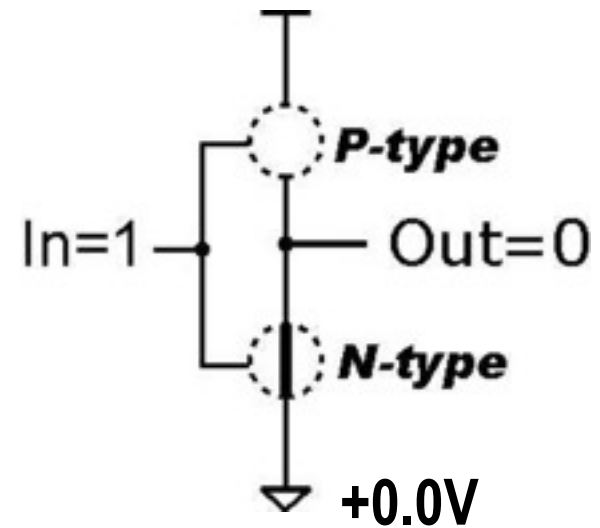
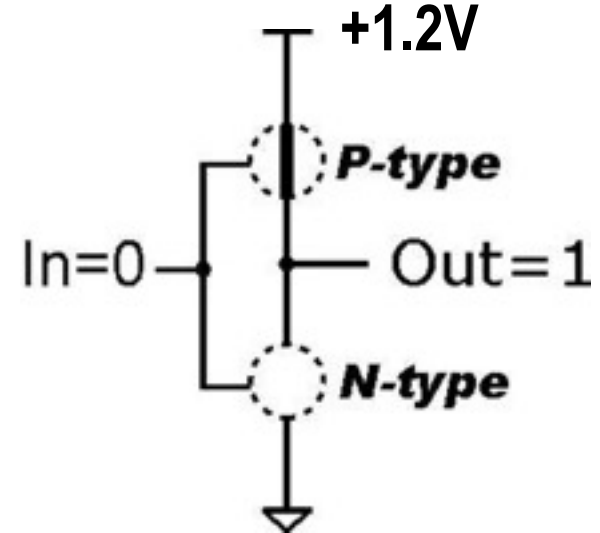
Inverter (NOT Gate)



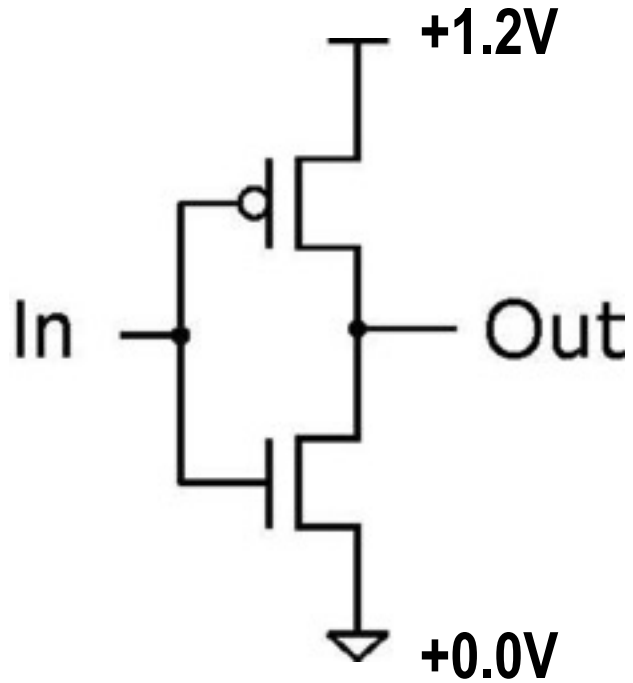
Inverter (NOT Gate)



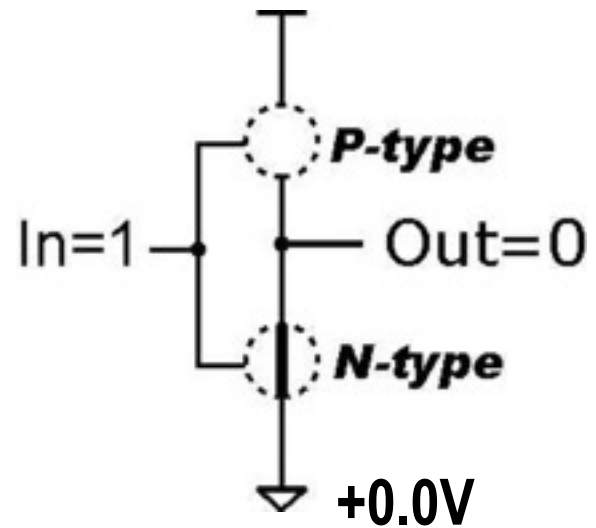
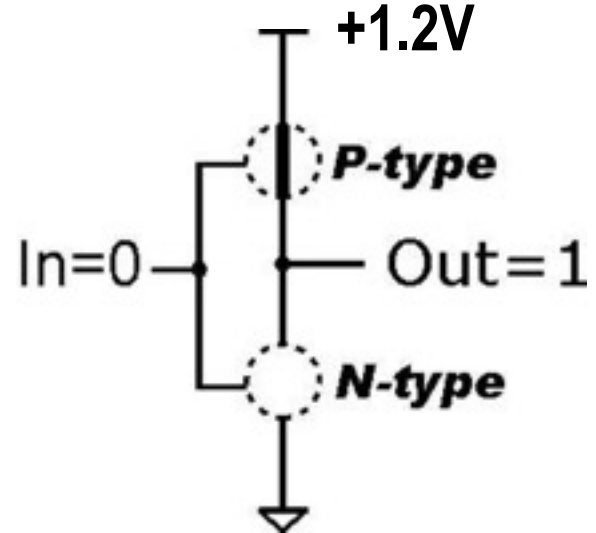
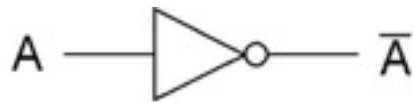
In	Out
0	1
1	0



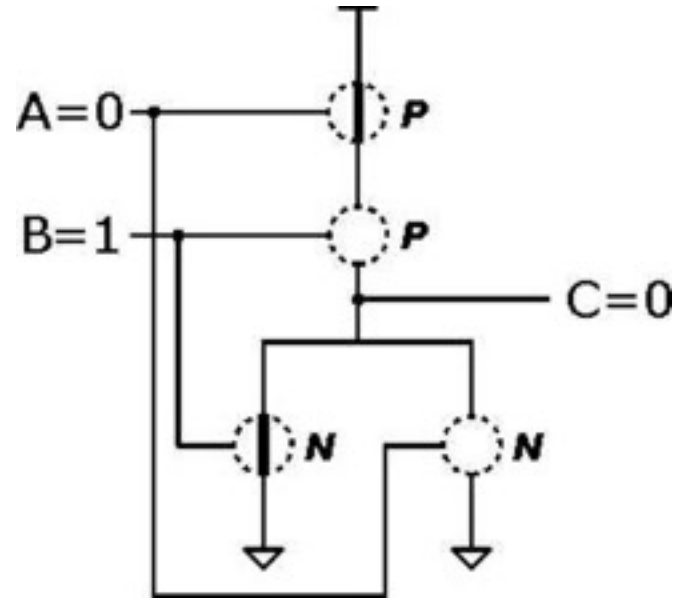
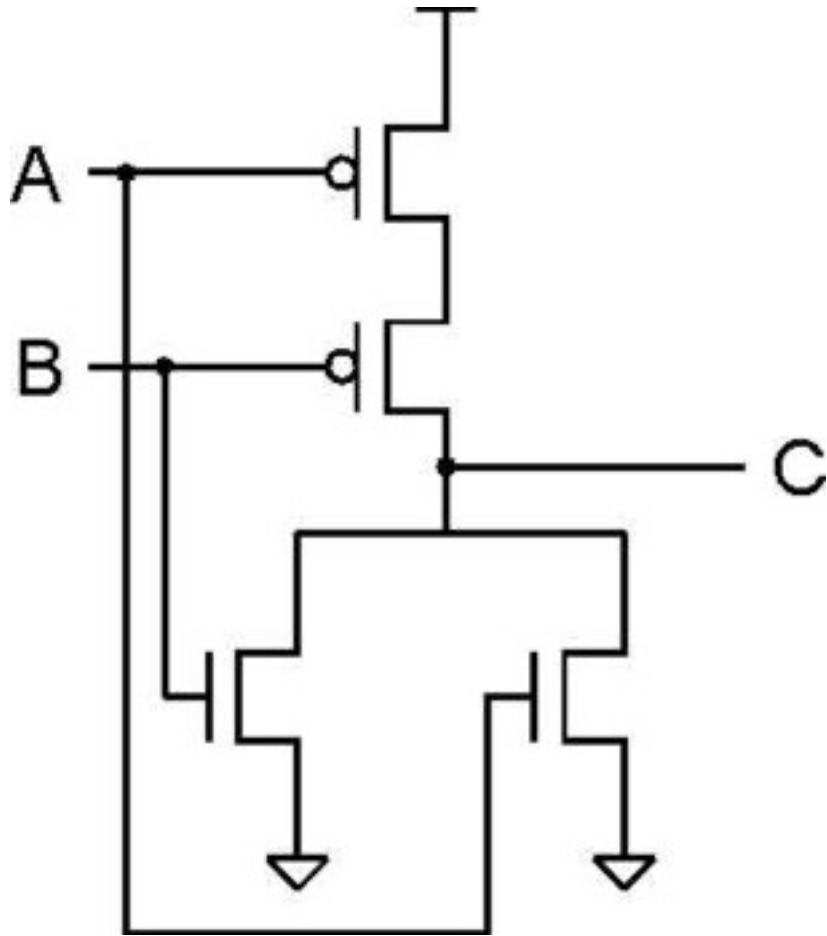
Inverter (NOT Gate)



In	Out
0	1
1	0



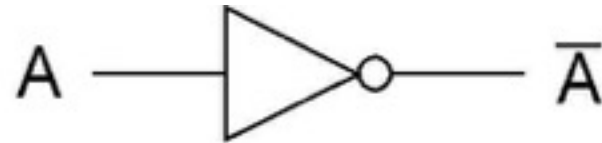
NOR Gate (NOT + OR)



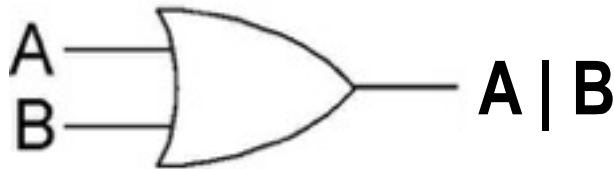
A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

Note: Serial structure on top, parallel on bottom.

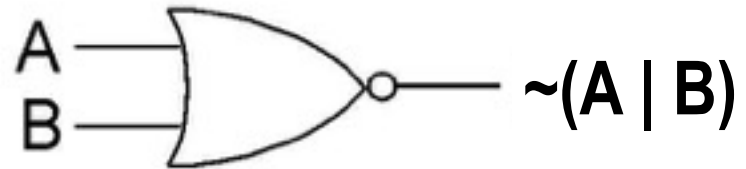
Basic Logic Gates



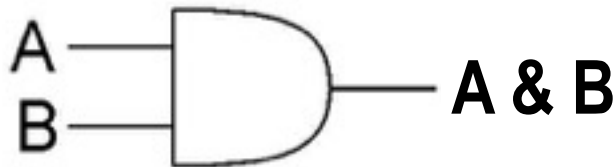
NOT



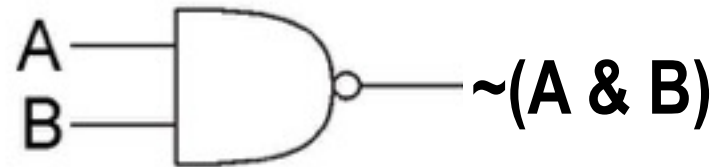
OR



NOR

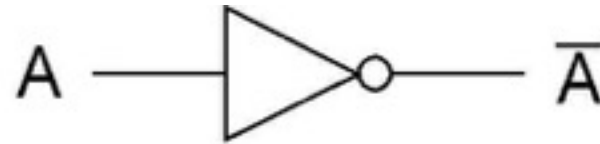


AND

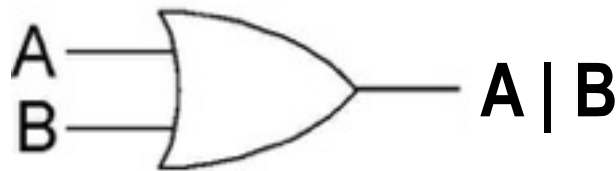


NAND

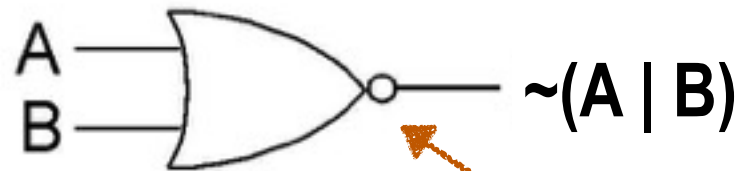
Basic Logic Gates



NOT

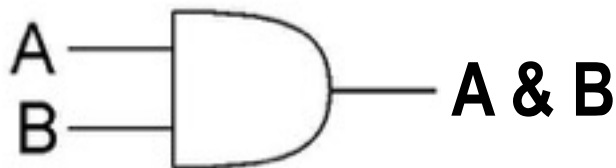


OR

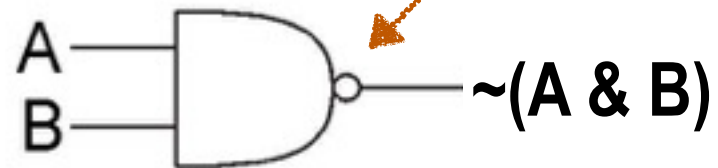


NOR

The little circle means NOT



AND



NAND

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

A	B	C_{in}	S	C_{ou} t
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

Truth Table

A	B	C_{in}	S	C_{ou} t
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

$$S = (\sim A \ \& \ \sim B \ \& \ C_{in})$$

Truth Table

A	B	C _{in}	S	C _{ou} t
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

$$S = (\sim A \& \sim B \& C_{in}) \\ | (\sim A \& B \& \sim C_{in})$$

Truth Table

A	B	C _{in}	S	C _{ou} t
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

$$\begin{aligned} S = & (\sim A \ \& \ \sim B \ \& \ C_{in}) \\ & | \ (\sim A \ \& \ B \ \& \ \sim C_{in}) \\ & | \ (A \ \& \ \sim B \ \& \ \sim C_{in}) \end{aligned}$$

Truth Table

A	B	C _{in}	S	C _{ou} t
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

$$\begin{aligned} S = & (\sim A \ \& \ \sim B \ \& \ C_{in}) \\ & | (\sim A \ \& \ B \ \& \ \sim C_{in}) \\ & | (A \ \& \ \sim B \ \& \ \sim C_{in}) \\ & | (A \ \& \ B \ \& \ C_{in}) \end{aligned}$$

Truth Table

A	B	C _{in}	S	C _{ou} t
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Full (1-bit) Adder

Truth Table

Add two bits and carry-in,
produce one-bit sum and carry-out.

$$\begin{aligned} S = & (\sim A \ \& \ \sim B \ \& \ C_{in}) \\ & | (\sim A \ \& \ B \ \& \ \sim C_{in}) \\ & | (A \ \& \ \sim B \ \& \ \sim C_{in}) \\ & | (A \ \& \ B \ \& \ C_{in}) \end{aligned}$$

$$\begin{aligned} C_{ou} = & (\sim A \ \& \ B \ \& \ C_{in}) \\ & | (A \ \& \ \sim B \ \& \ C_{in}) \\ & | (A \ \& \ B \ \& \ \sim C_{in}) \\ & | (A \ \& \ B \ \& \ C_{in}) \end{aligned}$$

A	B	C _{in}	S	C _{ou}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

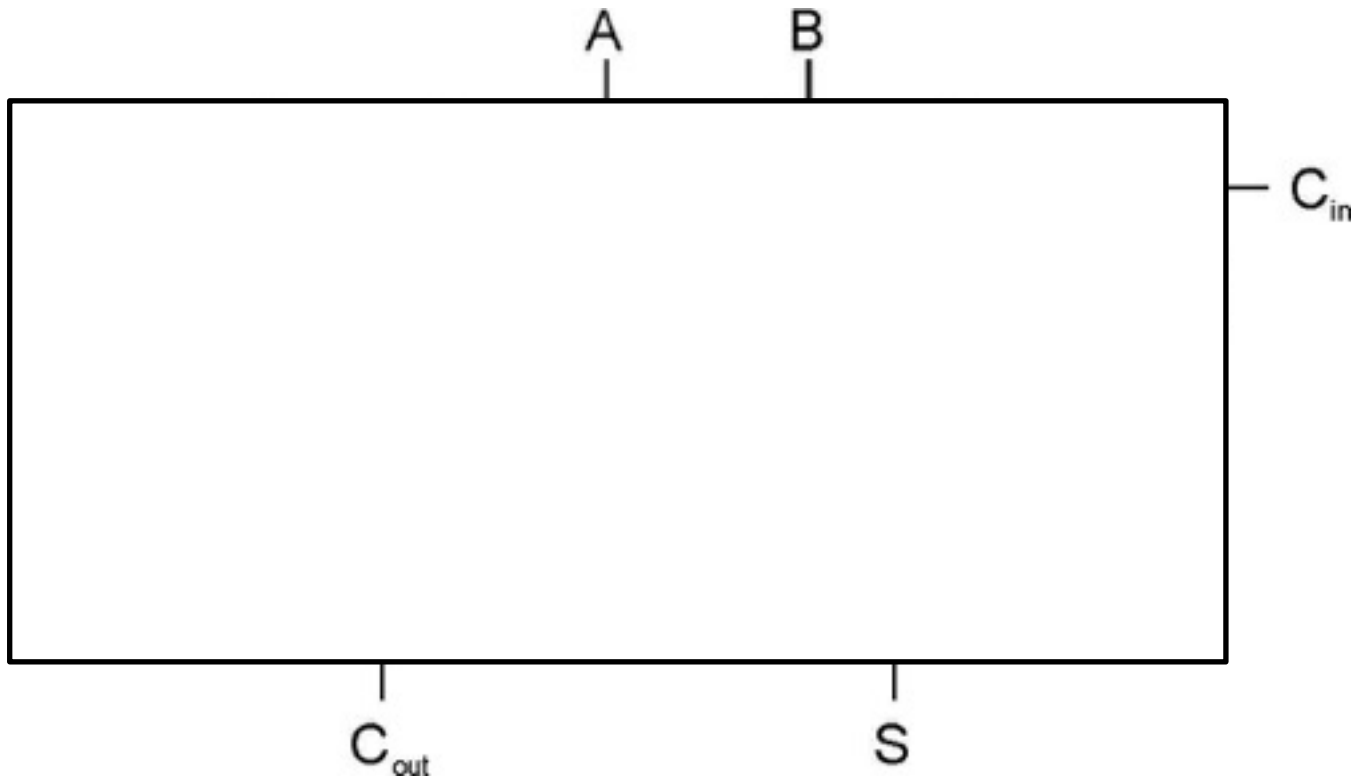
Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

$$\begin{aligned} C_{ou} = & (\sim A \& B \& C_{in}) \\ & | (A \& \sim B \& C_{in}) \\ & | (A \& B \& \sim C_{in}) \\ & | (A \& B \& C_{in}) \end{aligned}$$

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

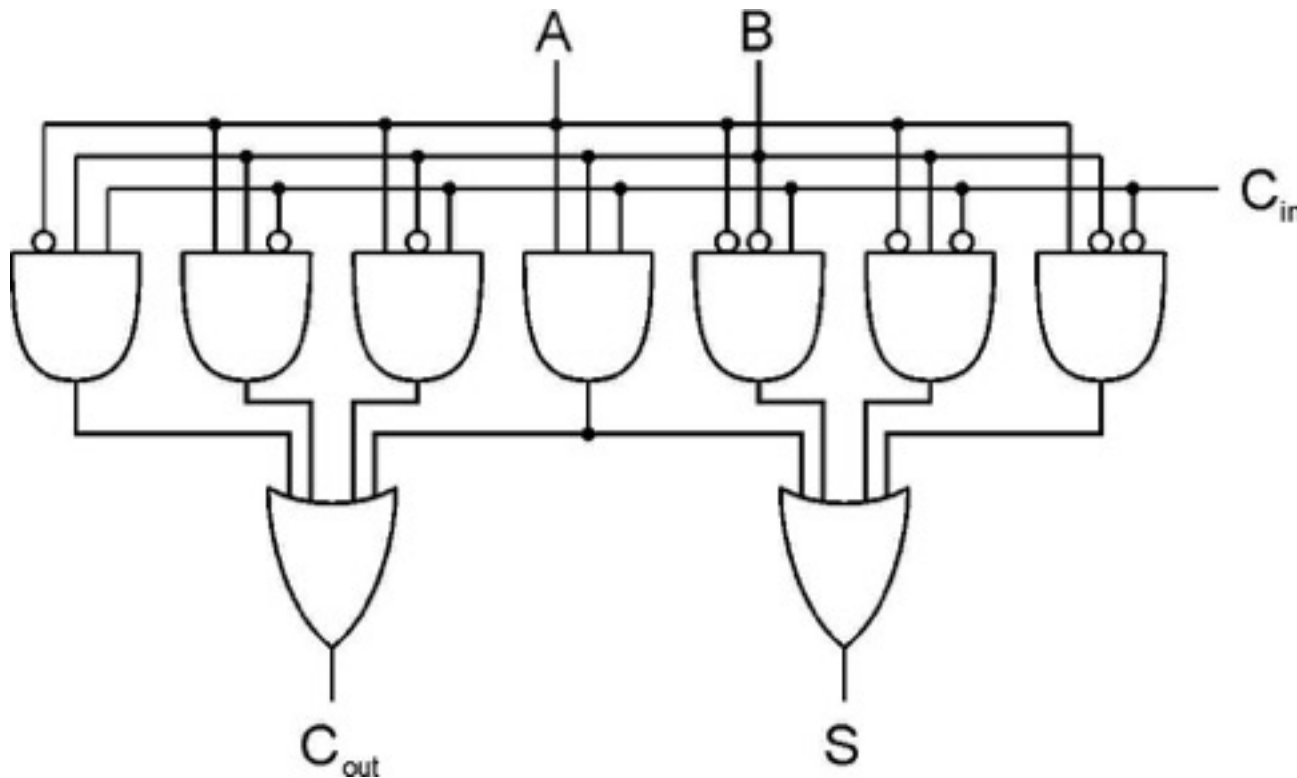


$$\begin{aligned} C_{ou} = & (\sim A \& B \& C_{in}) \\ & | (A \& \sim B \& C_{in}) \\ & | (A \& B \& \sim C_{in}) \\ & | (A \& B \& C_{in}) \end{aligned}$$

Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

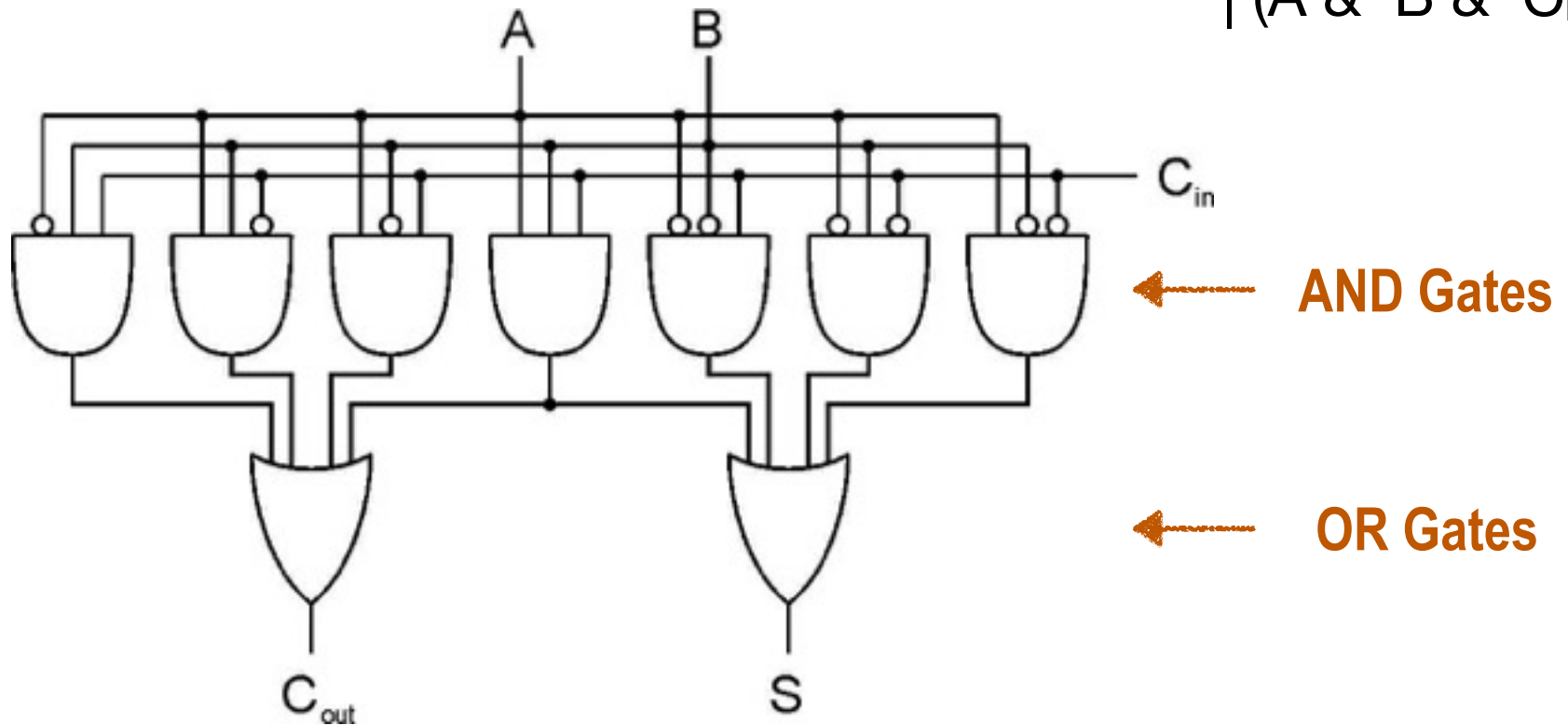
$$\begin{aligned} C_{ou} = & (\sim A \& B \& C_{in}) \\ & | (A \& \sim B \& C_{in}) \\ & | (A \& B \& \sim C_{in}) \\ & | (A \& B \& C_{in}) \end{aligned}$$



Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

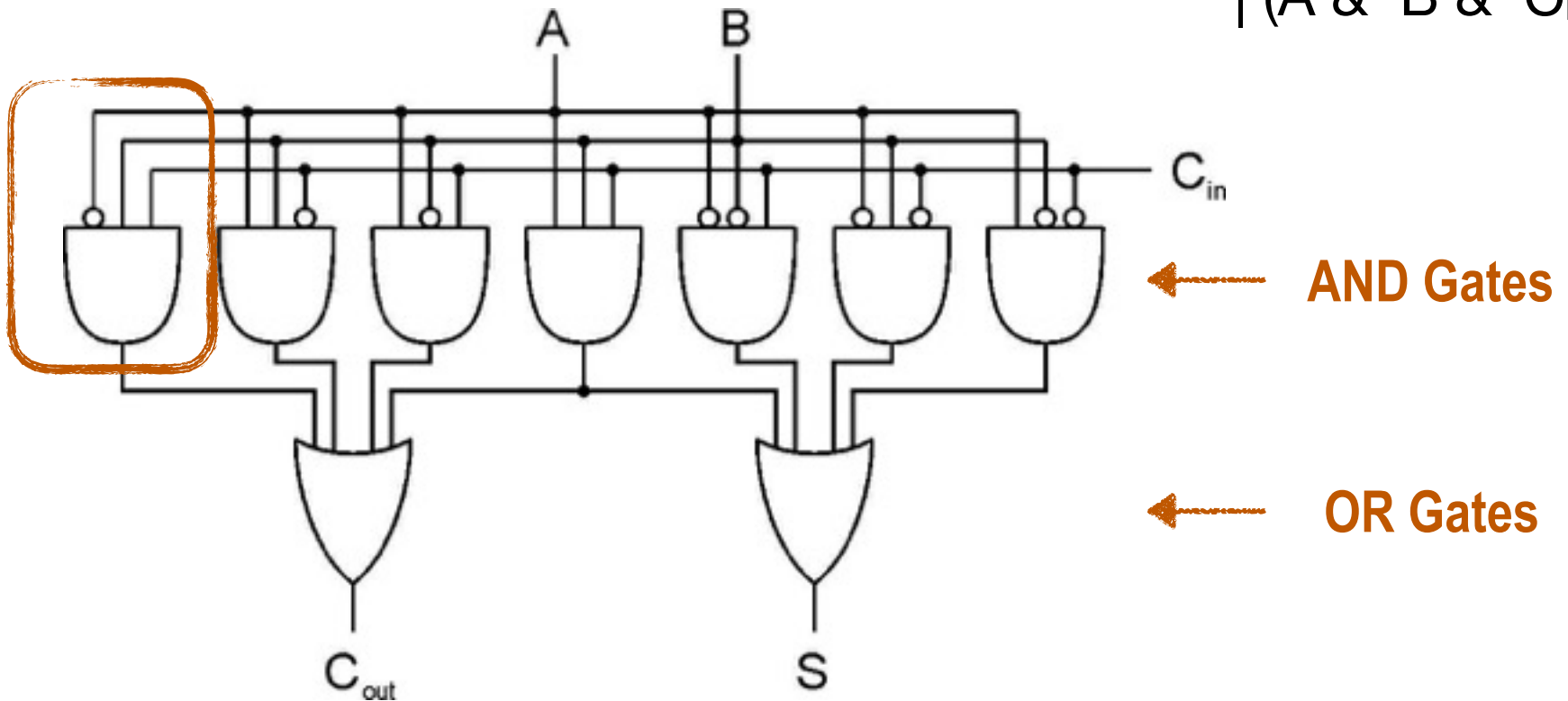
$$C_{ou} = (\sim A \& B \& C_{in}) \vee (A \& \sim B \& C_{in}) \vee (A \& B \& \sim C_{in}) \vee (A \& B \& C_{in})$$



Full (1-bit) Adder

Add two bits and carry-in,
produce one-bit sum and carry-out.

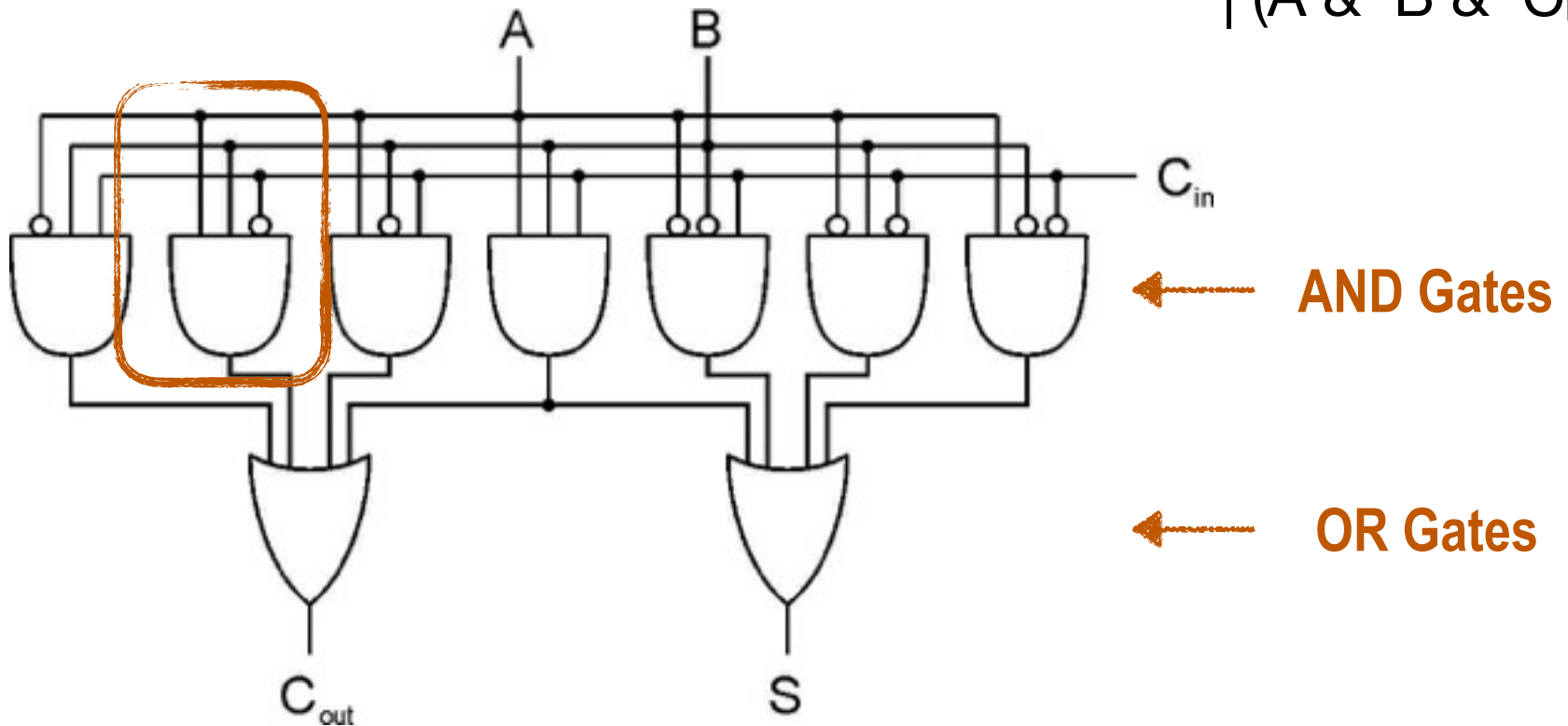
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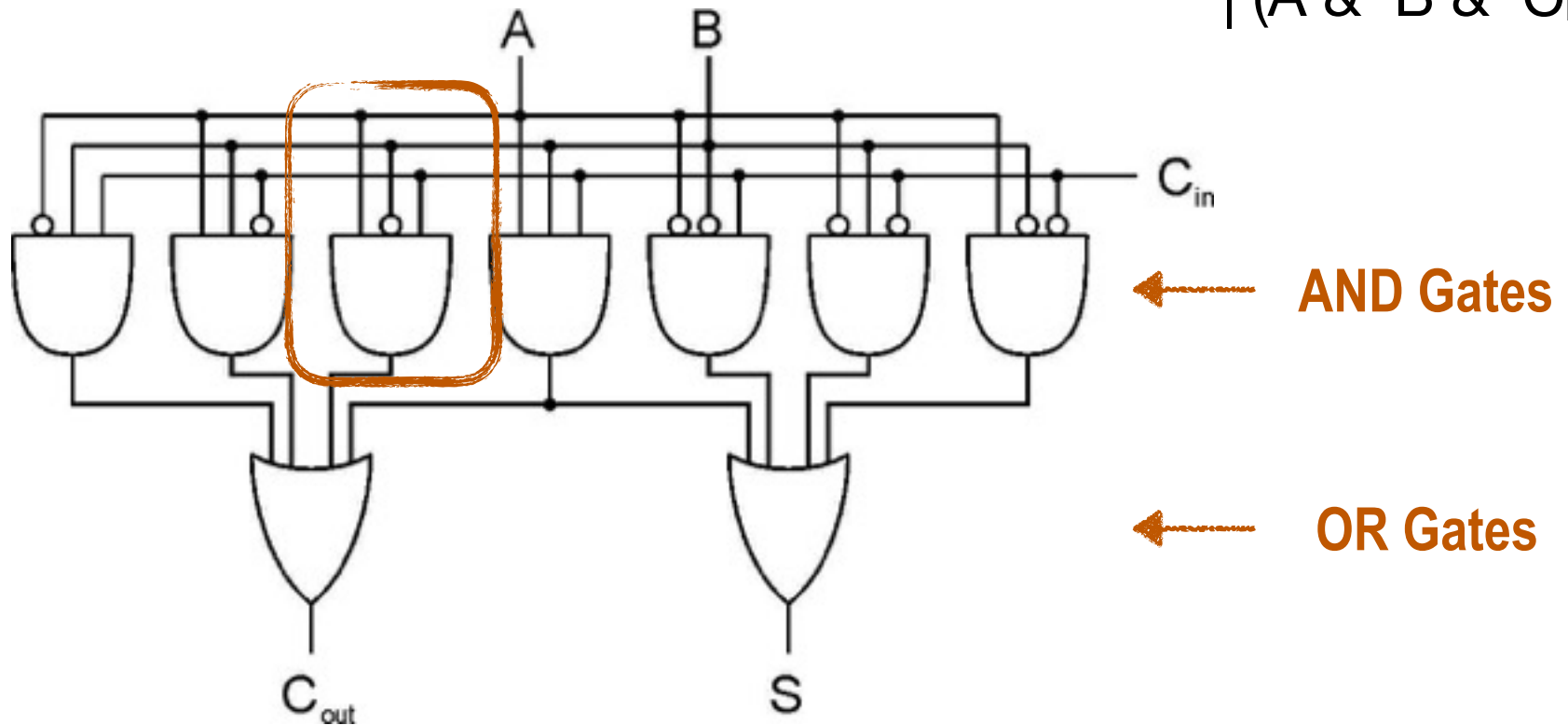
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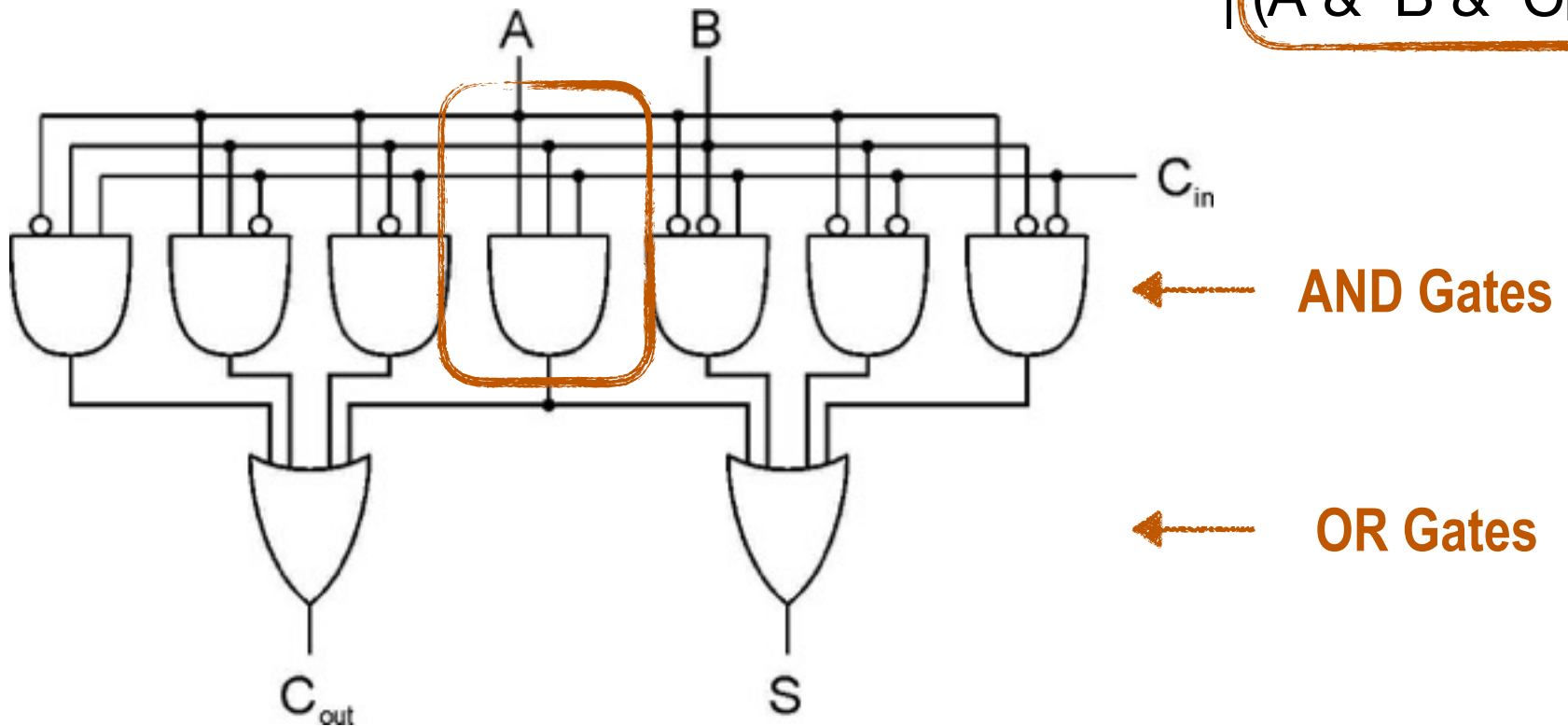
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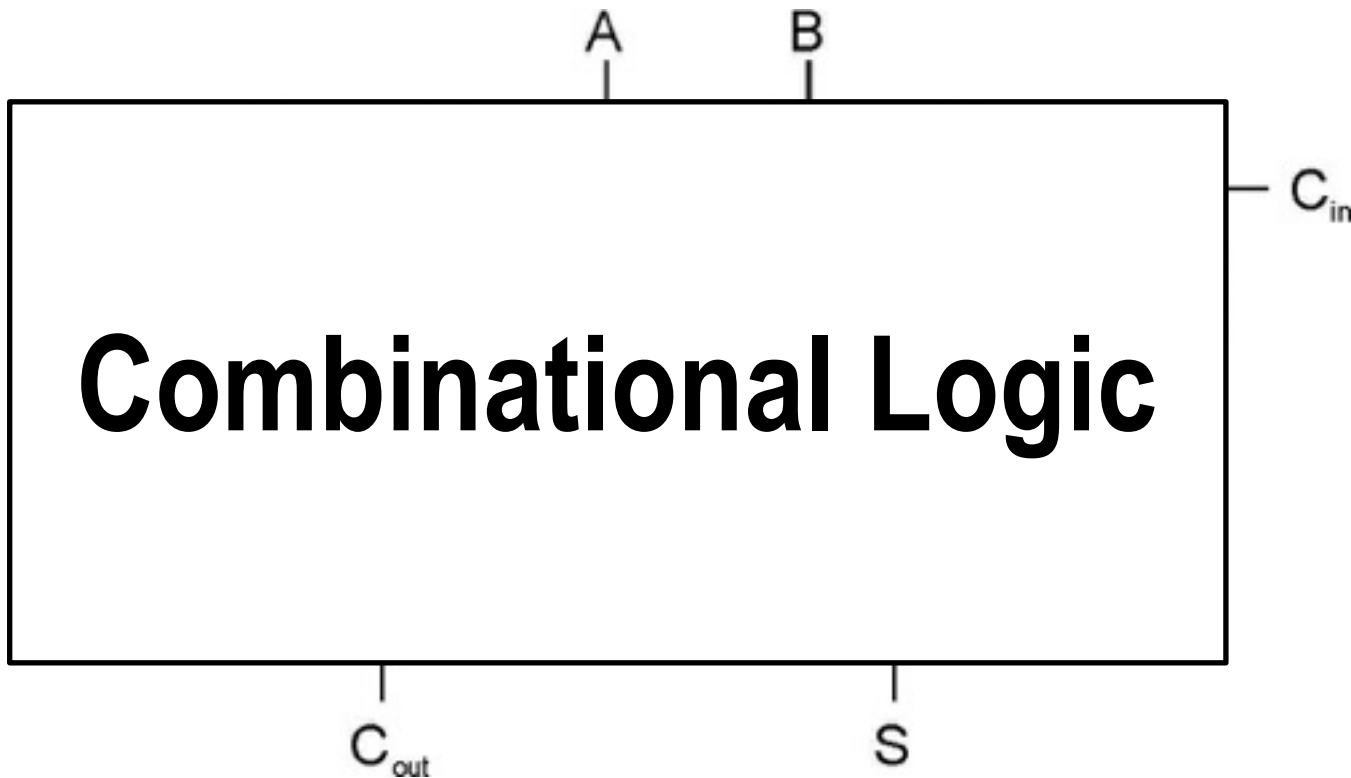
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$$\begin{aligned} C_{ou} = & (\sim A \& B \& C_{in}) \\ & | (A \& \sim B \& C_{in}) \\ & | (A \& B \& \sim C_{in}) \\ & | (A \& B \& C_{in}) \end{aligned}$$



Full (1-bit) Adder

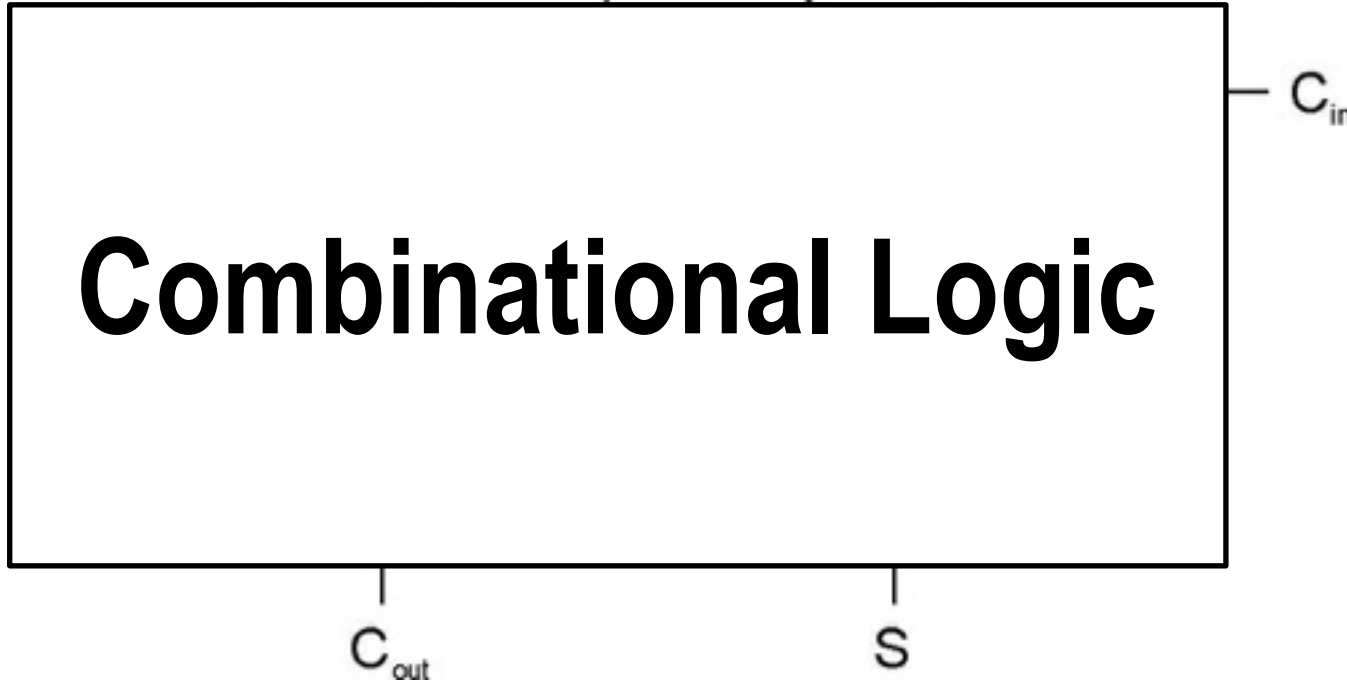
$$C_{ou} = (\sim A \& B \& C_{in})$$

$$| (A \& \sim B \& C_{in})$$

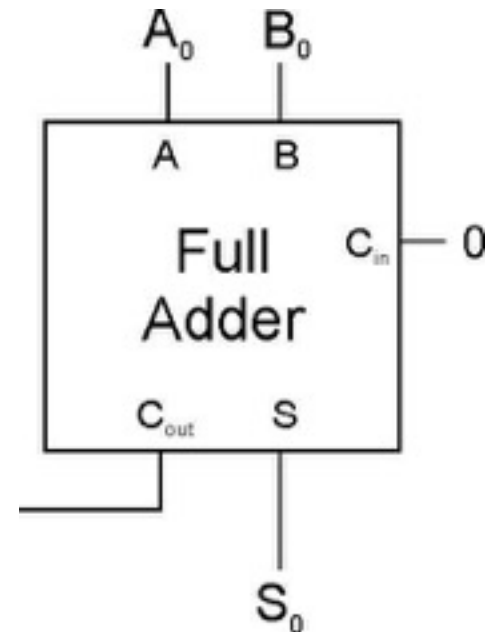
Outputs depend only on current inputs (i.e., not the past inputs), continuously (with some delay)

A B

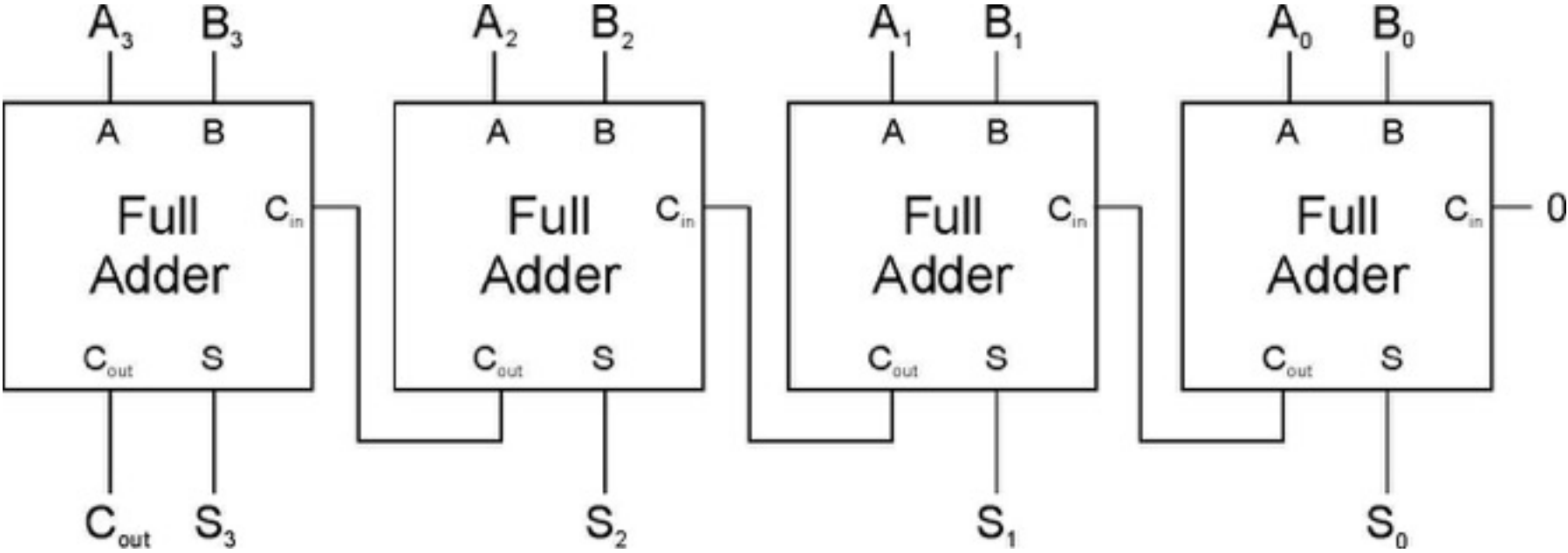
$$| (A \& B \& C_{in})$$



Four-bit Adder

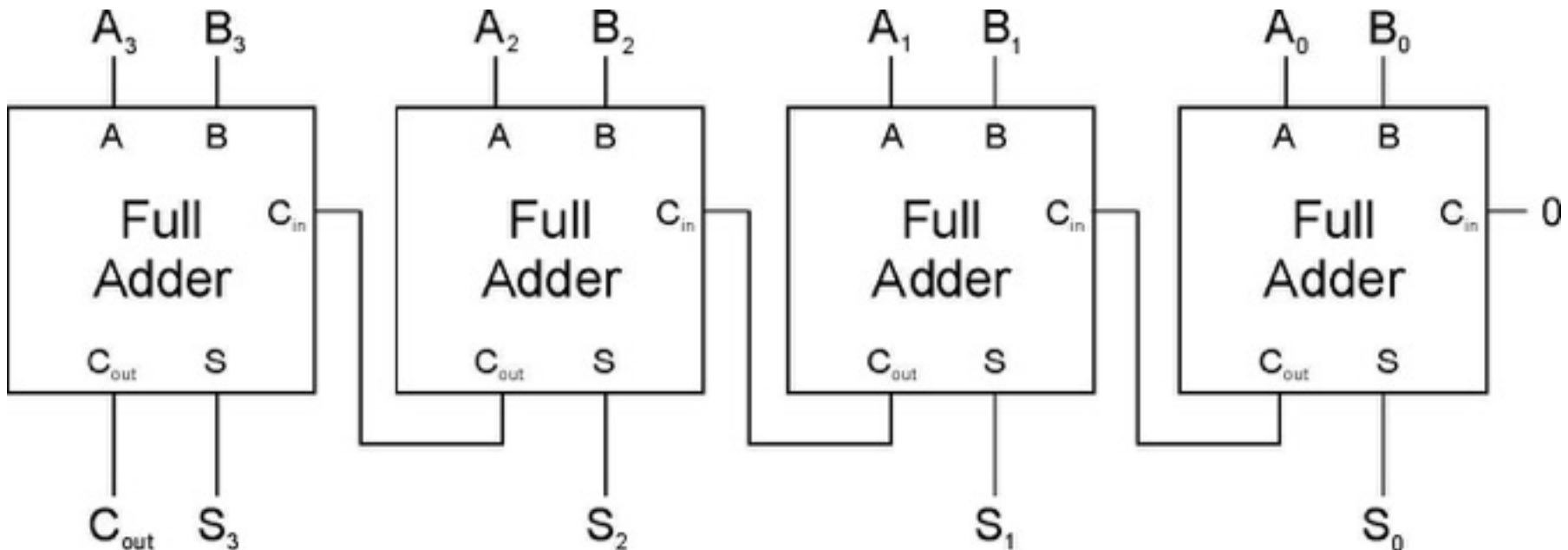


Four-bit Adder



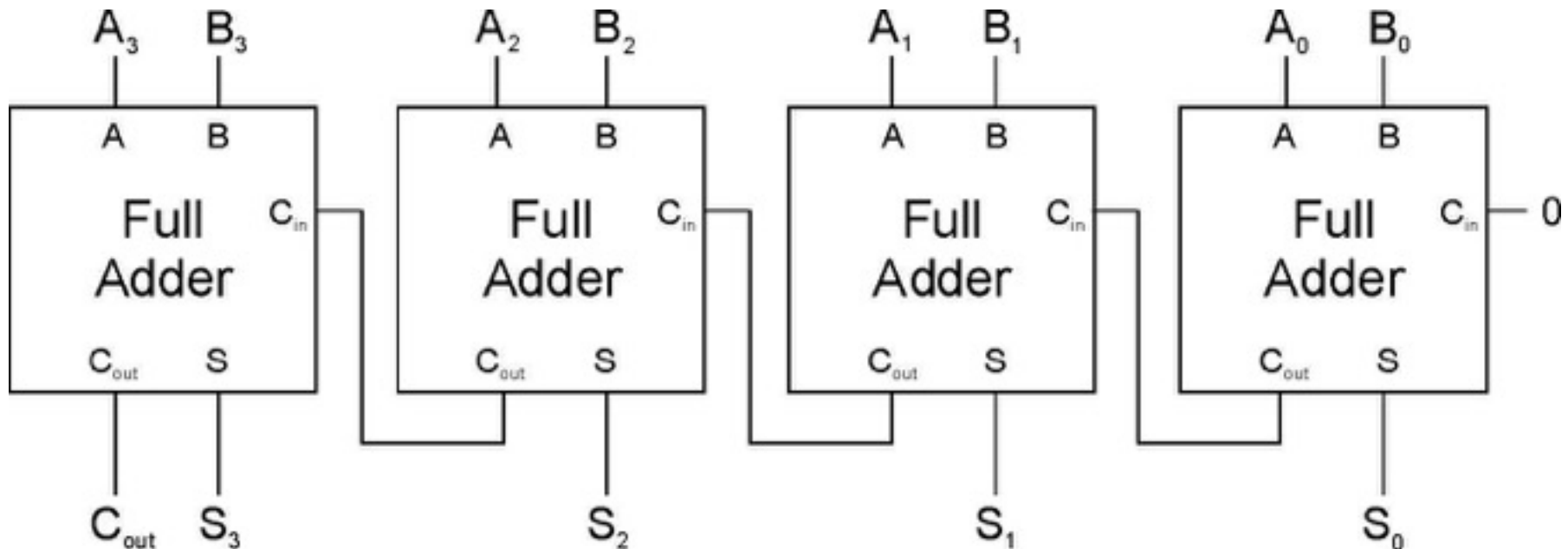
Four-bit Adder

- Ripple-carry Adder
 - Simple, but performance linear to bit width



Four-bit Adder

- Ripple-carry Adder
 - Simple, but performance linear to bit width
- Carry look-ahead adder (CLA)
 - Generate all carriers simultaneously



Logic Design

- Design digital components from basic logic gates

Logic Design

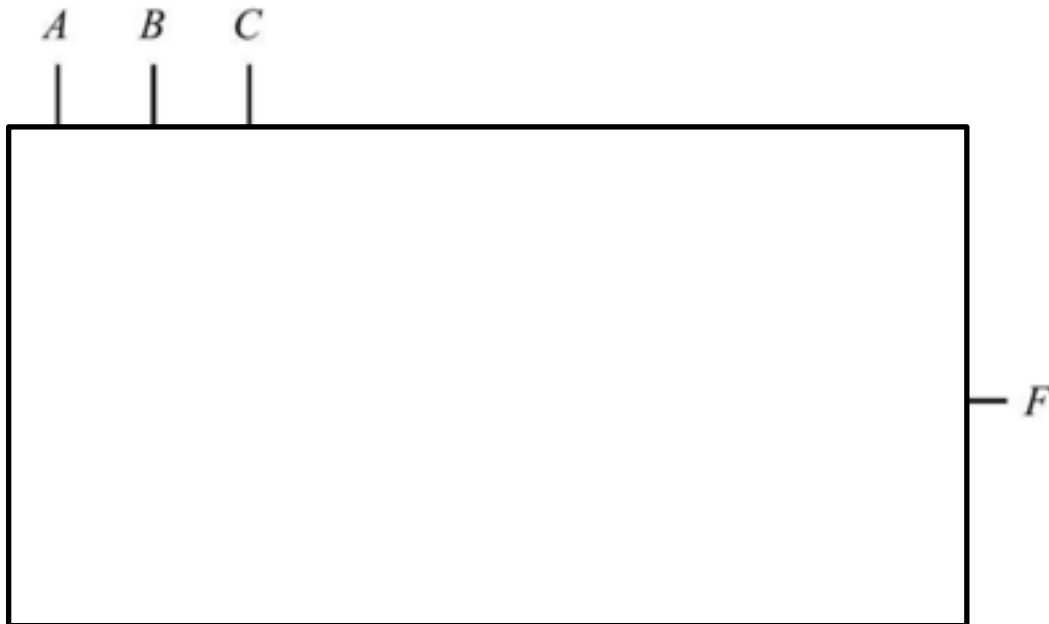
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Logic Design

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- Example: how to design a piece of circuit that does majority vote?

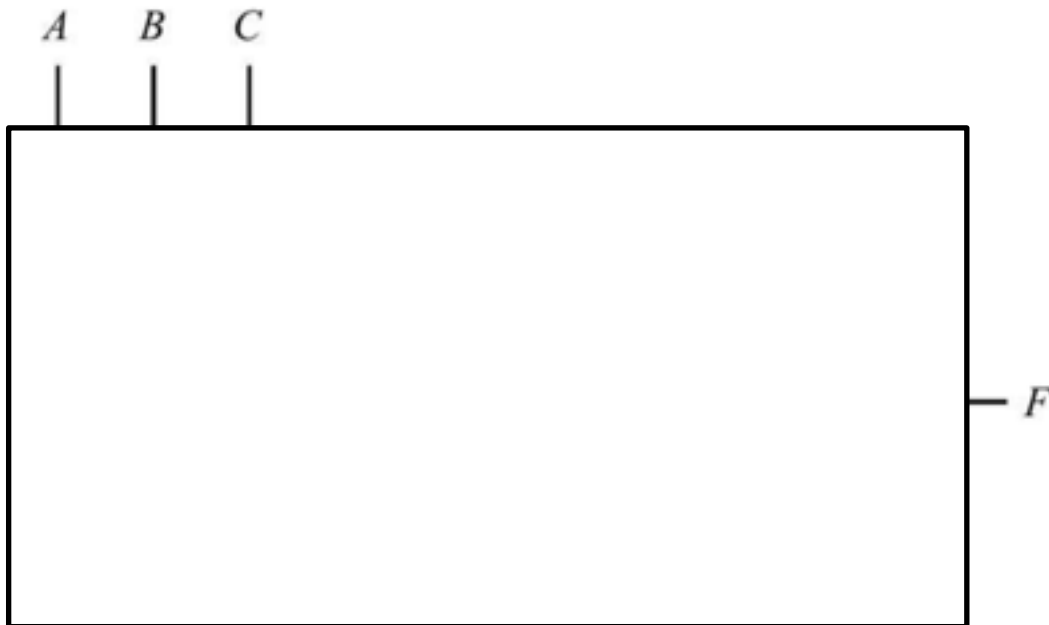
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Logic Design

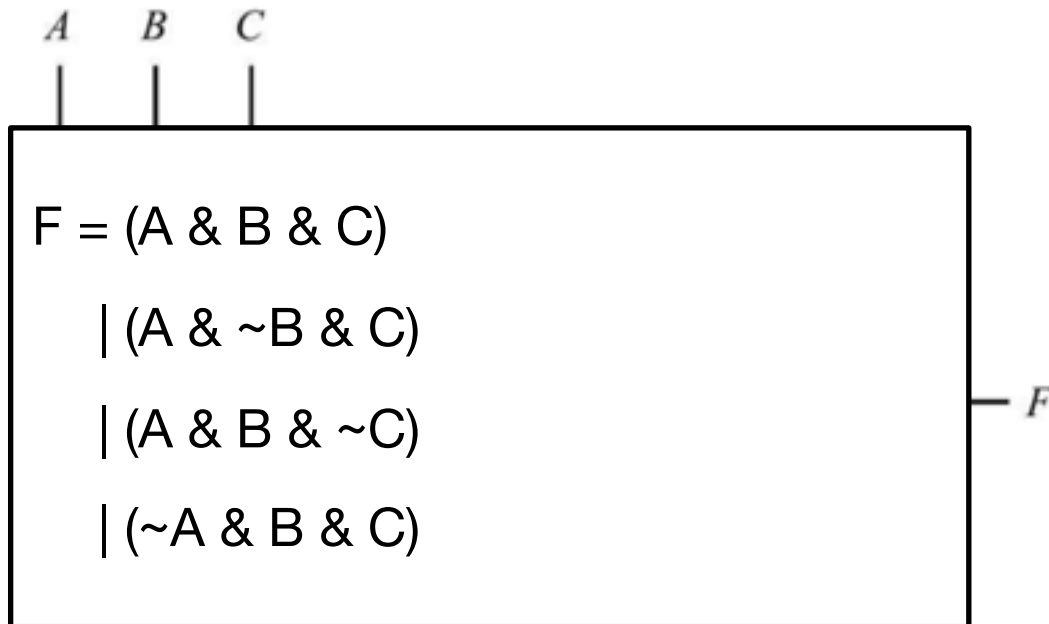
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- Example: how to design a piece of circuit that does majority vote?



A	B	C	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	1
1	1	1	1

Logic Design

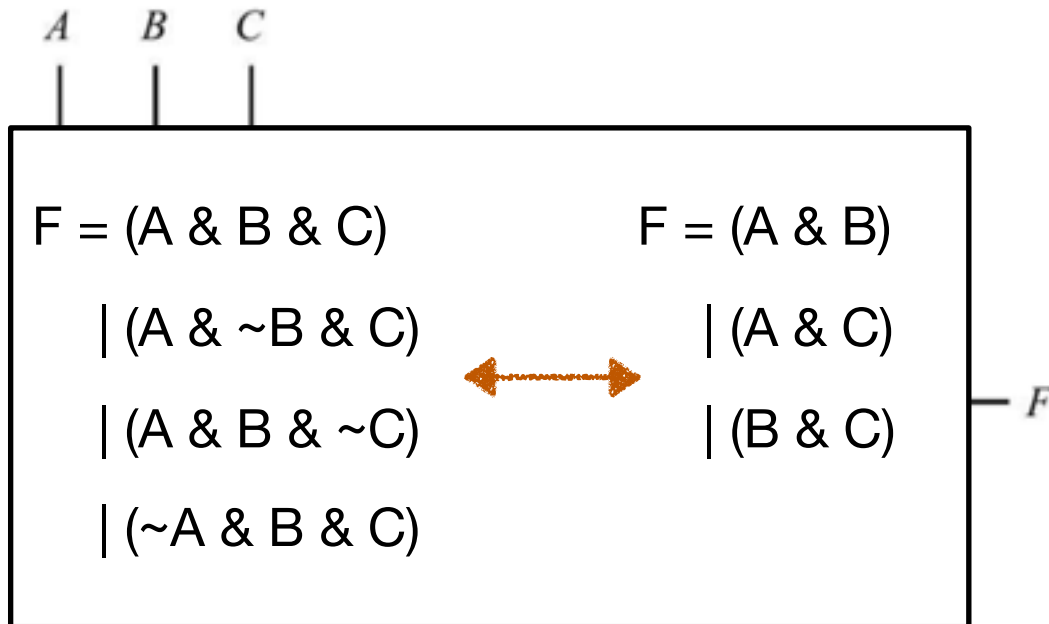
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Logic Design

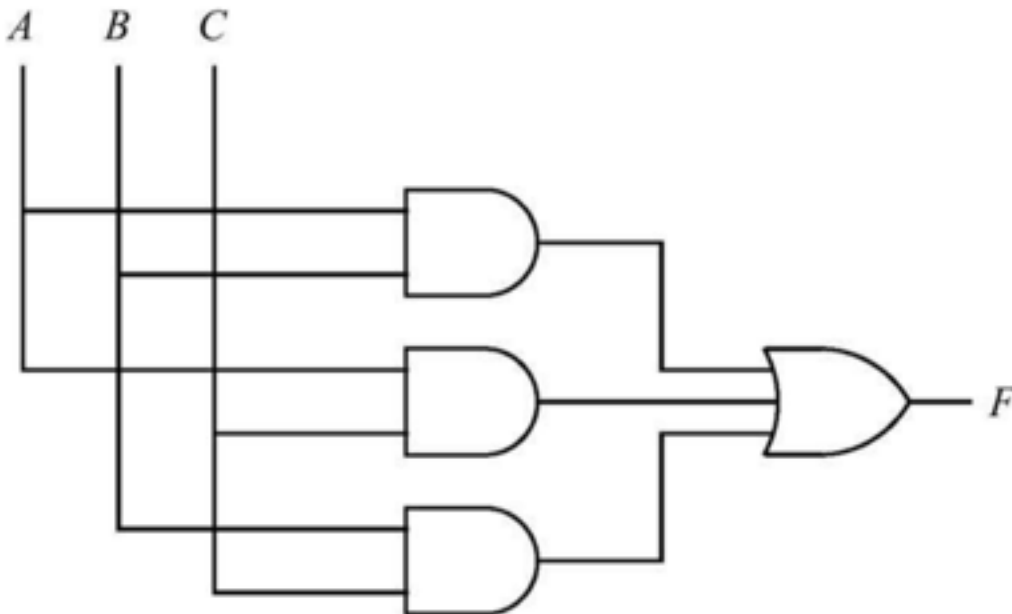
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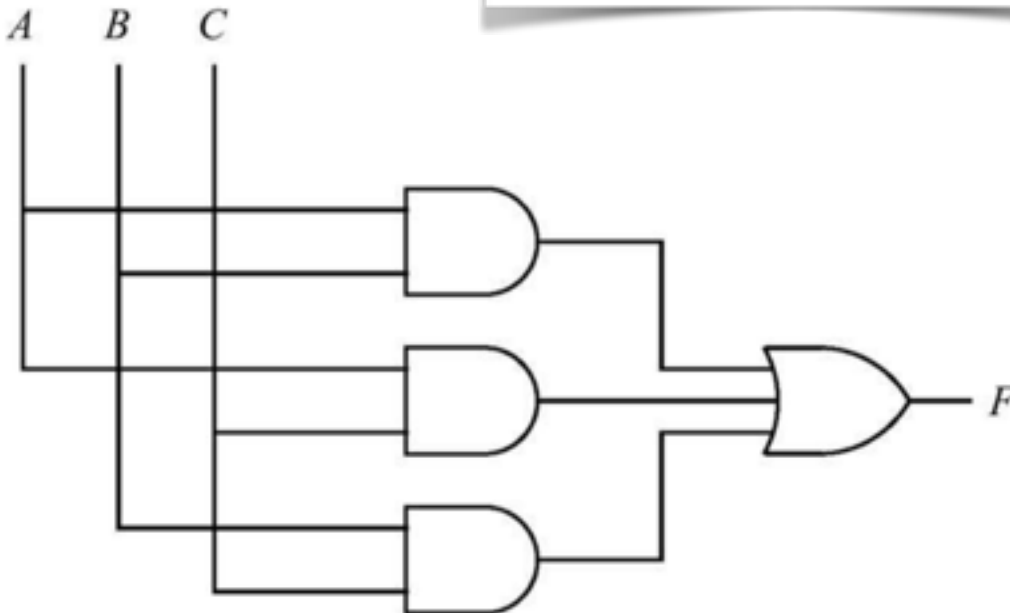


A	B	C	F
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1	0	1	1
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ECE112 Logic Design



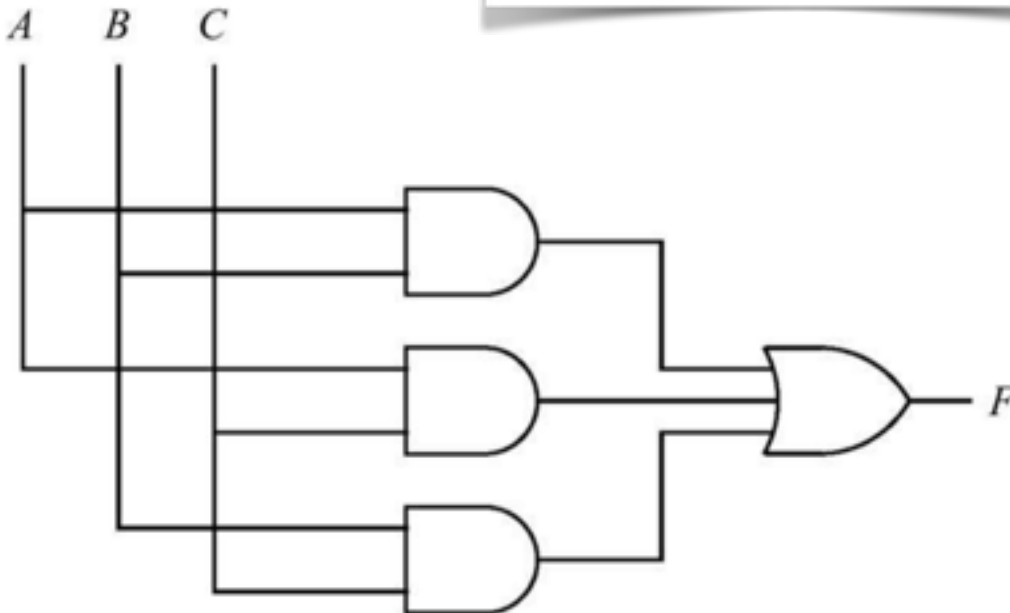
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Logic Design

Questions?

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ECE112 Logic Design



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0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
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Multiplication

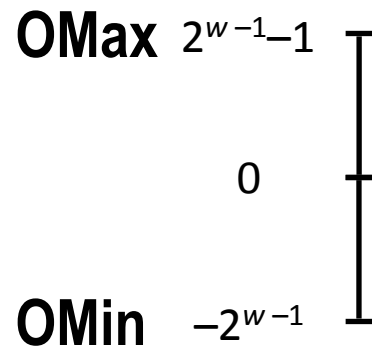
Multiplication

- Goal: Computing Product of w -bit numbers x, y

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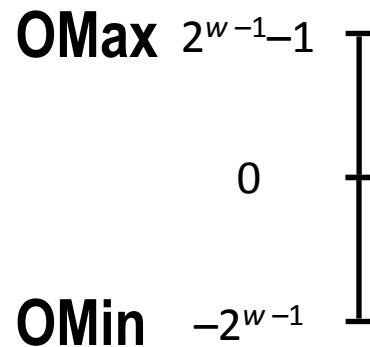
Original Number (w bits)



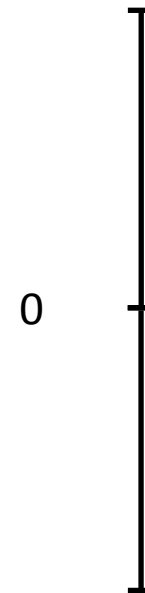
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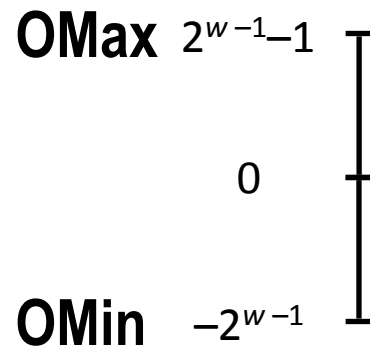
Product



Multiplication

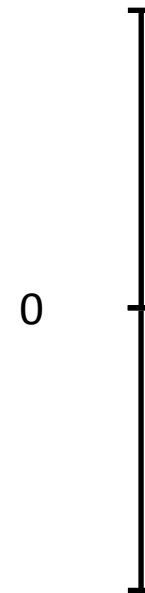
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Product

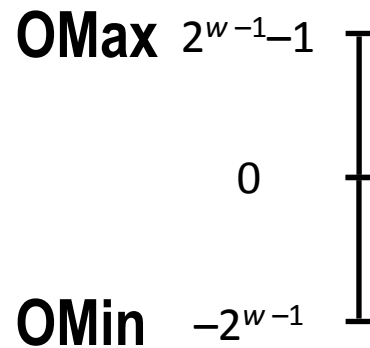
PMax



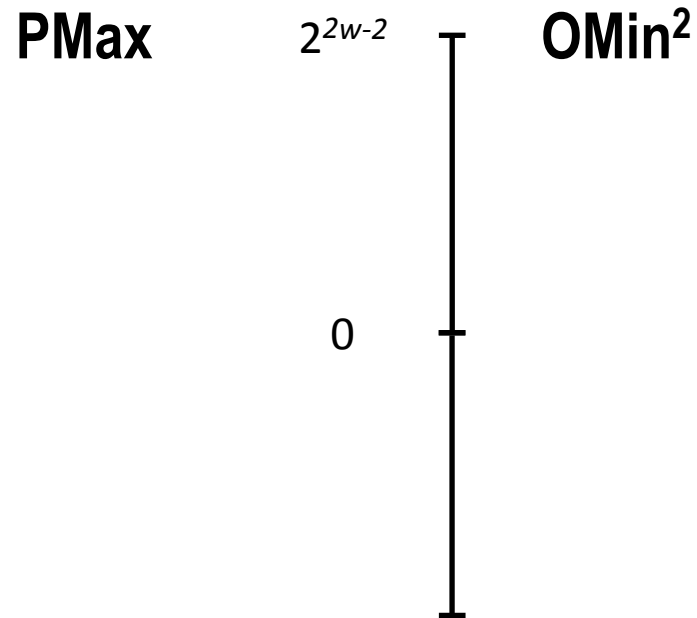
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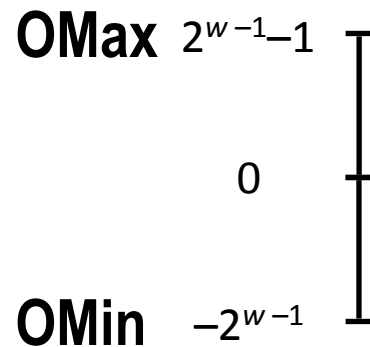
Product



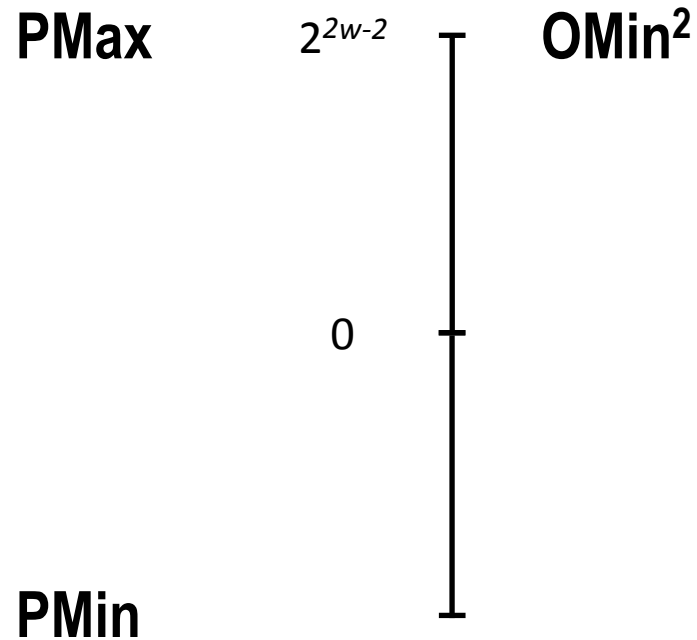
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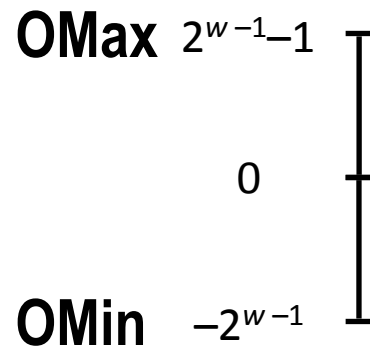
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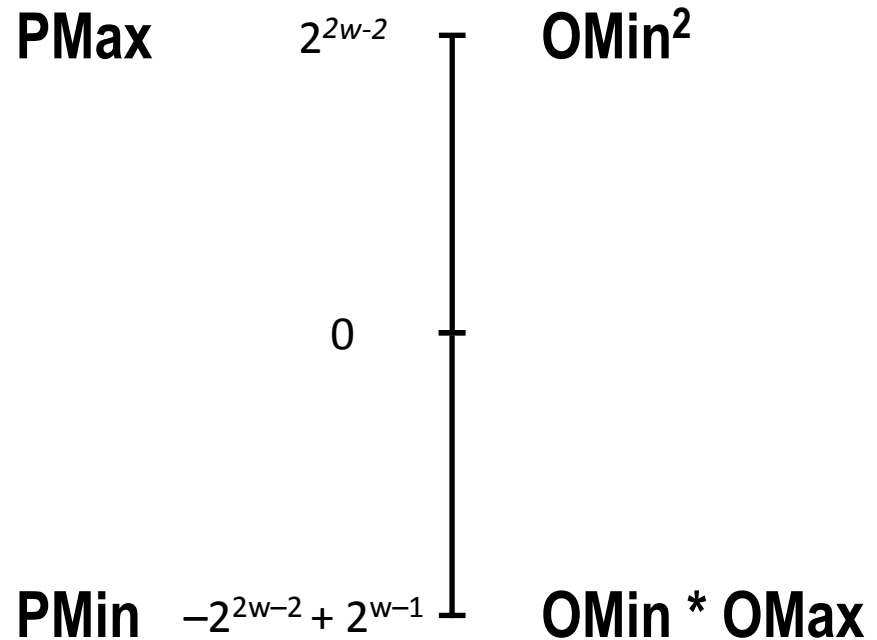
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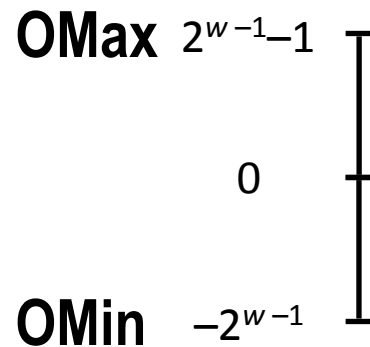
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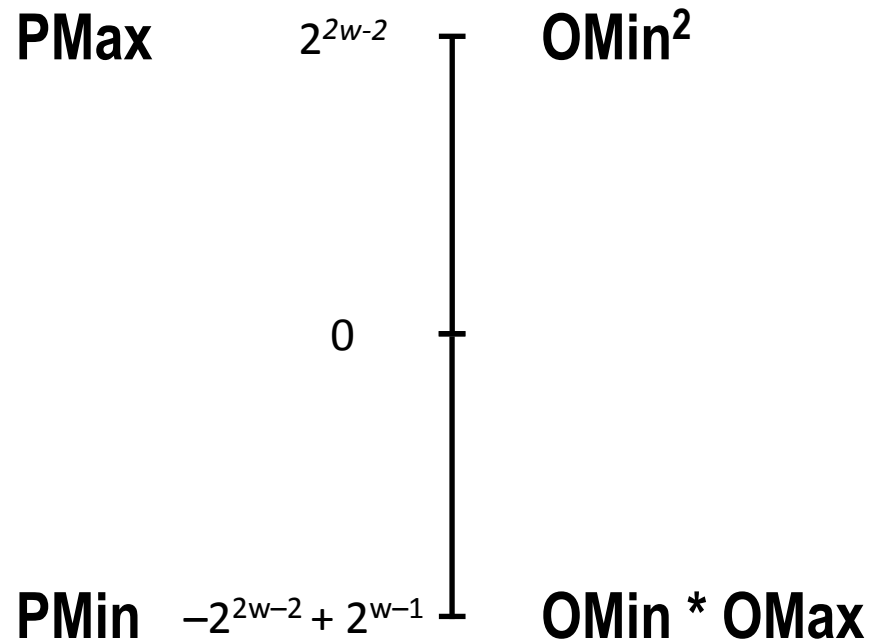
Multiplication

- Goal: Computing Product of w -bit numbers x, y

Original Number (w bits)



Product ($2w$ bits)

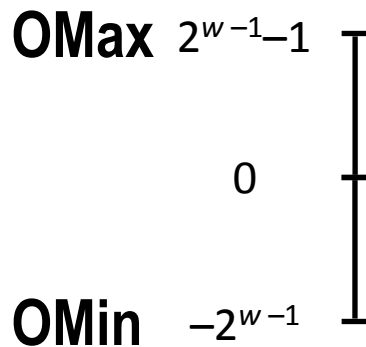


Multiplication

- Goal: Computing Product of w -bit numbers x, y
- Exact results can be bigger than w bits
 - Up to $2w$ bits (both signed and unsigned)

Original Number (w bits)

Product ($2w$ bits)



PMax

2^{2w-2}

OMin²

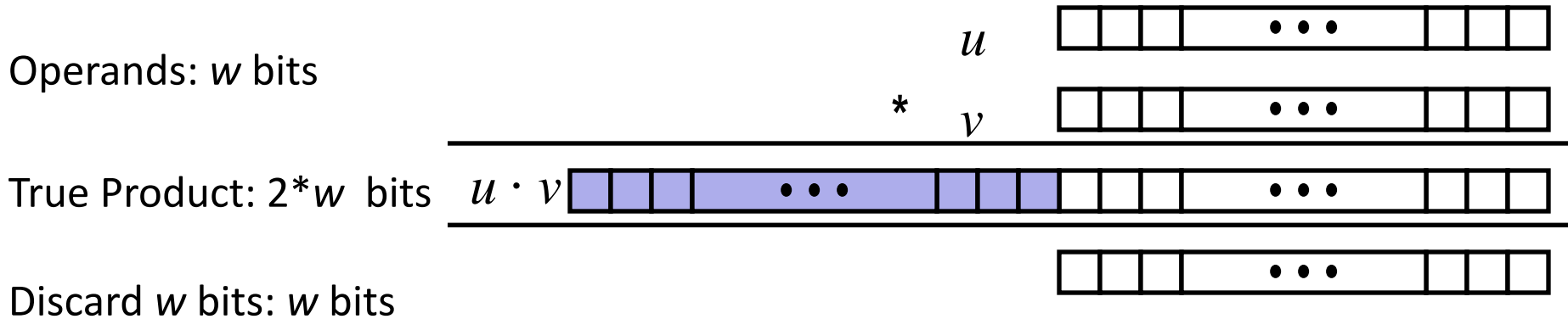
0

PMin

$-2^{2w-2} + 2^{w-1}$

OMin * OMax

Unsigned Multiplication in C



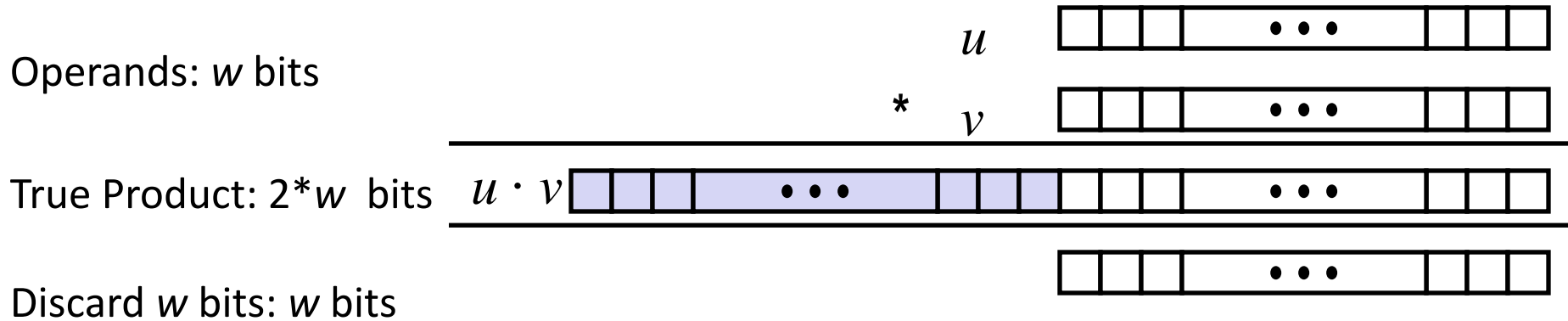
- Standard Multiplication Function

- Ignores high order w bits

- Implements Modular Arithmetic

$$\text{UMult}_w(u, v) = u \cdot v \bmod 2^w$$

Signed Multiplication in C



- Standard Multiplication Function

- Ignores high order w bits
- Some of which are different for signed vs. unsigned multiplication
- Lower bits are the same

Power-of-2 Multiply with Shift

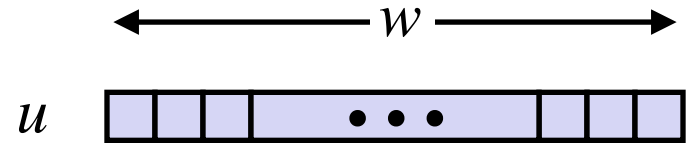
- Operation

- $u \ll k$ gives $u * 2^k$
- $001_2 \ll 2 = 100_2$ ($1 * 2^2 = 4$)
- Both signed and unsigned

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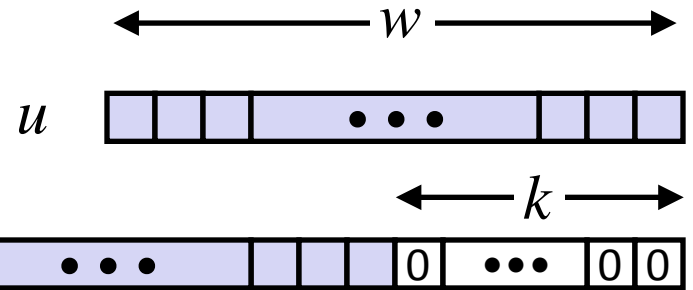
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True Product: $w+k$ bits

$$u \cdot 2^k$$



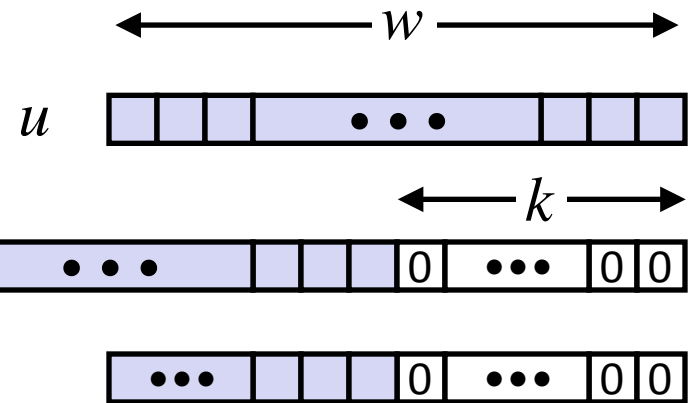
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Discard k bits (if overflow)



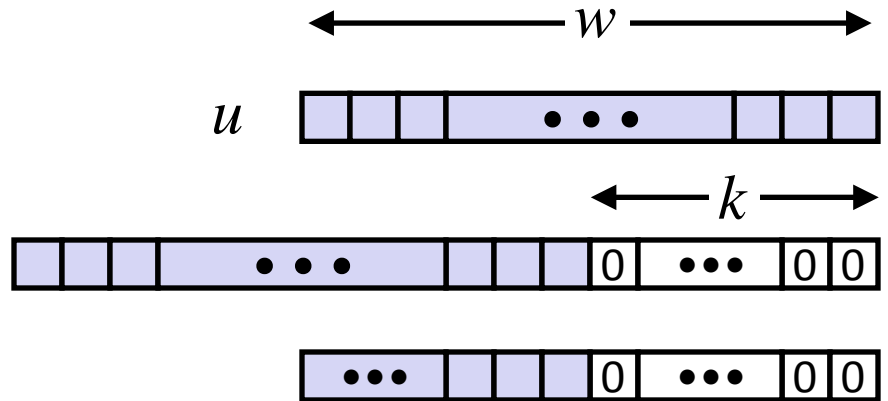
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- $001_2 \ll 2 = 100_2$ ($1 * 2^2 = 4$)
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$u \cdot 2^k$



Discard k bits (if overflow)

- Most machines shift and add faster than multiply

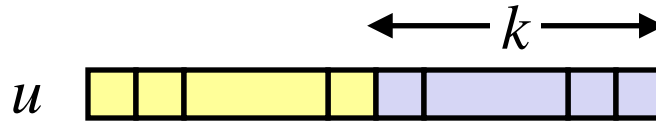
- Compiler generates this code automatically
- $u \ll 3 == u * 8$
- $(u \ll 5) - (u \ll 3) == u * 24$

Unsigned Power-of-2 Divide with Shift

- Implement power-of-2 divide with shift
 - $u \gg k$ gives $\lfloor u / 2^k \rfloor$ ($\lfloor 2.34 \rfloor = 2$)
 - Uses logical shift

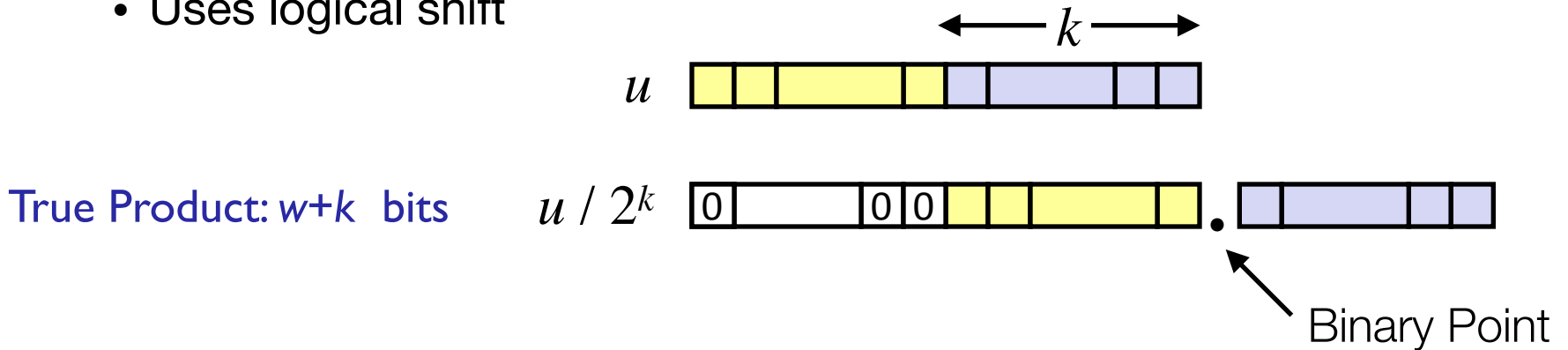
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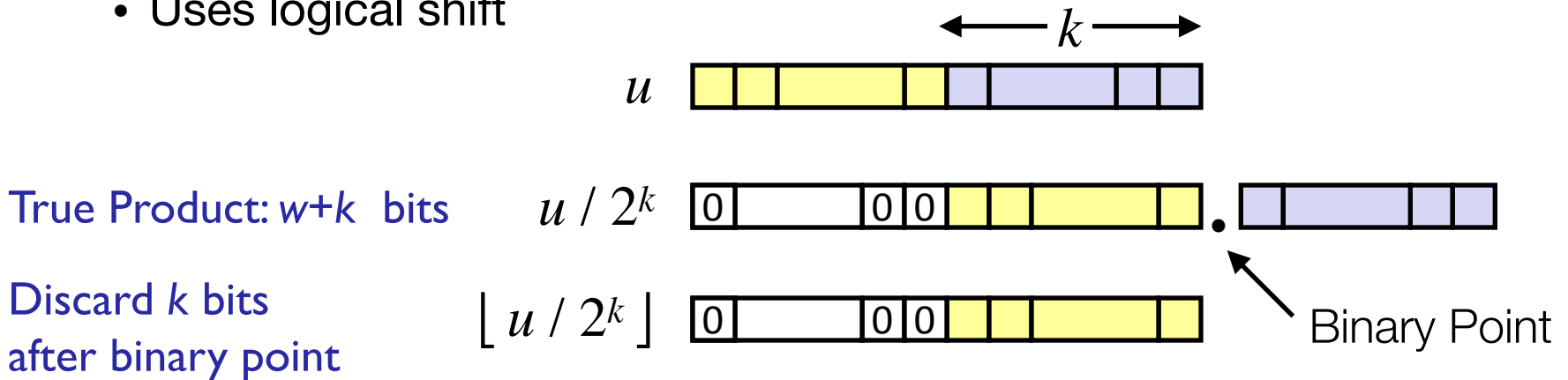
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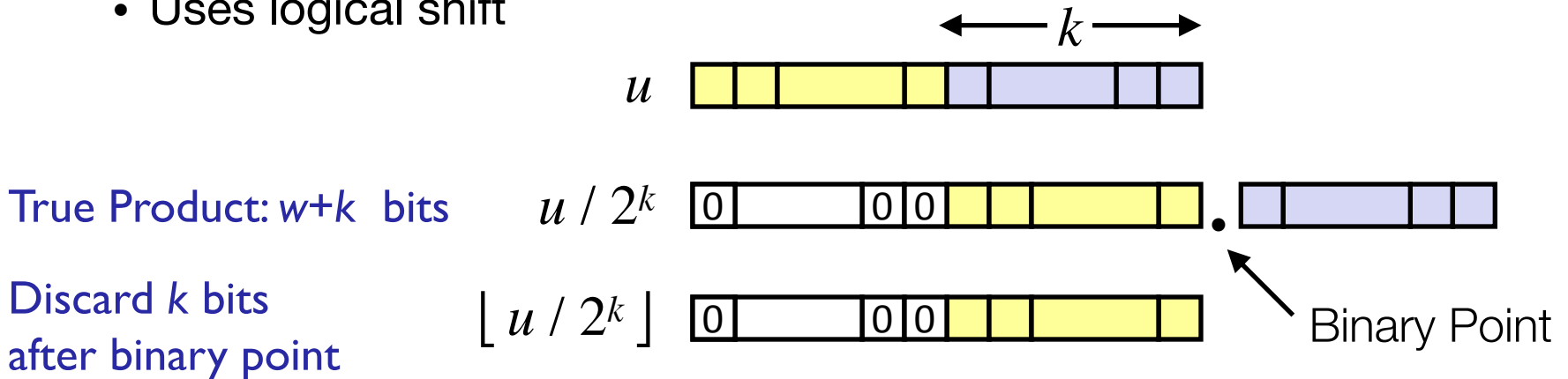
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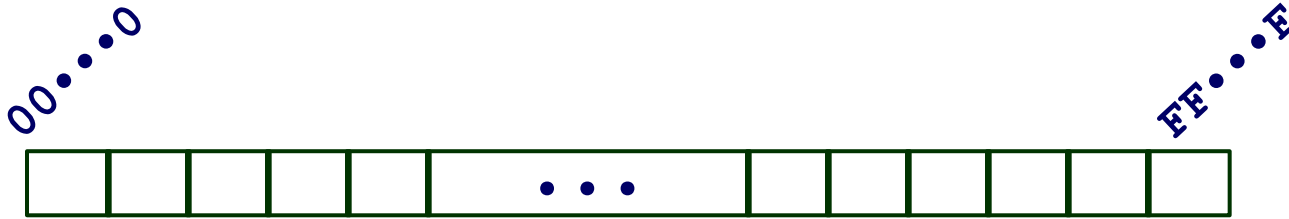


- $234_{10} \gg 2 = 2.34_{10}$, truncated result is 2 ($\lfloor 2.34 \rfloor = 2$)
- $1101_2 \gg 2 = 0011_2$ (true result: 11.01_2 . $\lfloor 13 / 4 \rfloor = 3$)

Today: Representing Information in Binary

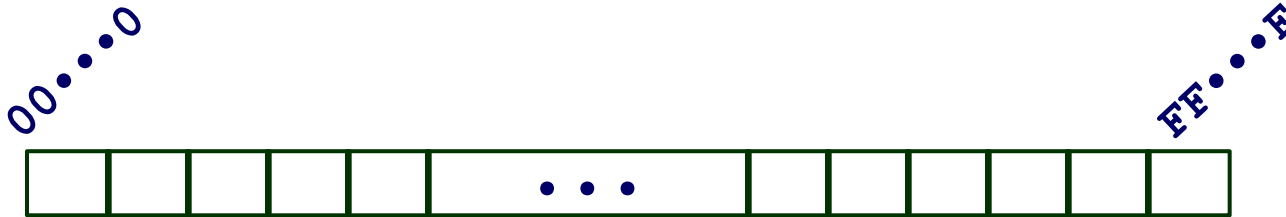
- Why Binary (bits)?
- Bit-level manipulations
- Integers
 - Representation: unsigned and signed
 - Conversion, casting
 - Expanding, truncating
 - Addition, negation, multiplication, shifting
 - Summary
- Representations in memory, pointers, strings

Byte-Oriented Memory Organization



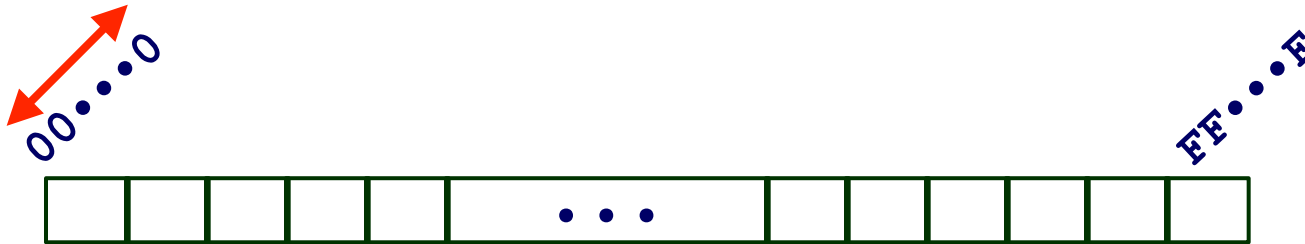
- Programs refer to data by address
 - Conceptually, envision it as a very large array of bytes: **byte-addressable**
 - In reality, it's not, but can think of it that way
 - An address is like an index into that array
 - and, a pointer variable stores an address

Machine Words



- Any given computer has a “Word Size”
 - Nominal size of a memory address
 - Until recently, most machines used 32 bits (4 bytes) as word size
 - Limits addresses to 4GB (2^{32} bytes)
 - Increasingly, machines have 64-bit word size
 - Potentially, could have 18 EB (exabytes) of addressable memory
 - That's 18.4×10^{18}

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Example Data Representations (in Bytes)

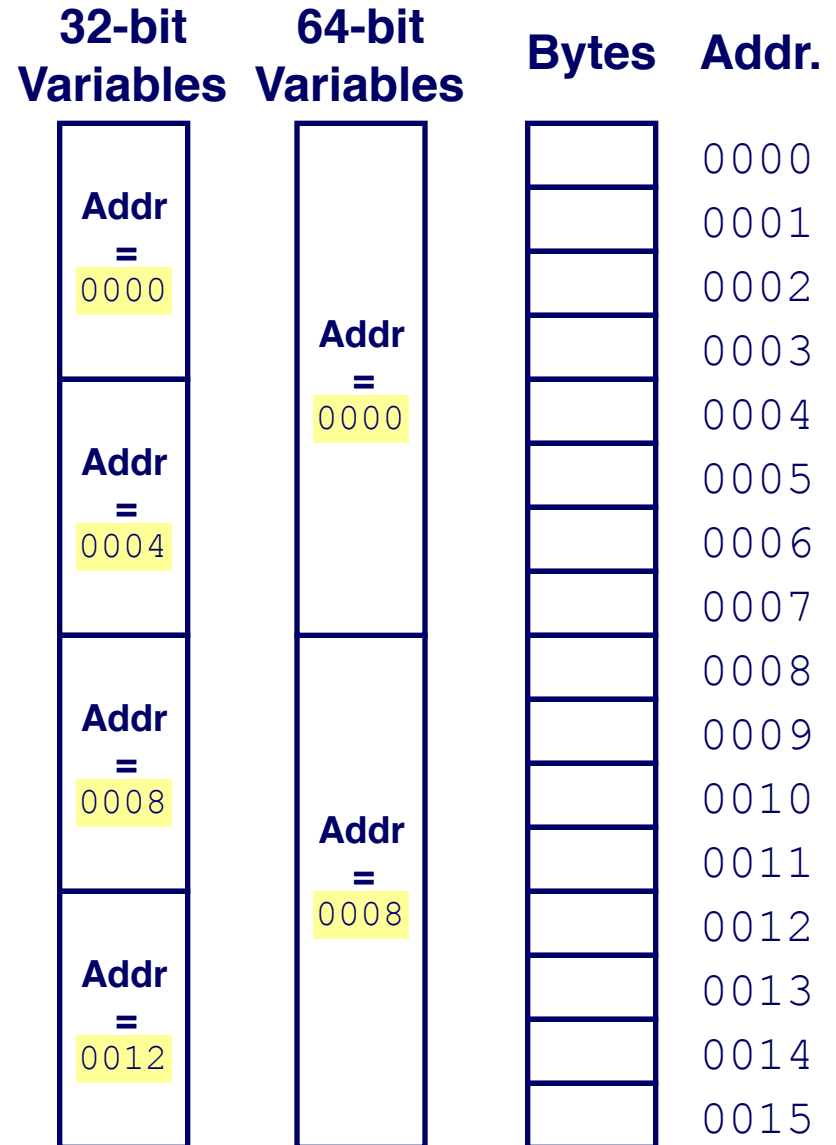
Word Size	4	8
C Data Type	32-bit	64-bit
<code>char</code>	1	1
<code>short</code>	2	2
<code>int</code>	4	4
<code>long</code>	4	8
<code>float</code>	4	4
<code>double</code>	8	8
<code>pointer</code>	4	8

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<code>float</code>	4	4
<code>double</code>	8	8
<code>pointer</code>	4	8

Word-Oriented Memory Organization

- Addresses Specify Byte Locations
 - Address of first byte in word
 - Addresses of successive words differ by 4 (32-bit) or 8 (64-bit)



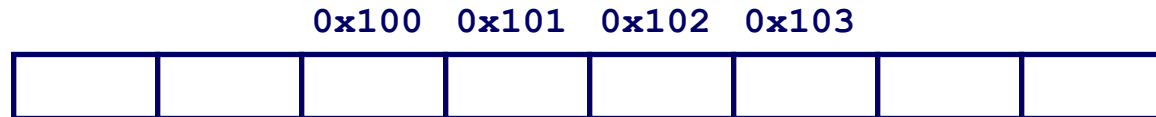
Byte Ordering

Byte Ordering

- How are the bytes within a multi-byte word ordered in memory?

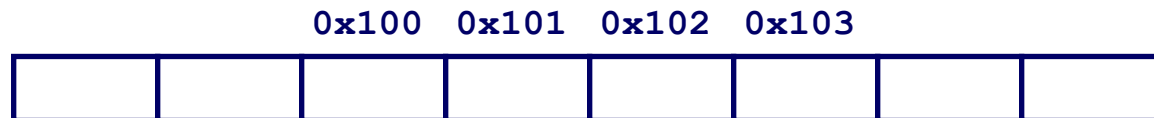
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 - Variable x has 4-byte value of 0x01234567
 - Address given by &x is 0x100



Byte Ordering

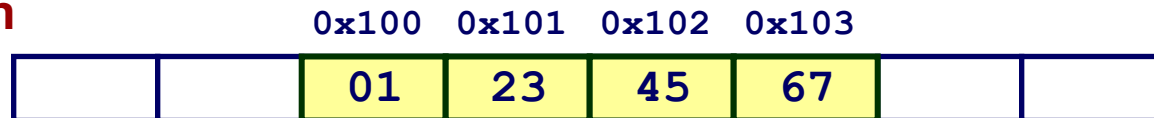
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- Conventions
 - **Big Endian**: Sun, PPC Mac, IBM z, Internet
 - Most significant byte has lowest address (**MSB first**)
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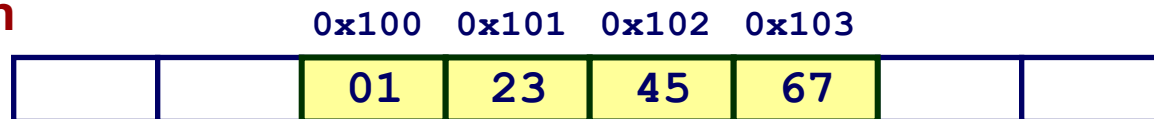
Big Endian



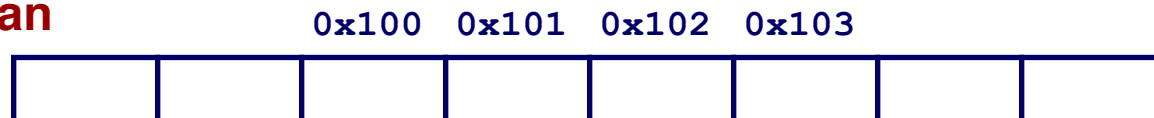
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 - Variable x has 4-byte value of 0x01234567
 - Address given by &x is 0x100
- Conventions
 - **Big Endian**: Sun, PPC Mac, IBM z, Internet
 - Most significant byte has lowest address (**MSB first**)
 - **Little Endian**: x86, ARM
 - Least significant byte has lowest address (**LSB first**)

Big Endian



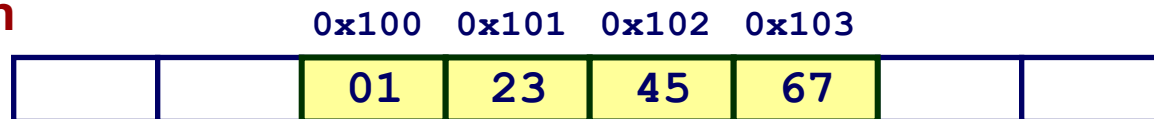
Little Endian



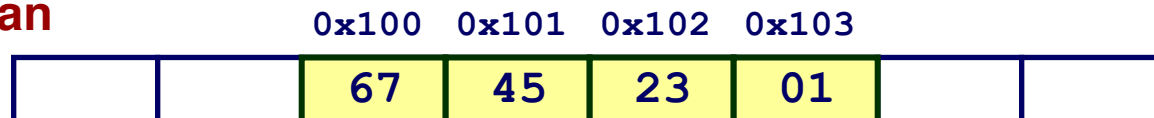
Byte Ordering

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Big Endian



Little Endian



Representing Integers

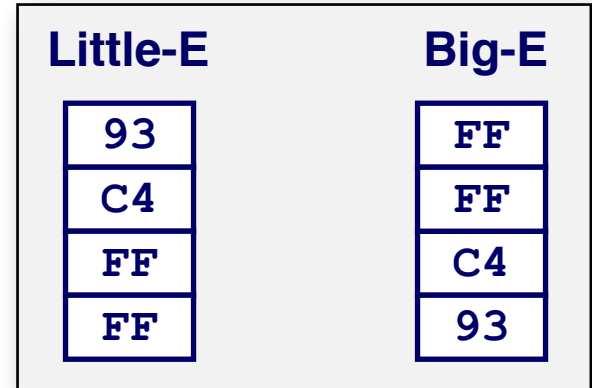
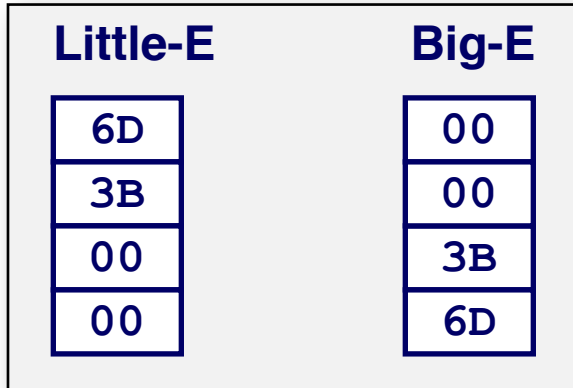
Hex: 00003B6D

Hex: FFFFC493

`int A = 15213;`

`int B = -15213;`

Address Increase



Representing Integers

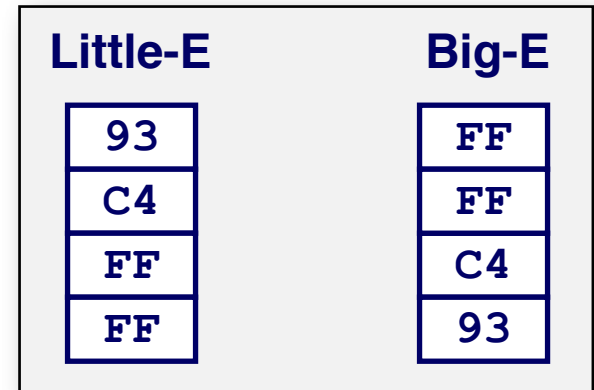
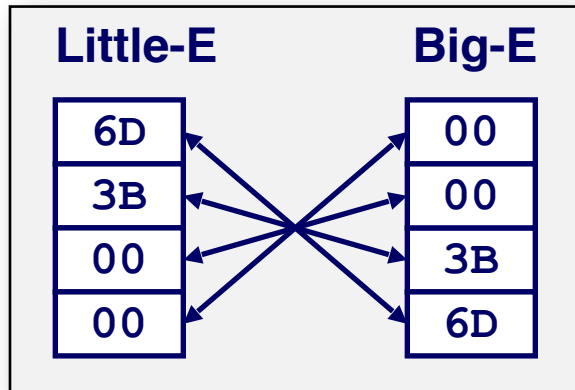
Hex: 00003B6D

Hex: FFFFC493

`int A = 15213;`

`int B = -15213;`

Address Increase
↓



Representing Integers

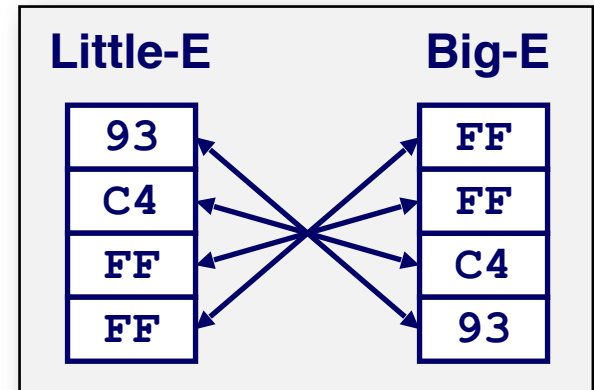
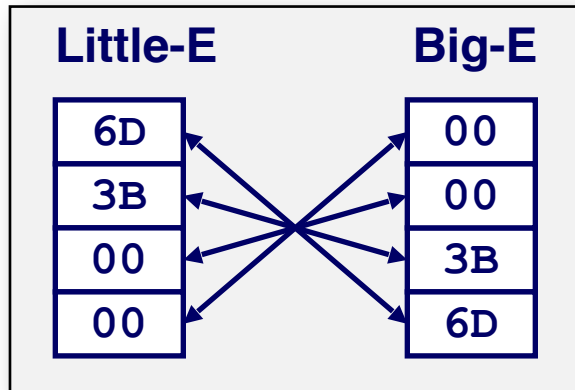
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Address Increase
↓



Announcement

- Check the course website before asking
 - <http://www.cs.rochester.edu/courses/252/spring2019/>
- Direct ALL questions regarding assignments to the TAs
 - They have done them. They have debugged them. They know them inside out.
 - If one doesn't know, ask another.
 - If all don't know, ask me.