

# CS107 Lecture 3

## Bits and Bytes; Integer Representations

reading:

*Bryant & O'Hallaron, Ch. 2.2-2.3*



masks recommended

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# PollEverywhere

- Today we're doing a “trial run” of using PollEverywhere for poll questions
  - Not counted for attendance (that starts Friday), just a chance to get a feel for the system
  - Participation info posted on Canvas Gradebook after lecture so you can confirm your responses were recorded
- Responses not anonymized, but we don't look at specific responses, just aggregated results and participation totals
- Visit [pollev.stanford.edu](http://pollev.stanford.edu) to log in (or use the PollEverywhere app) and sign in with your **@stanford.edu email – NOT your personal email!**
- You can use any device with a web browser, or download the PollEverywhere app, or respond via text – **however, to respond via text you must first log in via a web browser and add your phone number to your profile.**
- Whenever we reach a poll question in the slides, it will automatically activate the poll and allow you to respond at [pollev.com/cs107](http://pollev.com/cs107).

# **CS107 Topic 1: How can a computer represent integer numbers?**

# CS107 Topic 1

## How can a computer represent integer numbers?

Why is answering this question important?

- Helps us understand the limitations of computer arithmetic (today)
- Shows us how to more efficiently perform arithmetic (next time)
- Shows us how we can encode data more compactly and efficiently (next time)

**assign1:** implement 3 programs that manipulate binary representations to (1) work around the limitations of arithmetic with addition, (2) simulate an evolving colony of cells, and (3) print Unicode text to the terminal.

# Learning Goals

- Understand the limitations of computer arithmetic and how that can impact our programs, such as with overflow
- Understand how positive and negative numbers stored in **ints**, **longs**, etc. are represented in binary
- Learn about the binary and hexadecimal number systems and how to convert between number systems

# Delta/Comair Airline Holiday Chaos

Case study: Comair/Delta airline had to cancel thousands of flights days before Christmas due to a system malfunction. An unusually high number of crew reassessments caused a bug in the system. What happened?

# Demo: Unexpected Behavior



```
cp -r /afs/ir/class/cs107/lecture-code/lect3 .
```

# Lecture Plan

- Integer Representations
- Bits and Bytes
- Hexadecimal
- Unsigned Integers
- Signed Integers
- Overflow

# Lecture Plan

- **Integer Representations**
  - Bits and Bytes
  - Hexadecimal
  - Unsigned Integers
  - Signed Integers
  - Overflow

# Number Representations

- Numeric types are generally a fixed size (e.g. `int` is 4 bytes). This means there is a limit to the range of numbers they can store.
- **Overflow** occurs when we exceed the maximum value or go below the minimum value of what a numeric type can store. It can cause unintended bugs!

C Declaration	Size (Bytes)
<code>int</code>	4
<code>double</code>	8
<code>float</code>	4
<code>char</code>	1
<code>short</code>	2
<code>long</code>	8

# Number Representations

- **Unsigned Integers:** positive and 0 integers. (e.g. 0, 1, 2, ... 99999...)
- **Signed Integers:** negative, positive and 0 integers. (e.g. ...-2, -1, 0, 1,... 9999...)
- **Floating Point Numbers:** real numbers. (e.g. 0.1, -12.2,  $1.5 \times 10^{12}$ )  


Look up IEEE floating point if you're interested!

# Lecture Plan

- Integer Representations
- **Bits and Bytes**
- Hexadecimal
- Unsigned Integers
- Signed Integers
- Overflow

# One Bit At a Time

- A bit is 0 or 1
- Computers are built around the idea of two states: “on” and “off”. Bits represent this idea in software! (transistors represent this in hardware).
- We can combine bits, like with base-10 numbers, to represent more data. **8 bits = 1 byte.**
- Computer memory is just a large array of bytes! It is *byte-addressable*; you can’t address (store location of) a bit; only a byte.
- Computers fundamentally operate on bits; but we creatively represent different data as bits!
  - Images
  - Video
  - Text
  - And more...

# Base 10

5 9 3 4

Digits 0-9 (*0 to base-1*)

# Base 10

5 9 3 4

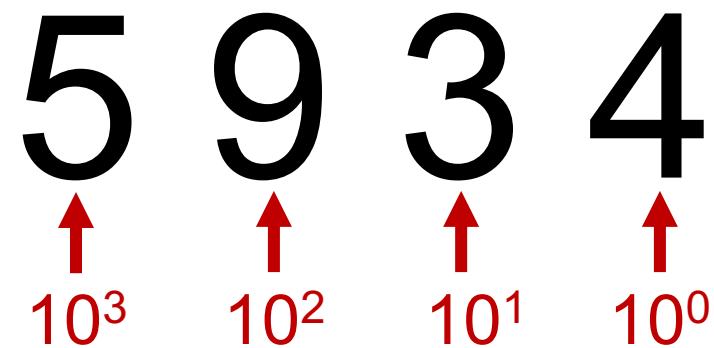
↑ ↑ ↑ ↑

thousands hundreds tens ones

$$= 5*1000 + 9*100 + 3*10 + 4*1$$

# Base 10

5 9 3 4



$10^3$   $10^2$   $10^1$   $10^0$

# Base 10

5 9 3 4  
10<sup>x</sup>: 3 2 1 0

# Base 2

**1 0 1 1**  
**2<sup>x</sup>:**      3      2      1      0

Digits 0-1 (*0 to base-1*)

# Base 2

1 0 1 1  
 $2^3$     $2^2$     $2^1$     $2^0$

# Base 2

Most significant bit (MSB)

Least significant bit (LSB)

1 0 1 1

eights fours twos ones

$$= 1*8 + 0*4 + 1*2 + 1*1 = 11_{10}$$

# Base 10 to Base 2

**Question:** What is 6 in base 2?

- Strategy:
  - What is the largest power of  $2 \leq 6$ ?  $2^2=4$
  - Now, what is the largest power of  $2 \leq 6 - 2^2$ ?  $2^1=2$
  - $6 - 2^2 - 2^1 = 0$ !

$$\begin{array}{r} 0 \quad 1 \quad 1 \quad 0 \\ \hline 2^3 \quad 2^2 \quad 2^1 \quad 2^0 \\ = 0*8 + 1*4 + 1*2 + 0*1 = 6 \end{array}$$

# Practice: Base 2 to Base 10

What is the base-2 value 1010 in base-10?

- a) 20
- b) 101
- c) 10
- d) 5
- e) Other

When poll is active, respond at **pollev.com/cs107**

Text **CS107** to **22333** once to join

## What is the base-10 value 14 in base 2?

1111

1110

1010

Other

# What is the base-10 value 14 in base 2?



# What is the base-10 value 14 in base 2?



# Byte Values

What is the minimum and maximum base-10 value a single byte (8 bits) can store? **minimum = 0**      **maximum = 255**

**11111111**  
2<sup>x</sup>:      7 6 5 4 3 2 1 0

- **Strategy 1:**  $1*2^7 + 1*2^6 + 1*2^5 + 1*2^4 + 1*2^3 + 1*2^2 + 1*2^1 + 1*2^0 = 255$
- **Strategy 2:**  $2^8 - 1 = 255$

# Multiplying by Base

$$1450 \times 10 = 1450\text{_____}$$

$$1100_2 \times 2 = 1100\text{_____}$$

*Key Idea:* inserting 0 at the end multiplies by the base!

# Dividing by Base

$$1450 / 10 = 145$$

$$1100_2 / 2 = 110$$

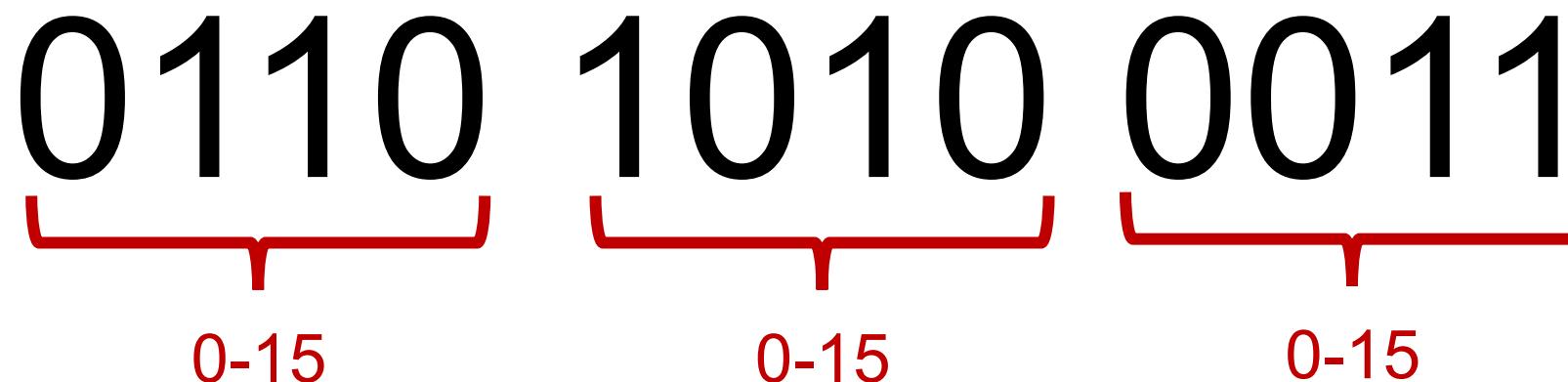
*Key Idea:* removing 0 at the end divides by the base!

# Lecture Plan

- Integer Representations
- Bits and Bytes
- **Hexadecimal**
- Unsigned Integers
- Signed Integers
- Overflow

# Hexadecimal

- When working with bits, oftentimes we have large numbers with 32 or 64 bits.
- Instead, we'll represent bits in *base-16 instead*; this is called **hexadecimal**.

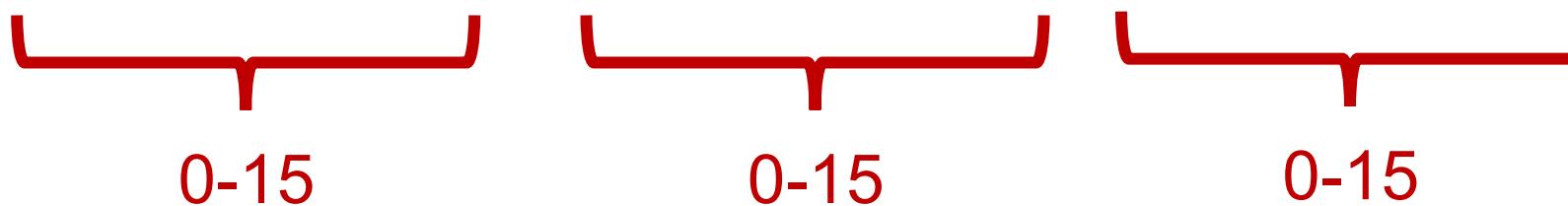


0110 1010 0011

0-15      0-15      0-15

# Hexadecimal

- When working with bits, oftentimes we have large numbers with 32 or 64 bits.
- Instead, we'll represent bits in *base-16 instead*; this is called **hexadecimal**.



Each is a base-16 digit!

# Hexadecimal

Hexadecimal is *base-16*, so we need digits for 1-15. How do we do this?

0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
										10	11	12	13	14	15

# Hexadecimal

<b>Hex digit</b>	0	1	2	3	4	5	6	7
<b>Decimal value</b>	0	1	2	3	4	5	6	7
<b>Binary value</b>	0000	0001	0010	0011	0100	0101	0110	0111
<hr/>								
<b>Hex digit</b>	8	9	A	B	C	D	E	F
<b>Decimal value</b>	8	9	10	11	12	13	14	15
<b>Binary value</b>	1000	1001	1010	1011	1100	1101	1110	1111

# Hexadecimal

- We distinguish hexadecimal numbers by prefixing them with **0x**, and binary numbers with **0b**.
- E.g. **0xf5** is **0b11110101**

0x f 5  
1111 0101

# Practice: Hexadecimal to Binary

What is **0x173A** in binary?

---

<b>Hexadecimal</b>	1	7	3	A
<b>Binary</b>	<b>0001</b>	<b>0111</b>	<b>0011</b>	<b>1010</b>

---

# Practice: Hexadecimal to Binary

What is **0b1111001010** in hexadecimal? (*Hint: start from the right*)

---

<b>Binary</b>	11	1100	1010
<b>Hexadecimal</b>	3	C	A

---

# Hexadecimal: It's funky but concise

Let's take a byte (8 bits):

165

Base-10: Human-readable,  
but cannot easily interpret on/off bits

0b10100101

Base-2: Yes, computers use this,  
but not human-readable

0xa5

Base-16: Easy to convert to Base-2,  
More “portable” as a human-readable format  
(fun fact: a half-byte is called a nibble or nybble)

# Lecture Plan

- Integer Representations
- Bits and Bytes
- Hexadecimal
- **Unsigned Integers**
- Signed Integers
- Overflow

# Unsigned Integers

- An **unsigned** integer is 0 or a positive integer (no negatives).
- We have already discussed converting between decimal and binary, which is a nice 1:1 relationship. Examples:

0b0001 = 1

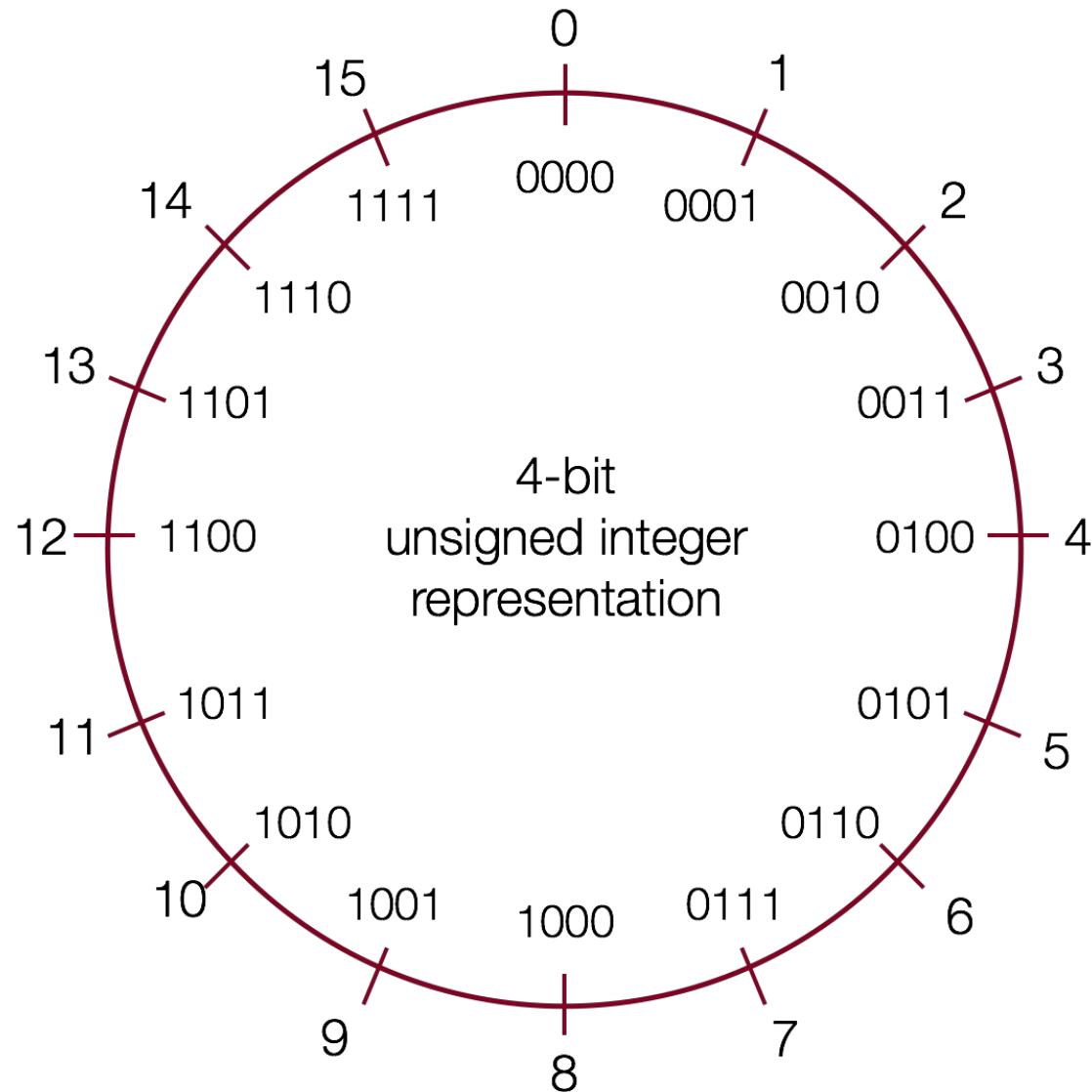
0b0101 = 5

0b1011 = 11

0b1111 = 15

- The range of an unsigned number is  $0 \rightarrow 2^w - 1$ , where  $w$  is the number of bits. E.g. a 32-bit integer can represent 0 to  $2^{32} - 1$  (4,294,967,295).

# Unsigned Integers



# From Unsigned to Signed

A **signed** integer is a negative, 0, or positive integer. How can we represent both negative *and* positive numbers in binary?

# Lecture Plan

- Integer Representations
- Bits and Bytes
- Hexadecimal
- Unsigned Integers
- **Signed Integers**
- Overflow

# Signed Integers

A **signed** integer is a negative integer, 0, or a positive integer.

- *Problem:* How can we represent negative *and* positive numbers in binary?

**Idea:** let's reserve the *most significant bit* to store the sign.

# Sign Magnitude Representation

0110



positive 6

1011



negative 3

# Sign Magnitude Representation

0000



positive 0

1000



negative 0



# Sign Magnitude Representation

$$1\ 000 = -0 \quad 0\ 000 = 0$$

$$1\ 001 = -1 \quad 0\ 001 = 1$$

$$1\ 010 = -2 \quad 0\ 010 = 2$$

$$1\ 011 = -3 \quad 0\ 011 = 3$$

$$1\ 100 = -4 \quad 0\ 100 = 4$$

$$1\ 101 = -5 \quad 0\ 101 = 5$$

$$1\ 110 = -6 \quad 0\ 110 = 6$$

$$1\ 111 = -7 \quad 0\ 111 = 7$$

We've only represented 15 of our 16 available numbers!

# Sign Magnitude Representation

- **Pro:** easy to represent, and easy to convert to/from decimal.
- **Con:**  $+0$  is not intuitive
- **Con:** we lose a bit that could be used to store more numbers
- **Con:** arithmetic is tricky: we need to find the sign, then maybe subtract (borrow and carry, etc.), then maybe change the sign. This complicates the hardware support for something as fundamental as addition.

Can we do better?

# A Better Idea

- Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

$$\begin{array}{r} 0101 \\ + \textcolor{red}{????} \\ \hline 0000 \end{array}$$

# A Better Idea

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# A Better Idea

- Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

$$\begin{array}{r} 0011 \\ + 1101 \\ \hline 0000 \end{array}$$

# A Better Idea

- Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

$$\begin{array}{r} 0000 \\ + \textcolor{red}{????} \\ \hline 0000 \end{array}$$

# A Better Idea

- Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

$$\begin{array}{r} 0000 \\ +0000 \\ \hline 0000 \end{array}$$

# A Better Idea

Decimal	Positive	Negative
0	0000	0000
1	0001	1111
2	0010	1110
3	0011	1101
4	0100	1100
5	0101	1011
6	0110	1010
7	0111	1001

Decimal	Positive	Negative
8	1000	1000
9	1001 (same as -7!)	NA
10	1010 (same as -6!)	NA
11	1011 (same as -5!)	NA
12	1100 (same as -4!)	NA
13	1101 (same as -3!)	NA
14	1110 (same as -2!)	NA
15	1111 (same as -1!)	NA

# There Seems Like a Pattern Here...

$$\begin{array}{r} 0101 \\ + 1011 \\ \hline 0000 \end{array}$$

$$\begin{array}{r} 0011 \\ + 1101 \\ \hline 0000 \end{array}$$

$$\begin{array}{r} 0000 \\ + 0000 \\ \hline 0000 \end{array}$$

The negative number is the positive number **inverted, plus one!**

# There Seems Like a Pattern Here...

A binary number plus its inverse is all 1s.

---

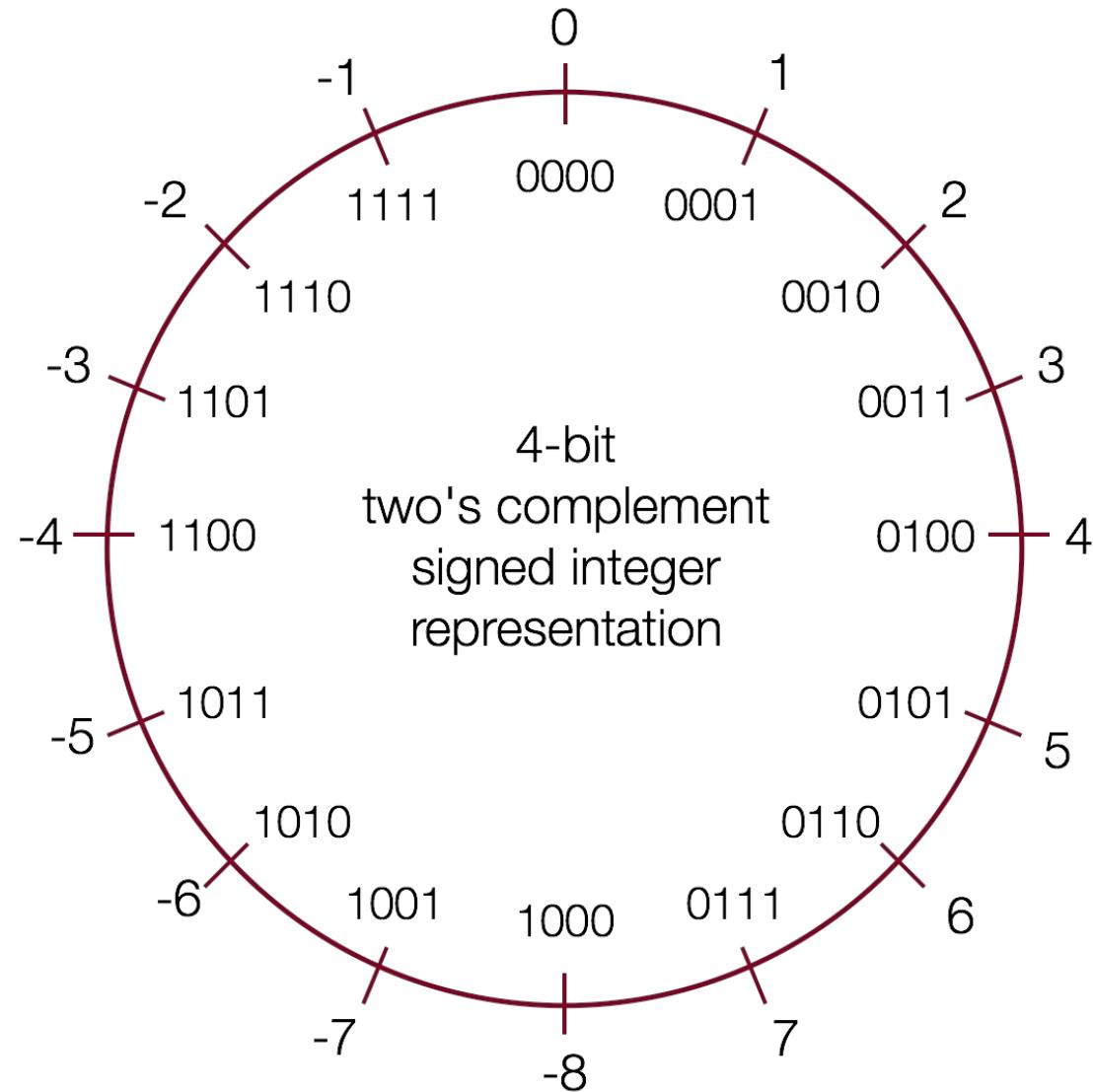
$$\begin{array}{r} 0101 \\ + 1010 \\ \hline 1111 \end{array}$$

Add 1 to this to carry over all 1s and get 0!

---

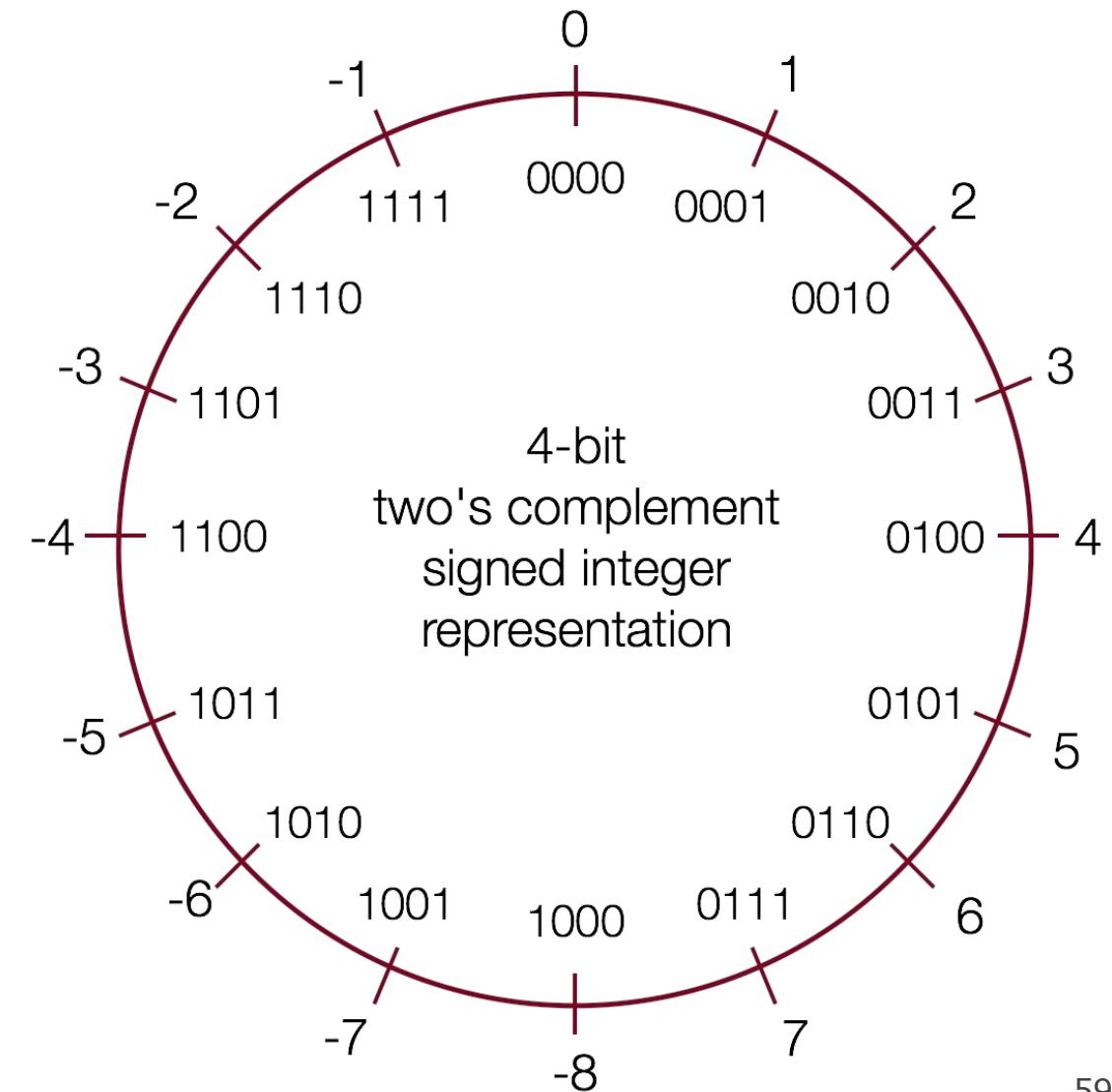
$$\begin{array}{r} 1111 \\ + 0001 \\ \hline 0000 \end{array}$$

# Two's Complement



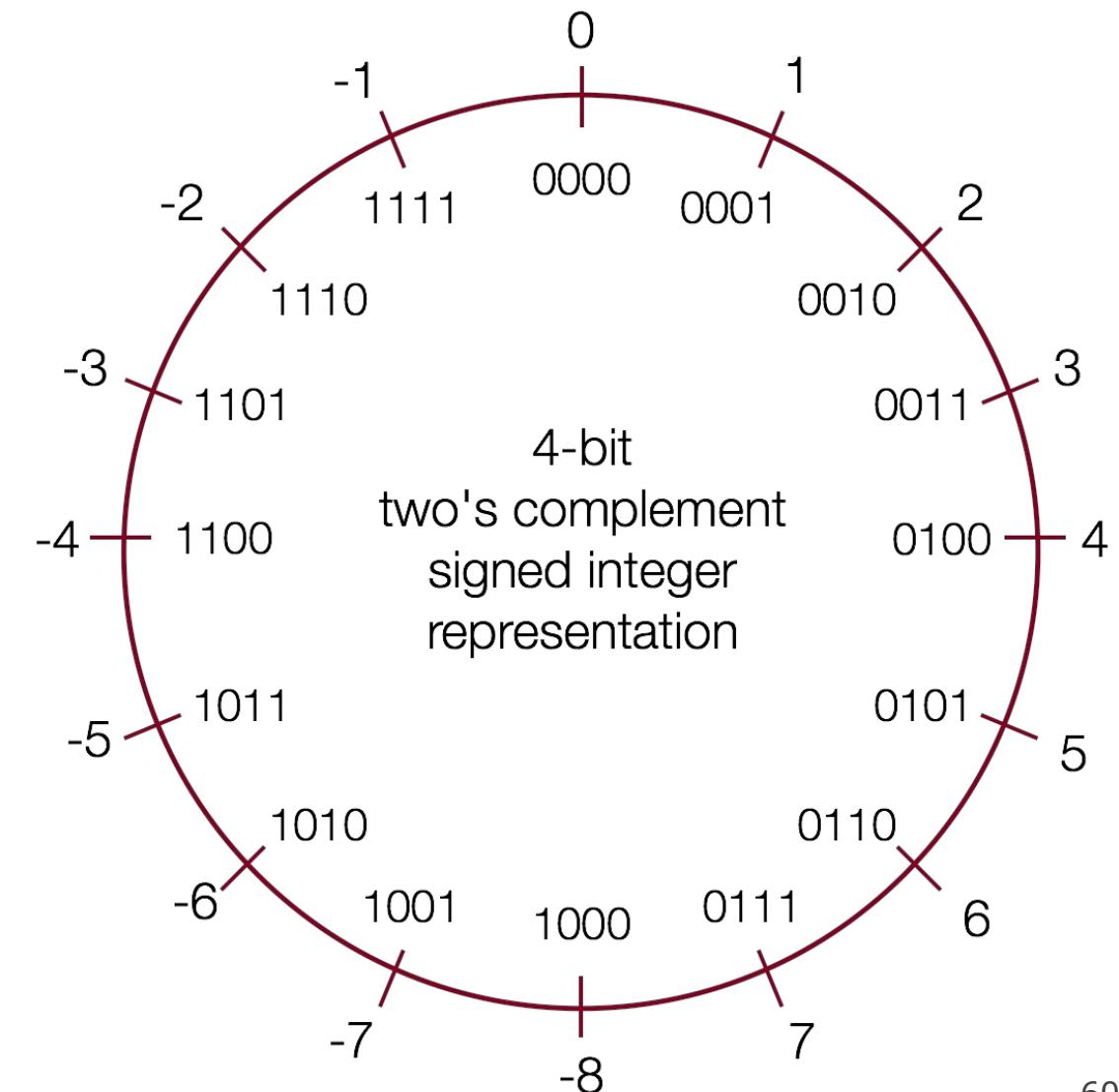
# Two's Complement

- In **two's complement**, we represent a positive number as **itself**, and its negative equivalent as the **two's complement of itself**.
- The **two's complement** of a number is the binary digits inverted, plus 1.
- This works to convert from positive to negative, **and** back from negative to positive!



# Two's Complement

- **Con:** more difficult to represent, and difficult to convert to/from decimal and between positive and negative.
- **Pro:** only 1 representation for 0!
- **Pro:** all bits are used to represent as many numbers as possible
- **Pro:** the most significant bit still indicates the sign of a number.
- **Pro:** addition works for any combination of positive and negative!



# Two's Complement

Adding two numbers is just...adding! There is no special case needed for negatives. E.g. what is  $2 + -5$ ?

$$\begin{array}{r} 0010 \\ + 1011 \\ \hline 1101 \end{array} \quad \begin{array}{r} 2 \\ -5 \\ -3 \end{array}$$

# Lecture Plan

- Integer Representations
- Bits and Bytes
- Hexadecimal
- Unsigned Integers
- Signed Integers
- **Overflow**

# Overflow

If you exceed the **maximum** value of your bit representation, you *wrap around* or *overflow* back to the **smallest** bit representation.

$$0b1111 + 0b1 = 0b0000$$

$$0b1111 + 0b10 = 0b0001$$

If you go below the **minimum** value of your bit representation, you *wrap around* or *overflow* back to the **largest** bit representation.

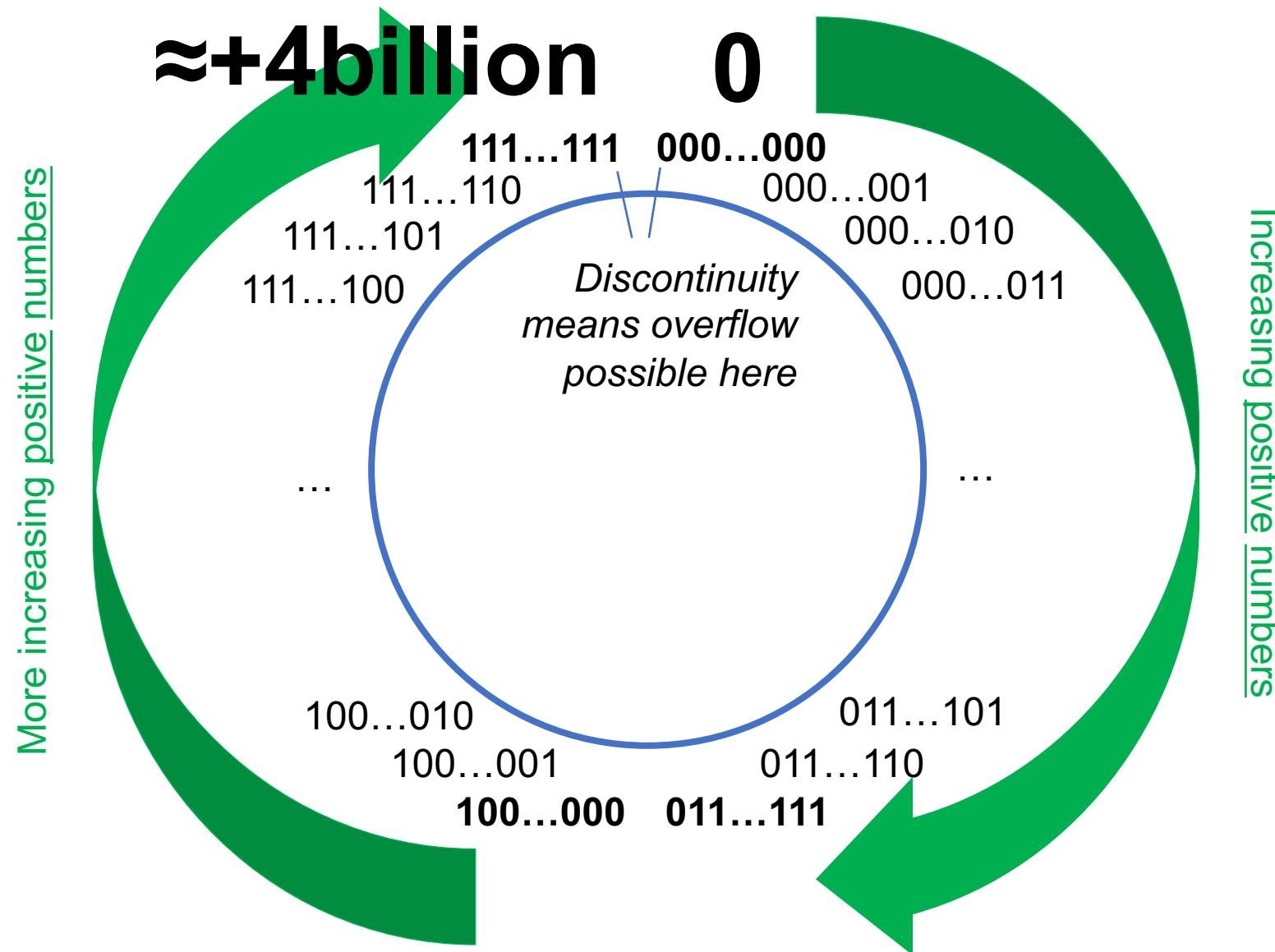
$$0b0000 - 0b1 = 0b1111$$

$$0b0000 - 0b10 = 0b1110$$

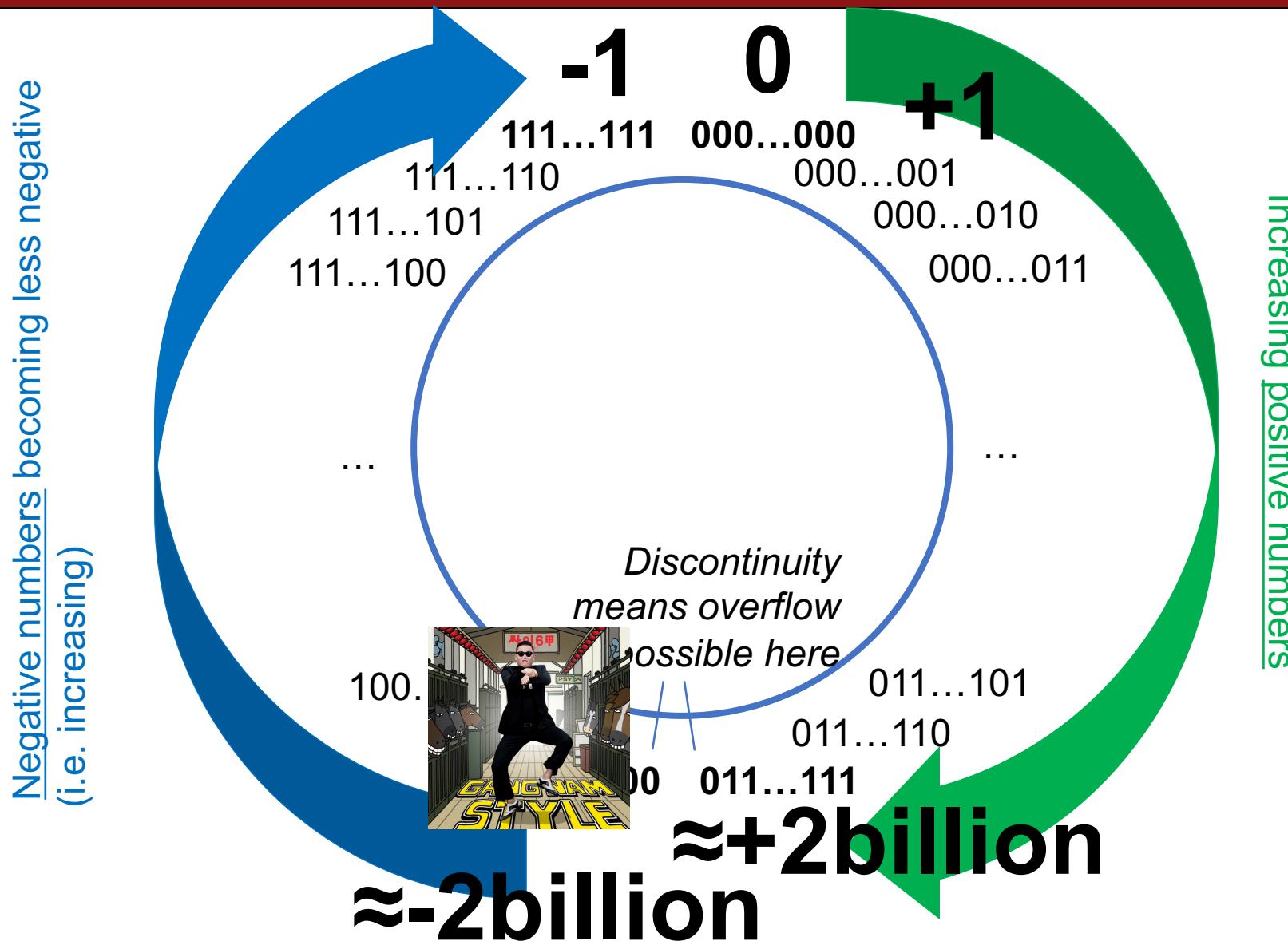
# Min and Max Integer Values

Type	Size (Bytes)	Minimum	Maximum
char	1	-128	127
unsigned char	1	0	255
short	2	-32768	32767
unsigned short	2	0	65535
int	4	-2147483648	2147483647
unsigned int	4	0	4294967295
long	8	-9223372036854775808	9223372036854775807
unsigned long	8	0	18446744073709551615

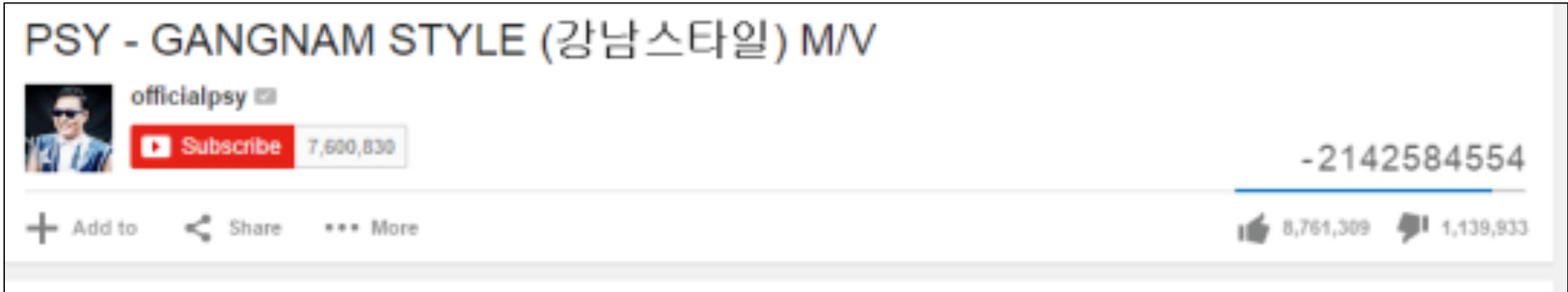
# Unsigned Integers



# Signed Numbers



# Overflow In Practice: PSY



**YouTube:** “We never thought a video would be watched in numbers greater than a 32-bit integer (=2,147,483,647 views), but that was before we met PSY. "Gangnam Style" has been viewed so many times we had to upgrade to a 64-bit integer (9,223,372,036,854,775,808)!” [\[link\]](#)

“We saw this coming a couple months ago and updated our systems to prepare for it” [\[link\]](#)

# Overflow In Practice: Timestamps

Many systems store timestamps as **the number of seconds since Jan. 1, 1970 in a signed 32-bit integer**.

- **Problem:** the latest timestamp that can be represented this way is 3:14:07 UTC on Jan. 13 2038!

# Overflow in Practice:

- [Pacman Level 256](#)
- Make sure to reboot Boeing Dreamliners [every 248 days](#)
- [Reported vulnerability CVE-2019-3857](#) in libssh2 may allow a hacker to remotely execute code
- [Donkey Kong Kill Screen](#)

# Demo Revisited: Unexpected Behavior

Comair/Delta airline had to [cancel thousands of flights](#) days before Christmas because of integer overflow – they exceeded 32,768 crew changes (limit of **short**).

```
int main(int argc, char *argv[]) {
    short airlineCrewChangesThisMonth = 0;

    for (int i = 0; i < 31; i++) {
        airlineCrewChangesThisMonth += 1200;
        printf(...);
    }
}
```

# Recap

- Integer Representations
- Bits and Bytes
- Hexadecimal
- Unsigned Integers
- Signed Integers
- Overflow

**Lecture 2 takeaway:** computers represent everything in binary. We must determine how to represent our data (e.g., base-10 numbers) in a binary format so a computer can manipulate it. There may be limitations to these representations! (overflow)

**Next time:** How can we manipulate individual bits and bytes?

# Extra Practice

# Practice: Two's Complement

Fill in the below table:

	<b>char x = _____;</b>		<b>char y = -x;</b>	
	decimal	binary	decimal	binary
1.		0b1111 1100		
2.		0b0001 1000		
3.		0b0010 0100		
4.		0b1101 1111		

It's easier to compute base-10 for positive numbers, so use two's complement first if negative.



# Practice: Two's Complement

Fill in the below table:

	<b>char x = _____;</b>		<b>char y = -x;</b>	
	decimal	binary	decimal	binary
1.	-4	0b1111 1100	4	0b0000 0100
2.		0b0001 1000		
3.		0b0010 0100		
4.		0b1101 1111		

It's easier to compute base-10 for positive numbers, so use two's complement first if negative.



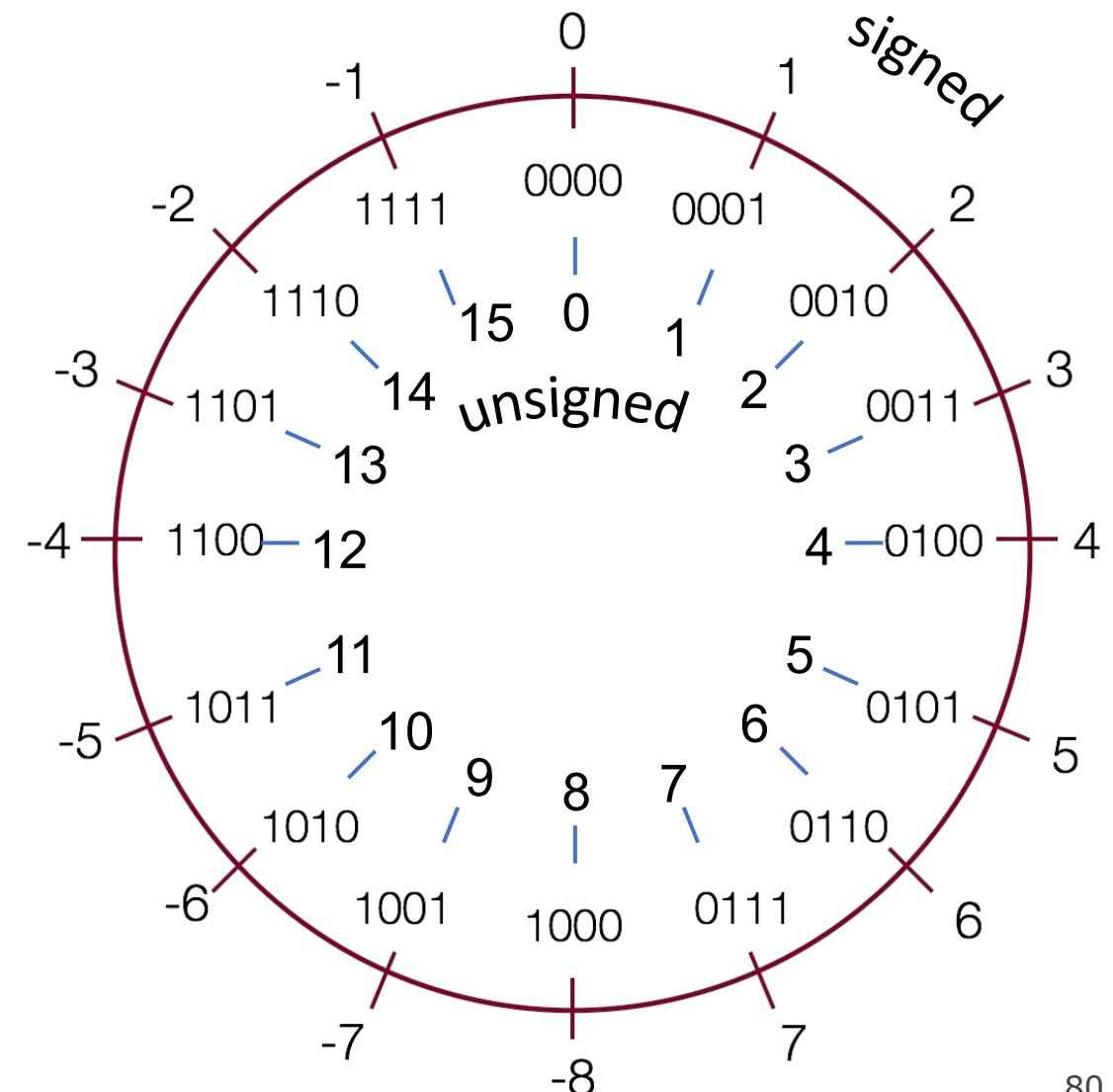
# Practice: Two's Complement

Fill in the below table:

	<b>char x = _____;</b>		<b>char y = -x;</b>	
	decimal	binary	decimal	binary
1.	-4	0b1111 1100	4	0b0000 0100
2.	24	0b0001 1000	-24	0b1110 1000
3.	36	0b0010 0100	-36	0b1101 1100
4.	-33	0b1101 1111	33	0b0010 0001

It's easier to compute base-10 for positive numbers, so use two's complement first if negative.

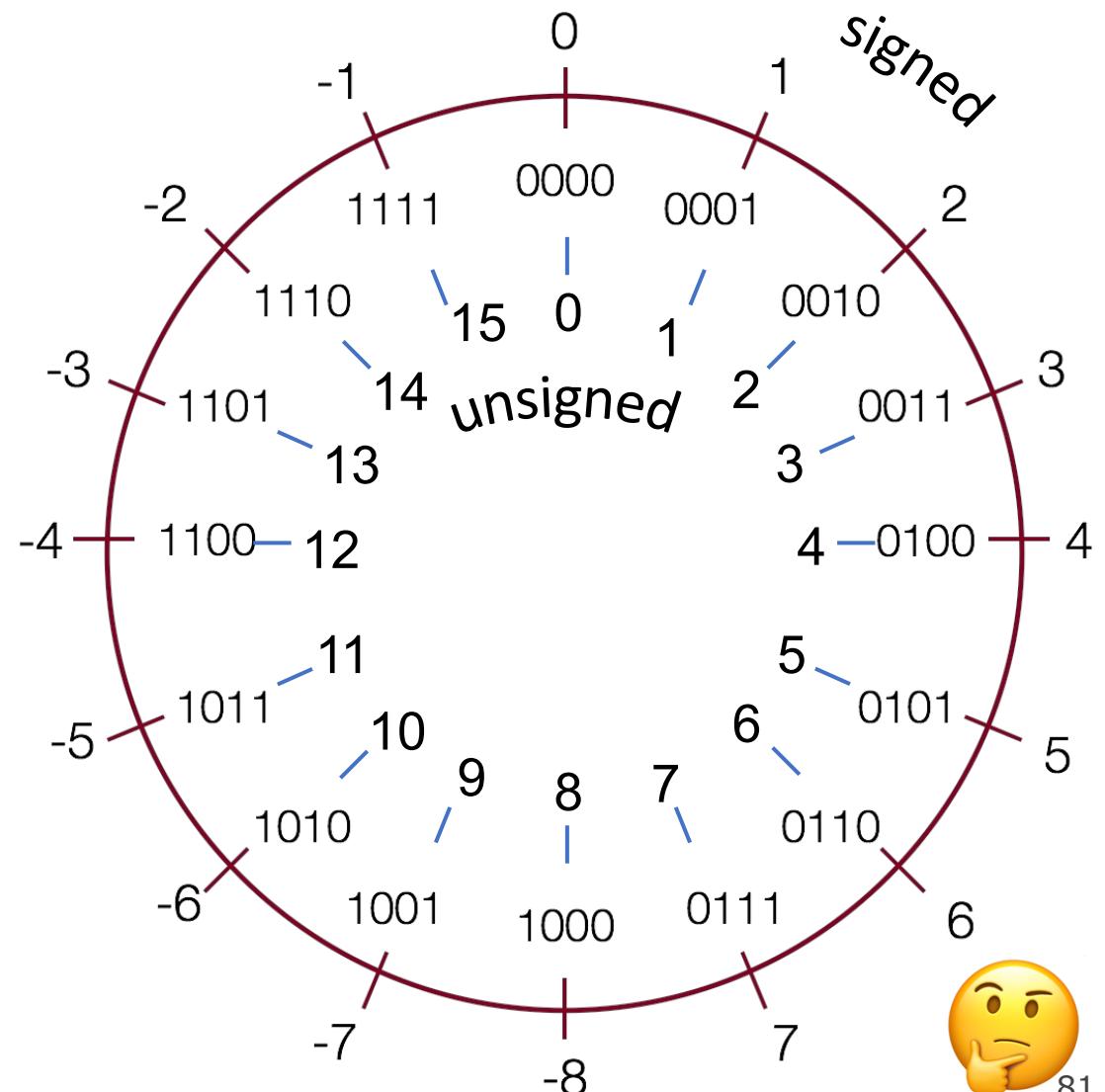
# Signed vs. Unsigned Integers



# Underspecified question

What is the following base-2 number in base-10?

0b1101



# Underspecified question

What is the following base-2 number in base-10?

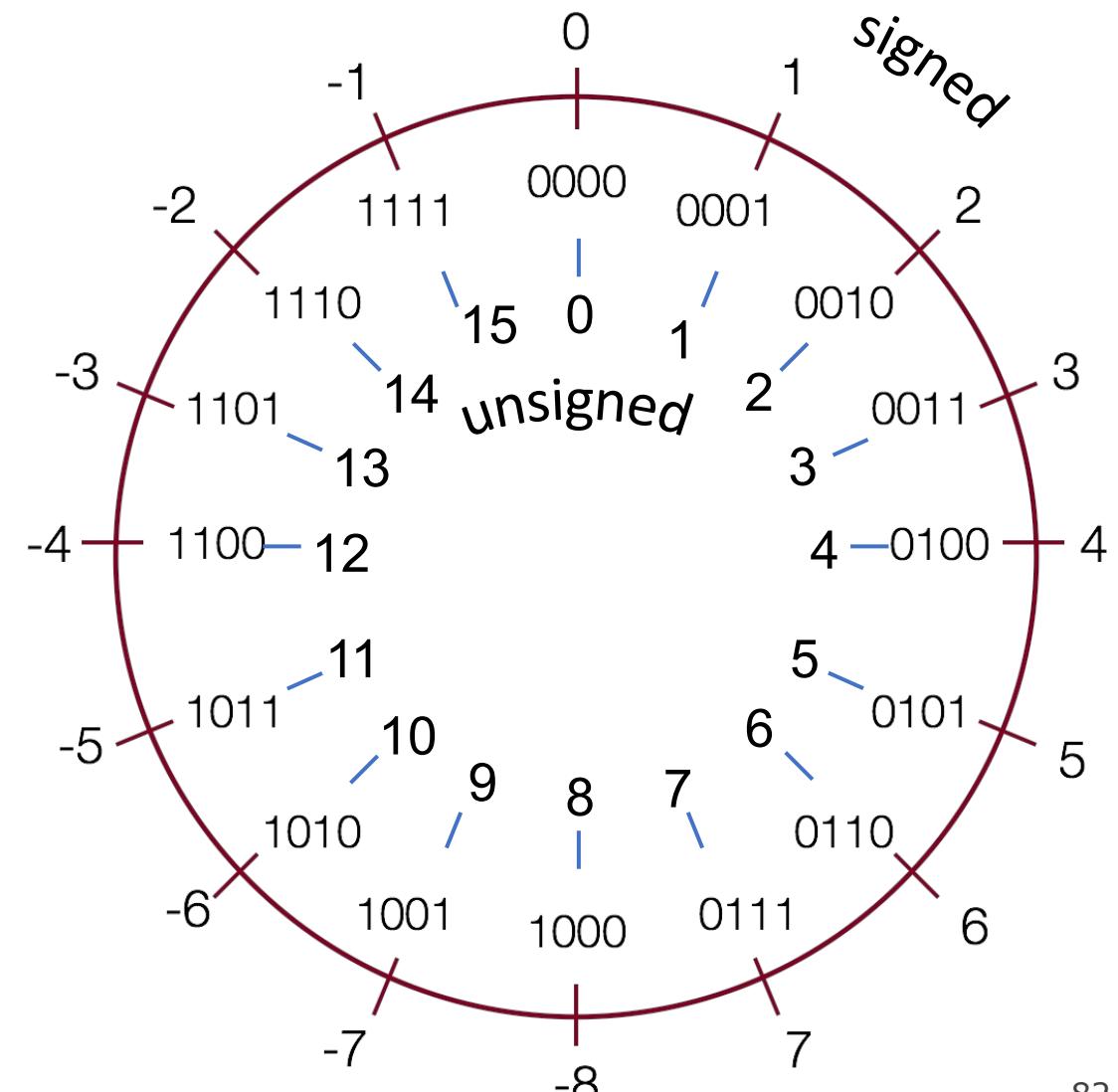
0b1101

If 4-bit signed: -3

If 4-bit unsigned: 13

If >4-bit signed or unsigned: 13

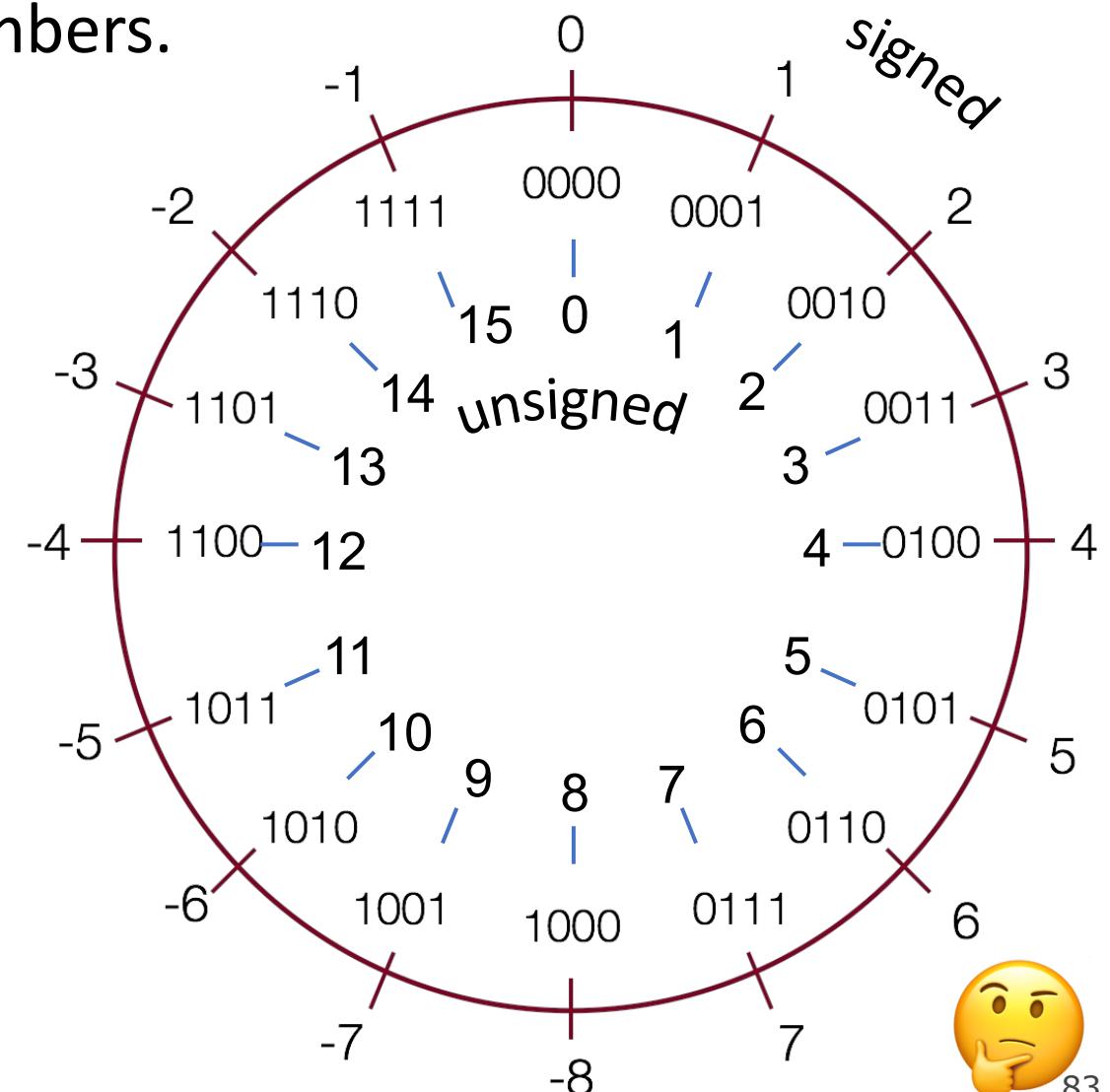
You need to know the type to determine the number! (Note by default, numeric constants in C are signed ints)



# Overflow

- What is happening here? Assume 4-bit numbers.

$$\begin{array}{r} 0b1101 \\ + 0b0100 \\ \hline \end{array}$$



# Overflow

- What is happening here? Assume 4-bit numbers.

$$\begin{array}{r} 0b1101 \\ + 0b0100 \\ \hline \end{array}$$

Signed

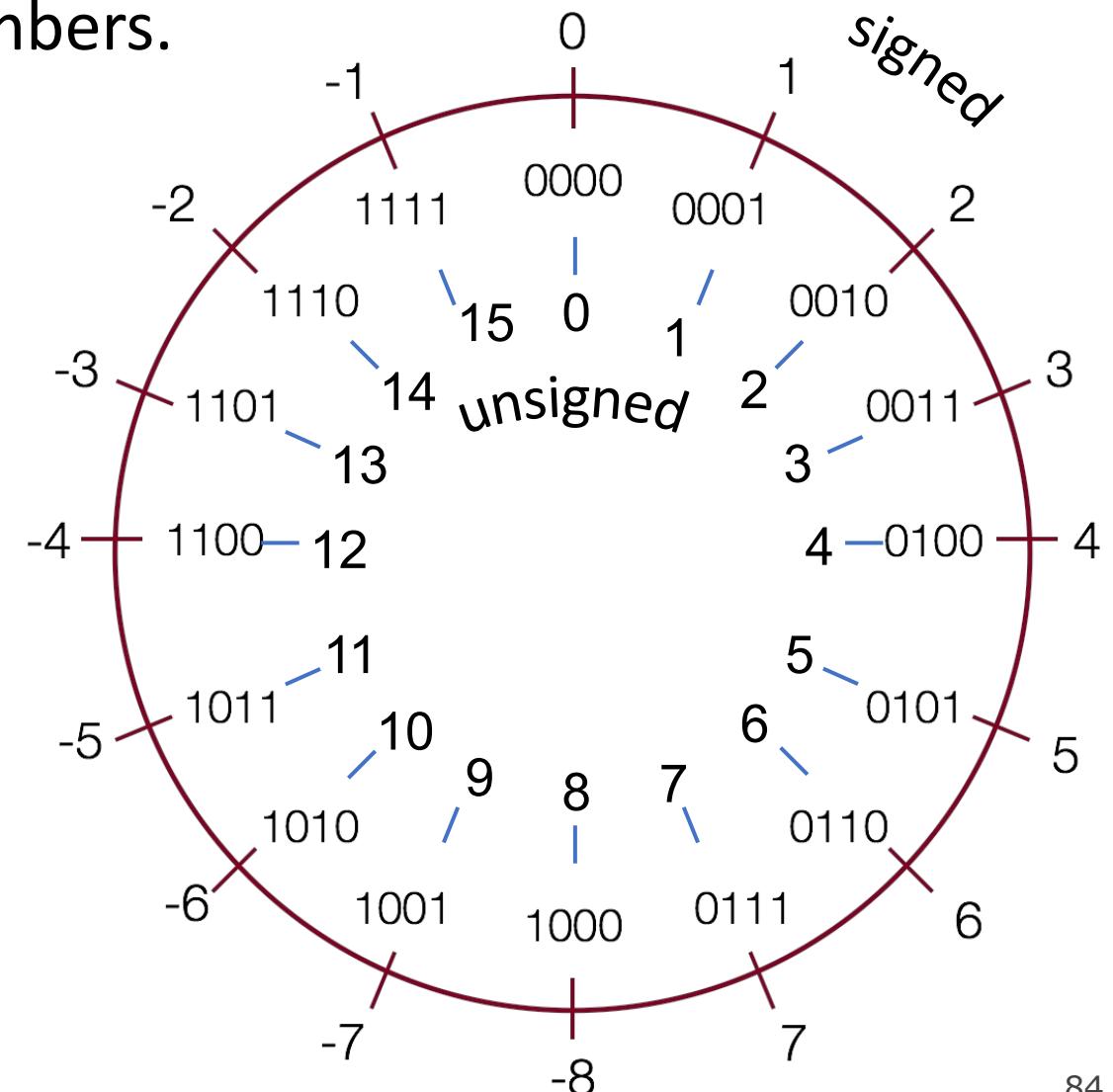
$$-3 + 4 = 1$$

No overflow

Unsigned

$$13 + 4 = 1$$

Overflow



# Limits and Comparisons

1. What is  
the...

	Largest unsigned?	Largest signed?	Smallest signed?
char			
int			



# Limits and Comparisons

1. What is  
the...

	Largest unsigned?	Largest signed?	Smallest signed?
char	$2^8 - 1 = 255$	$2^7 - 1 = 127$	$-2^7 = -128$
int	$2^{32} - 1 =$ <b>4294967296</b>	$2^{31} - 1 =$ <b>2147483647</b>	$-2^{31} =$ <b>-2147483648</b>

These are available as  
UCHAR\_MAX, INT\_MIN,  
INT\_MAX, etc. in the  
`<limits.h>` header.