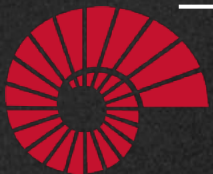


# COMP201

## Computer Systems & Programming

Lecture #02 – Bits and Bytes, Representing and  
Operating on Integers



**KOÇ**  
**UNIVERSITY**

Aykut Erdem // Koç University // Fall 2022

# Plan For Today

- Bits and Bytes
- Hexadecimal
- Integer Representations
- Unsigned Integers
- Signed Integers
- Overflow
- Casting and Combining Types

**Disclaimer:** Slides for this lecture were borrowed from  
—Nick Troccoli's Stanford CS107 class  
—Randal E. Bryant and David R. O'Hallaron's CMU 15-213 class

# Good news, everyone!

- Assg0 will be out today (due Oct 13)
- C bootcamp discussion on Friday!
- My office hour will be on Wednesdays btw 09:00-10:00



# COMP201 Topic 1: How can a computer represent integer numbers?





# Demo: Unexpected Behavior



airline.c

# Lecture Plan

- Bits and Bytes
- Hexadecimal
- Integer Representations
- Unsigned Integers
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- Overflow
- Casting and Combining Types

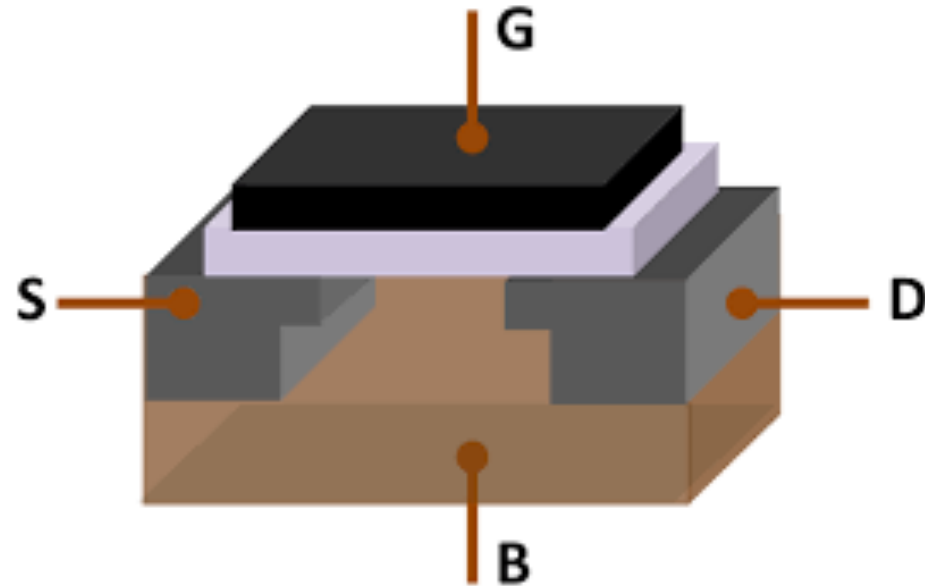
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1

# Bits

- Computers are built around the idea of two states: “on” and “off”. Transistors represent this in hardware, and bits represent this in software!



# One Bit At A Time

- 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 still fundamentally operate on bits; we have just gotten more creative about how to represent different data as bits!
  - Images
  - Audio
  - 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
$10^x$ :	3	2	1	0

# Base 2

	1	0	1	1
$2^x$ :	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  $2 \leq 6$ ?

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0	1		
<hr/>	<hr/>	<hr/>	<hr/>
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# 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  $2 \leq 6 - 2^2$ ?

0	1		
<hr/>	<hr/>	<hr/>	<hr/>
$2^3$	$2^2$	$2^1$	$2^0$

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0	1	1	
<hr/>	<hr/>	<hr/>	<hr/>
$2^3$	$2^2$	$2^1$	$2^0$

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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  $2 \leq 6 - 2^2$ ?  $2^1=2$
- $6 - 2^2 - 2^1 = 0$ !

$$\begin{array}{cccc} 0 & 1 & 1 & \\ \hline 2^3 & 2^2 & 2^1 & 2^0 \end{array}$$

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

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

# 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



# Practice: Base 10 to Base 2

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

- a) 1111
- b) 1110
- c) 1010
- d) Other

# Byte Values

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

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

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

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

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

# Byte Values

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

$2^x$ :      1 1 1 1 1 1 1 1  
             7 6 5 4 3 2 1 0

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



# Multiplying by Base

$$1450 \times 10 = 1450\underline{0}$$

$$1100_2 \times 2 = 1100\underline{0}$$

*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!

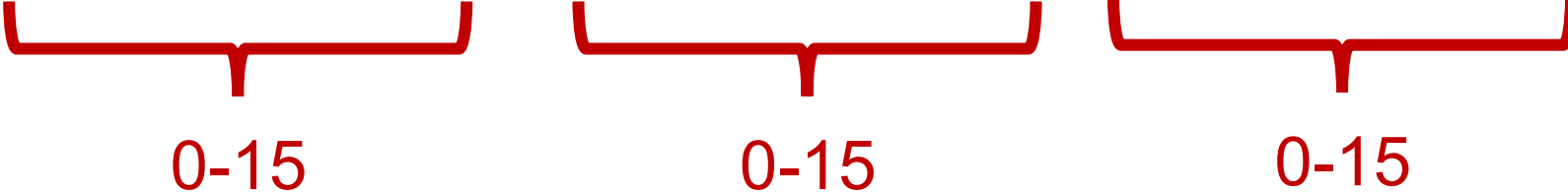
# Lecture Plan

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

# 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

Hex digit	0	1	2	3	4	5	6	7
Decimal value	0	1	2	3	4	5	6	7
Binary value	0000	0001	0010	0011	0100	0101	0110	0111

Hex digit	8	9	A	B	C	D	E	F
Decimal value	8	9	10	11	12	13	14	15
Binary value	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

The diagram illustrates the conversion of the hexadecimal number 0xf5 to its binary equivalent. The prefix '0x' is shown in black. The hexadecimal digits 'f' and '5' are also in black. Below 'f', a red curly brace groups the four bits '1111'. Below '5', a red curly brace groups the four bits '0101'. The binary representation '0b11110101' is not fully shown, only the bit groups corresponding to the hexadecimal digits.



# Practice: Hexadecimal to Binary

What is **0x173A** in binary?

---

<b>Hexadecimal</b>	<b>1</b>	<b>7</b>	<b>3</b>	<b>A</b>
<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>	<b>11</b>	<b>1100</b>	<b>1010</b>
<b>Hexadecimal</b>	<b>3</b>	<b>C</b>	<b>A</b>

---

Question Break!

# Lecture Plan

- Bits and Bytes
- Hexadecimal
- Integer Representations
- Unsigned Integers
- Signed Integers
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# 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,  $1.5 \times 10^{12}$ )

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 More on this next week!

# Number Representations

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

# In The Days Of Yore...

C Declaration	Size (Bytes)
<b>int</b>	<b>4</b>
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# Transitioning To Larger Datatypes



- **Early 2000s:** most computers were **32-bit**. This means that pointers were 4 bytes (32 bits).
- 32-bit pointers store a memory address from 0 to  $2^{32}-1$ , equaling  **$2^{32}$  bytes of addressable memory**. This equals **4 Gigabytes**, meaning that 32-bit computers could have at most **4GB** of memory (RAM)!
- Because of this, computers transitioned to **64-bit**. This means that datatypes were enlarged; pointers in programs were now **64 bits**.
- 64-bit pointers store a memory address from 0 to  $2^{64}-1$ , equaling  **$2^{64}$  bytes of addressable memory**. This equals **16 Exabytes**, meaning that 64-bit computers could have at most  **$1024*1024*1024$  GB** of memory (RAM)!

# Lecture Plan

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

# 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:

$$\text{0b0001} = 1$$

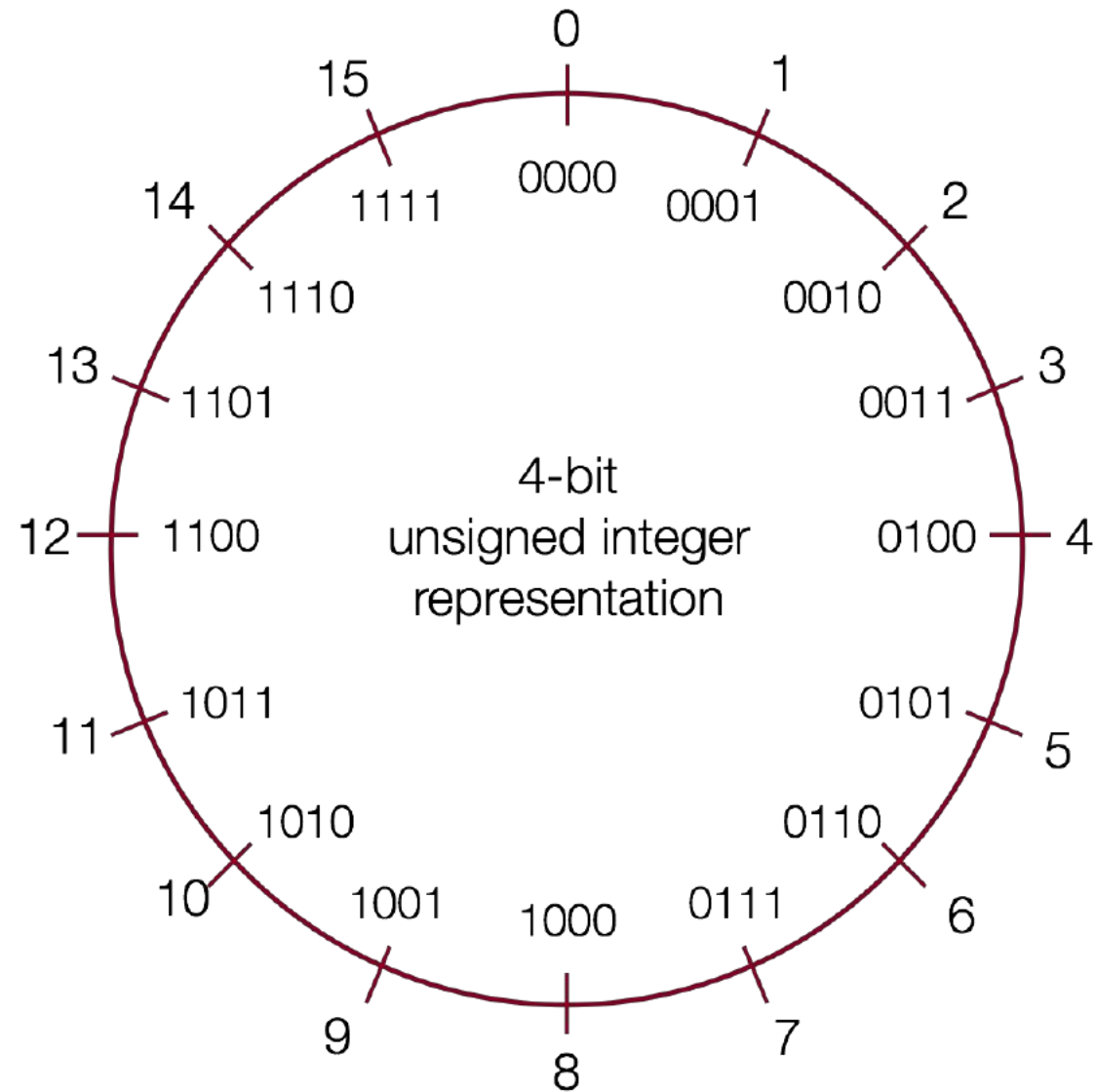
$$\text{0b0101} = 5$$

$$\text{0b1011} = 11$$

$$\text{0b1111} = 15$$

- 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



# Lecture Plan

- Bits and Bytes
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# 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?

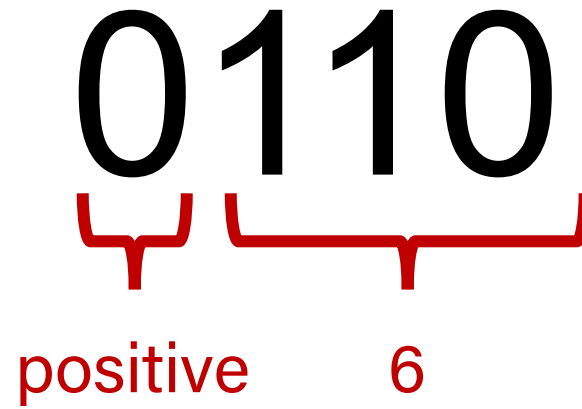
# Signed Integers

- 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.

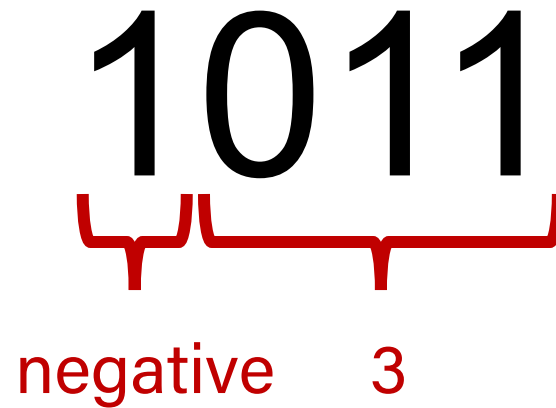
# Sign Magnitude Representation

0 1 1 0



positive 6

1 0 1 1



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:**  $\pm 0$  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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$$\begin{array}{r} 0101 \\ + 1011 \\ \hline 0000 \end{array}$$

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$$\begin{array}{r} 0011 \\ + \textcolor{red}{????} \\ \hline 0000 \end{array}$$

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

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



# 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...

$$\begin{array}{r} 0101 \\ + 1011 \\ \hline 0000 \end{array} \quad \begin{array}{r} 0011 \\ + 1101 \\ \hline 0000 \end{array} \quad \begin{array}{r} 0000 \\ + 0000 \\ \hline 0000 \end{array}$$

- 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!

---

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

# Another Trick

- To find the negative equivalent of a number, work right-to-left and write down all digits *through* when you reach a 1. Then, invert the rest of the digits.

$$\begin{array}{r} 100100 \\ + \textcolor{red}{??????} \\ \hline 000000 \end{array}$$

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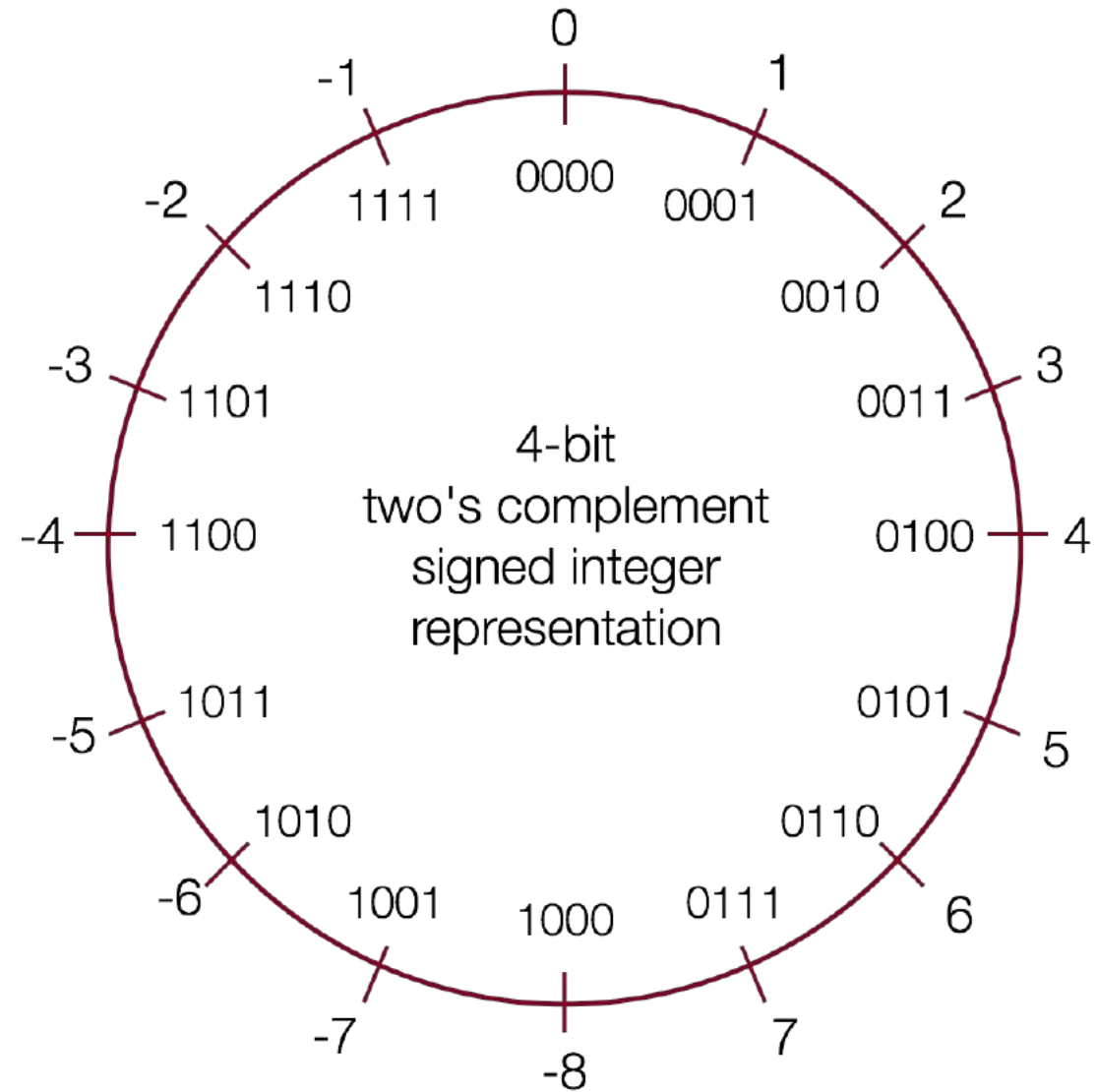
$$\begin{array}{r} 100100 \\ + \textcolor{red}{???100} \\ \hline 000000 \end{array}$$

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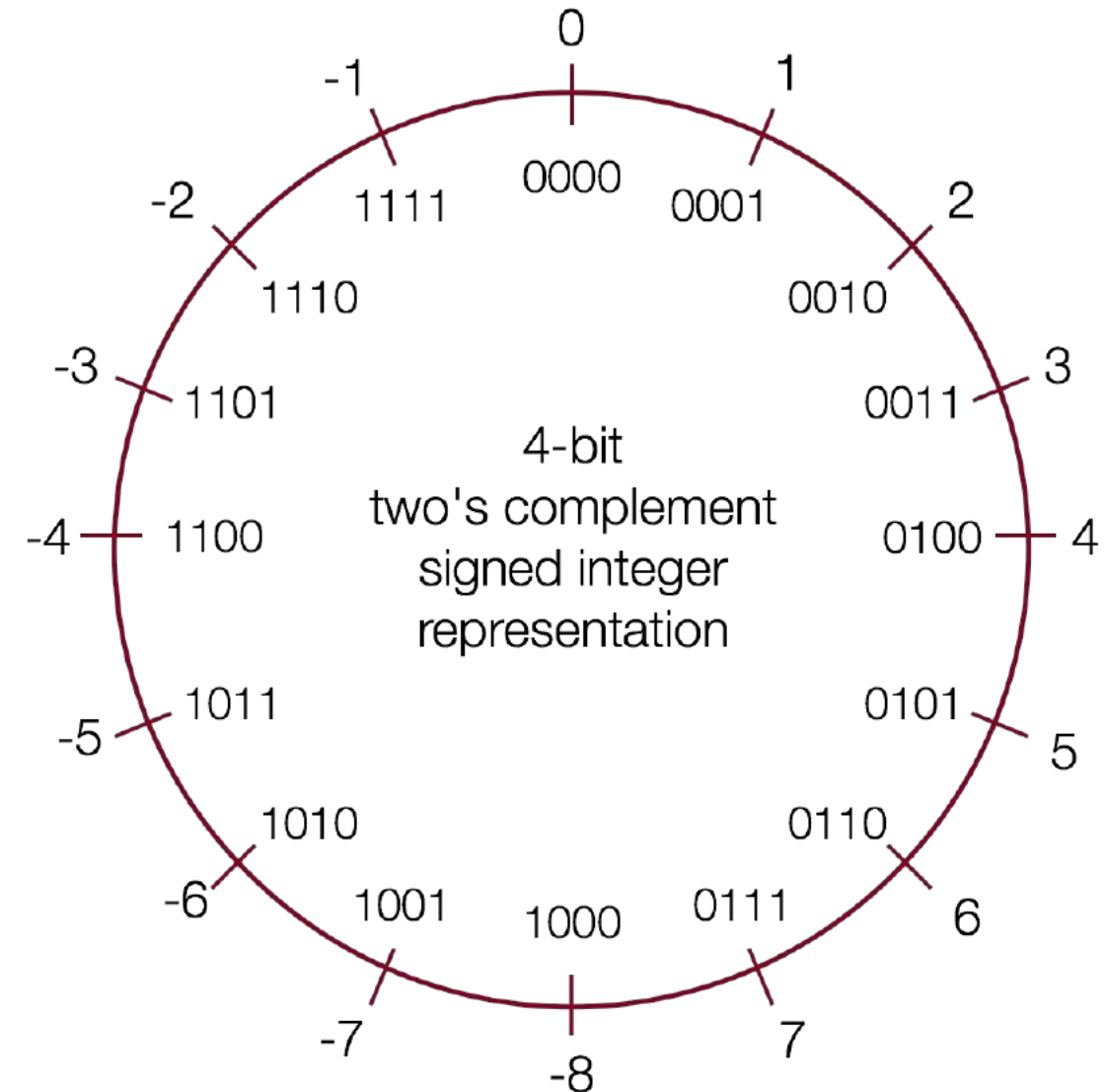
# Two's Complement





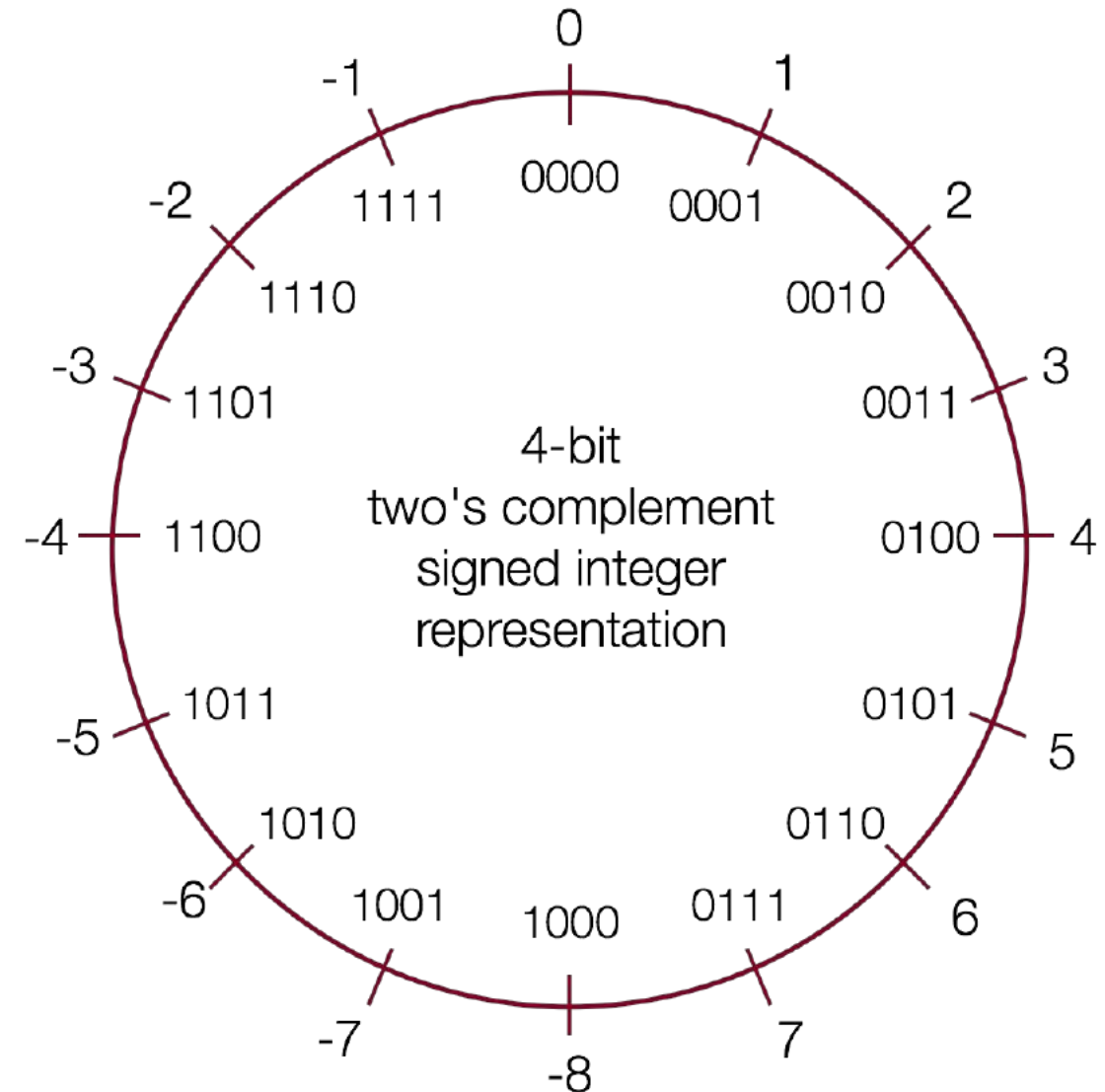
# Two's Complement

- 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  $2 + -5$ ?

$$\begin{array}{r} 0010 \\ + 1011 \\ \hline 1101 \end{array}$$

2  
-5  
-3

# Two's Complement

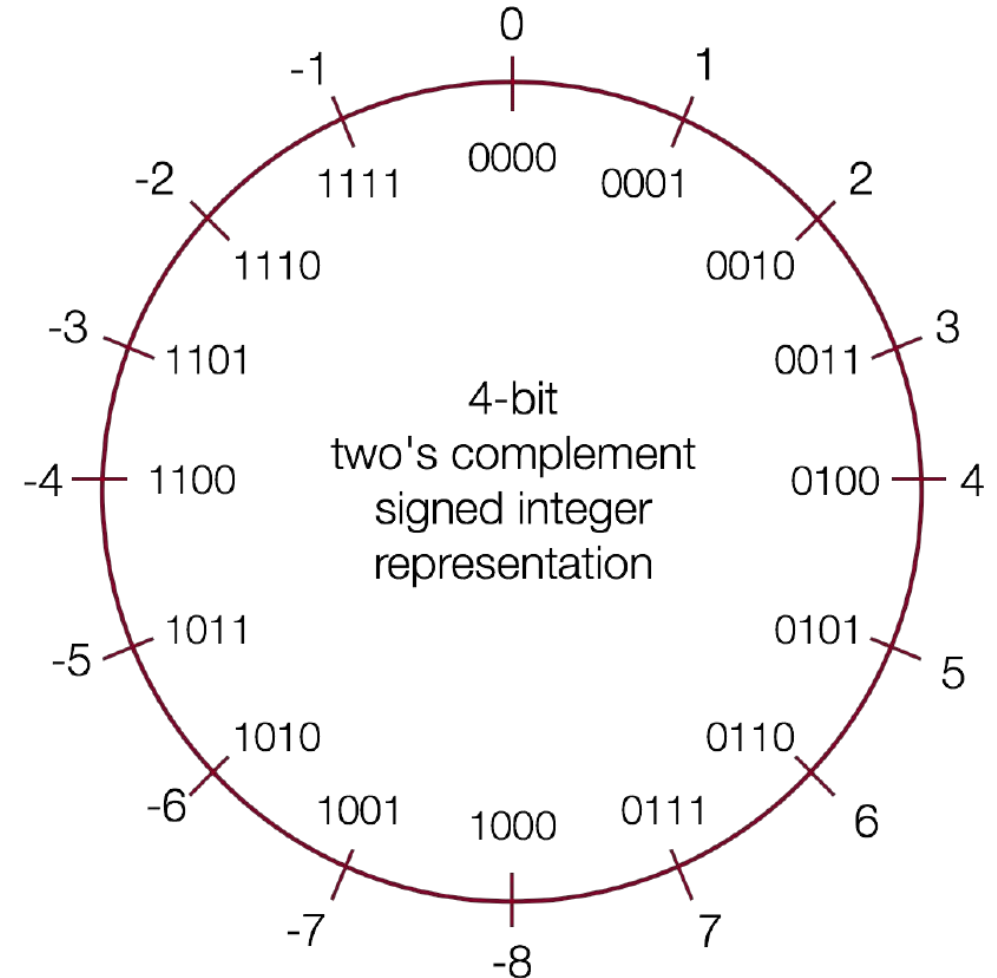
- Subtracting two numbers is just performing the two's complement on one of them and then adding. E.g.  $4 - 5 = -1$ .

0100	4		0100	4
-0101	5	→	+1011	-5
<hr/>			<hr/>	
			1111	-1

# Practice: Two's Complement

What are the negative or positive equivalents of the numbers below?

- a) -4 (1100)
- b) 7 (0111)
- c) 3 (0011)
- d) -8 (1000)



# Lecture Plan

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

# Overflow

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

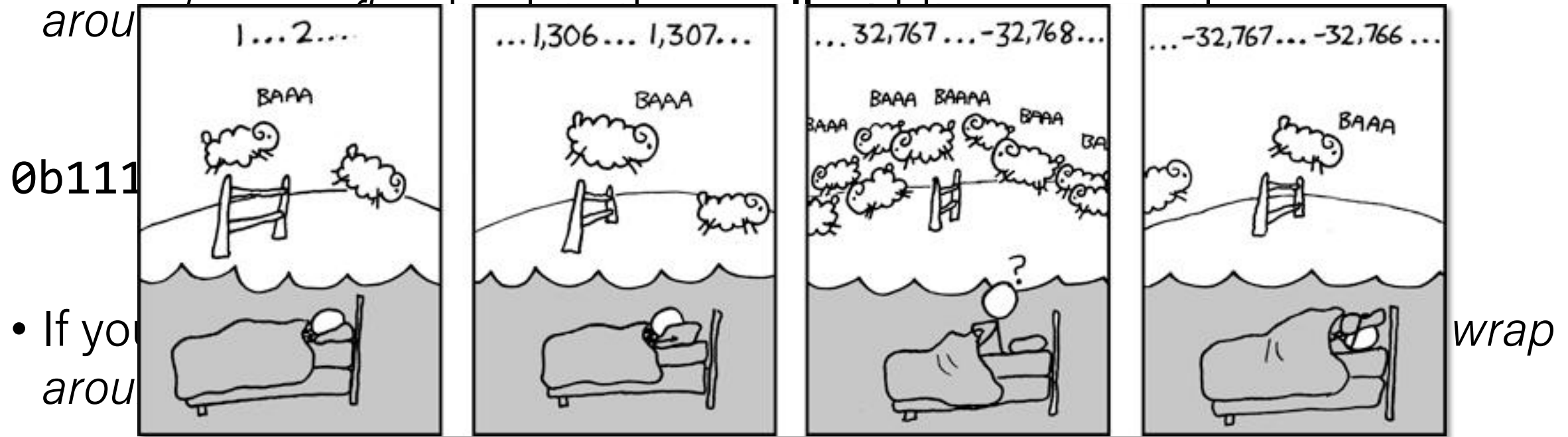
$$0b1111 + 0b1 = 0b0000$$

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

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

# Overflow

- If you exceed the **maximum** value of your bit representation, you *wrap around*



<https://xkcd.com/571> **Can't Sleep**

0b0000 - 0b1 = 0b1111

Title text: If androids someday DO dream of electric sheep, don't forget to declare sheepCount as a long int.



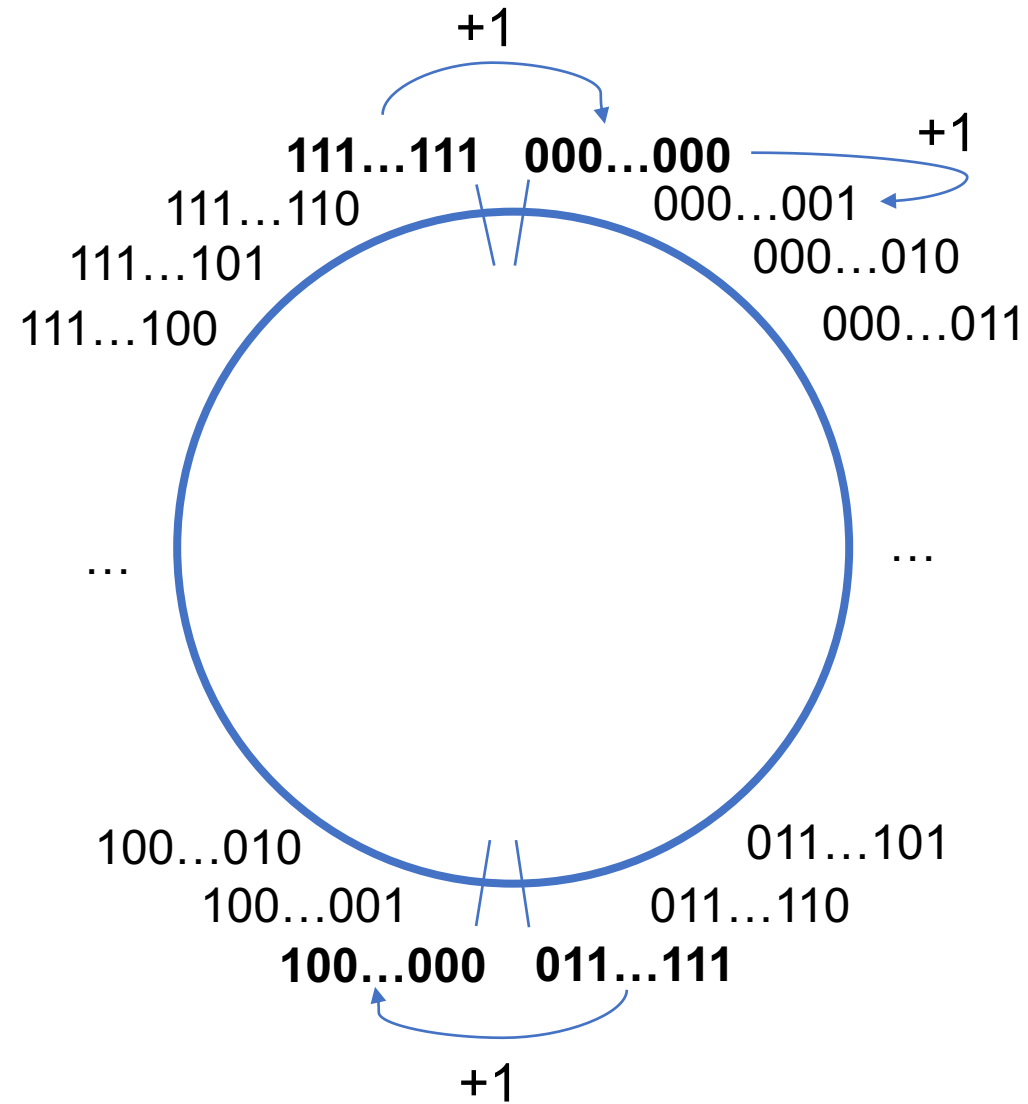
# Min and Max Integer Values

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

# Min and Max Integer Values

**INT\_MIN, INT\_MAX, UINT\_MAX, LONG\_MIN, LONG\_MAX, ULONG\_MAX, ...**

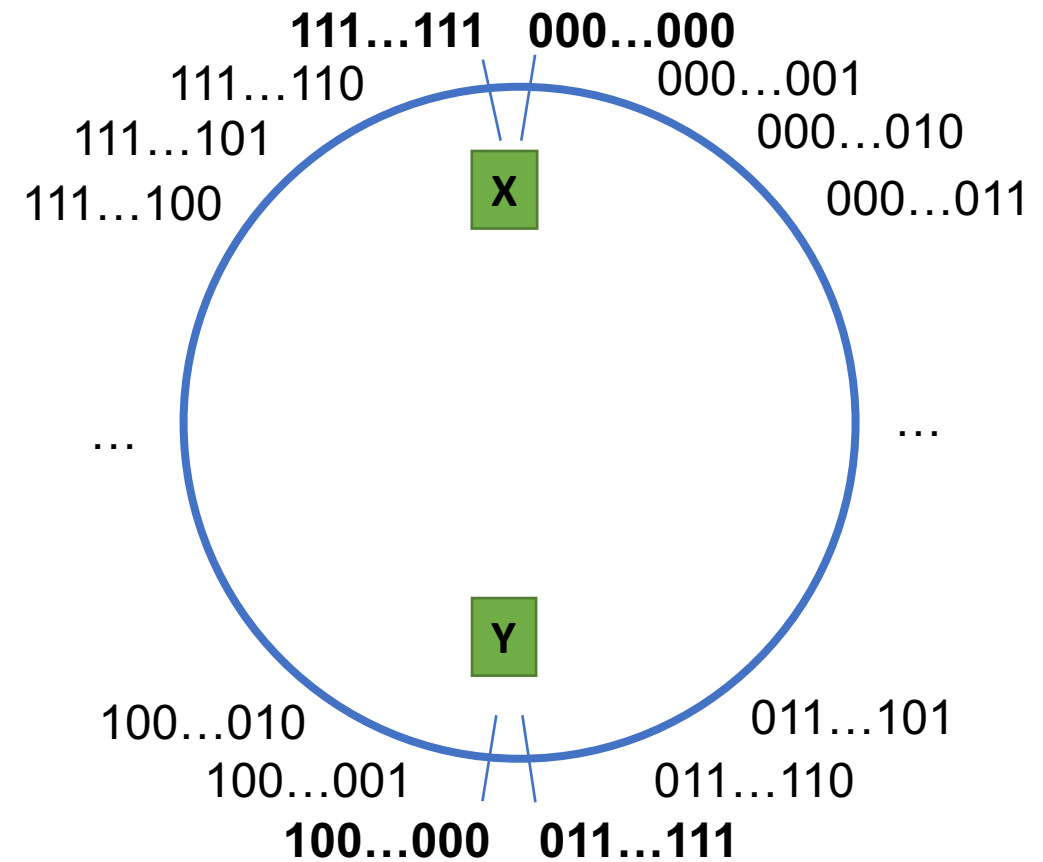
# Overflow



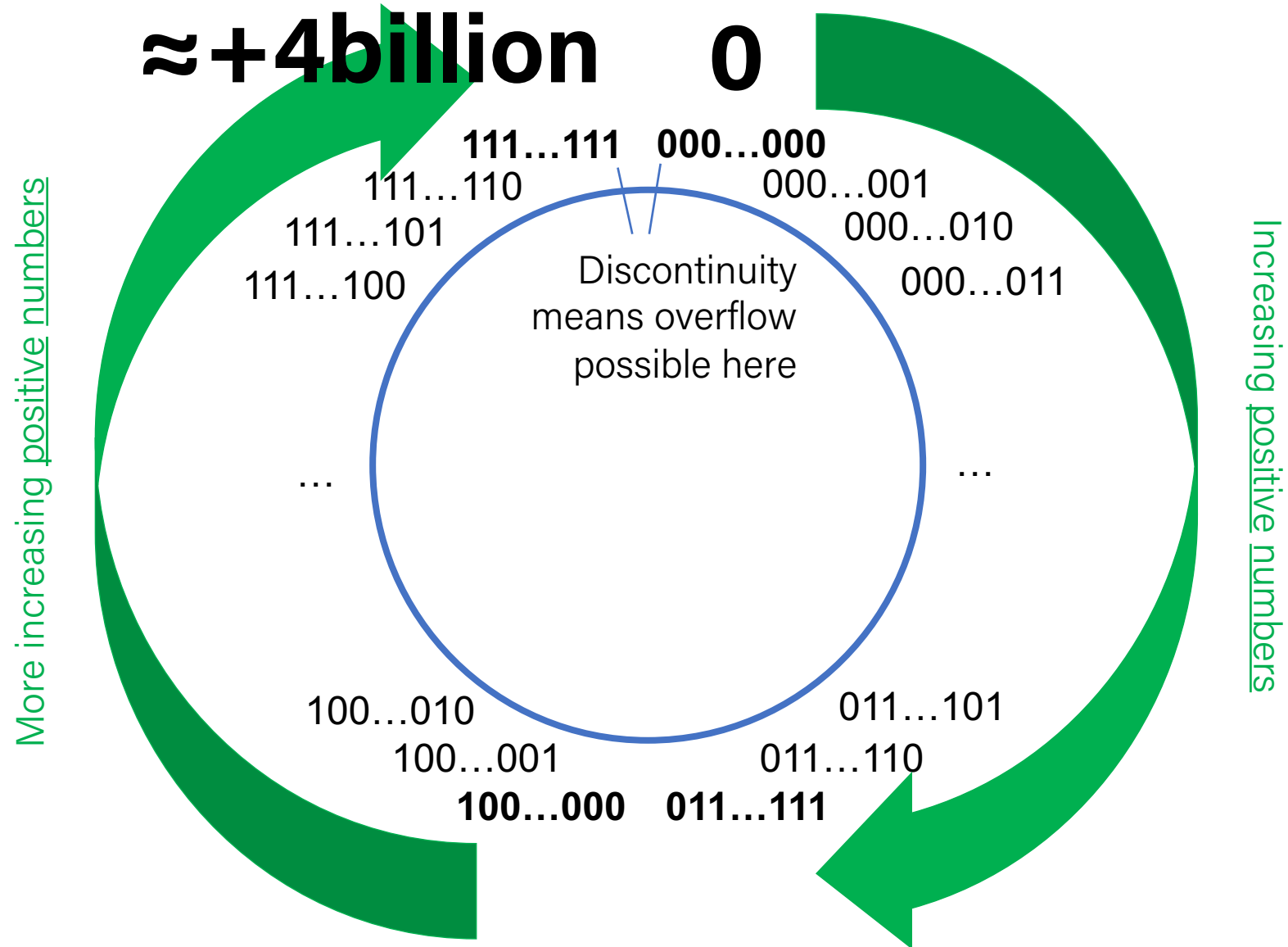
# Practice: Overflow

At which points can overflow occur for signed and unsigned int? (assume binary values shown are all 32 bits)

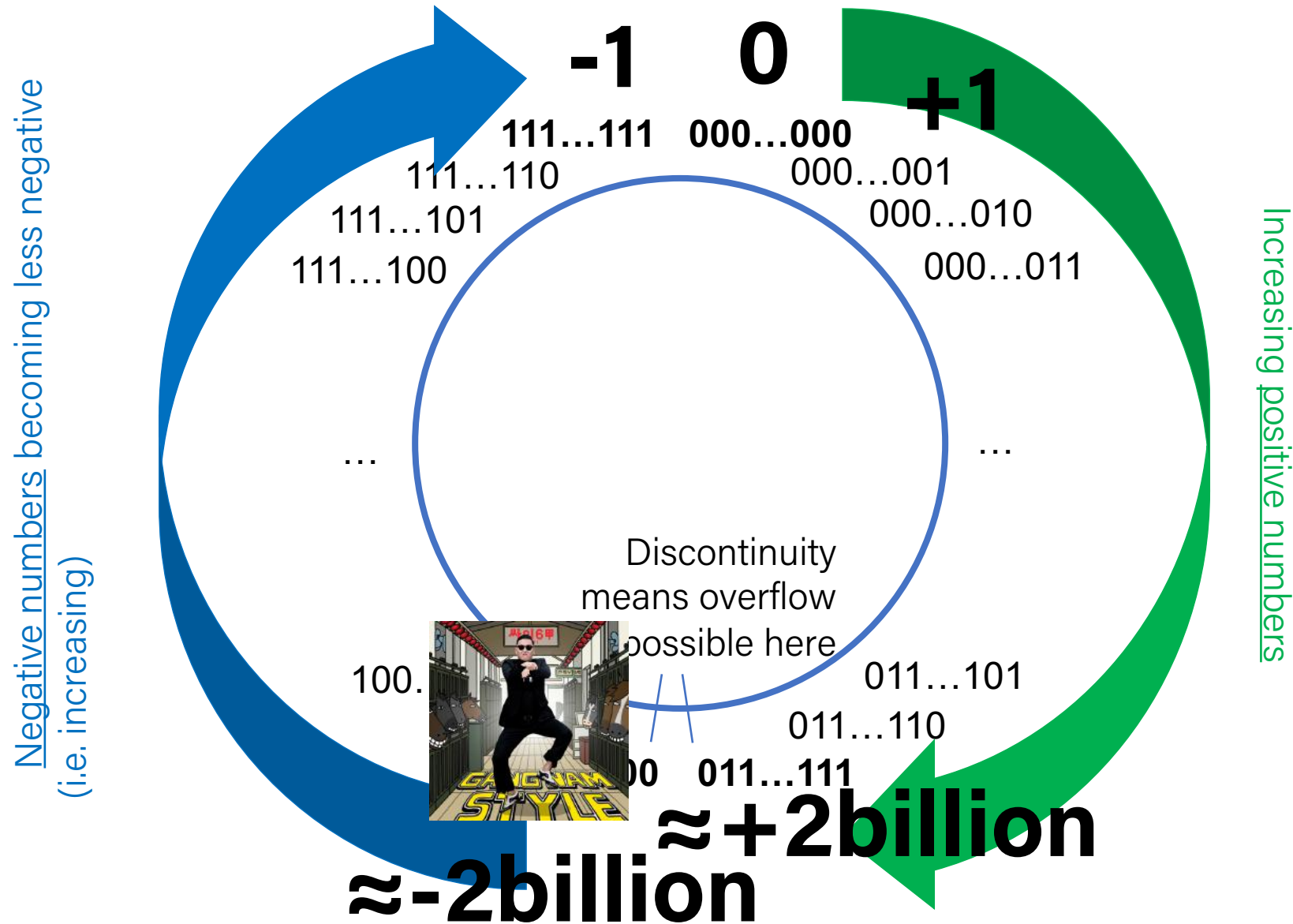
- A. Signed and unsigned can both overflow at points X and Y
- B. Signed can overflow only at X, unsigned only at Y
- C. Signed can overflow only at Y, unsigned only at X
- D. Signed can overflow at X and Y, unsigned only at X
- E. Other



# Unsigned Integers






# Signed Numbers




# Overflow In Practice: PSY



PSY - GANGNAM STYLE (강남스타일) M/V

 officialpsy 

 7,634,774

-2130754499

+ Add to  Share ... More

 8,871,284  1,154,582

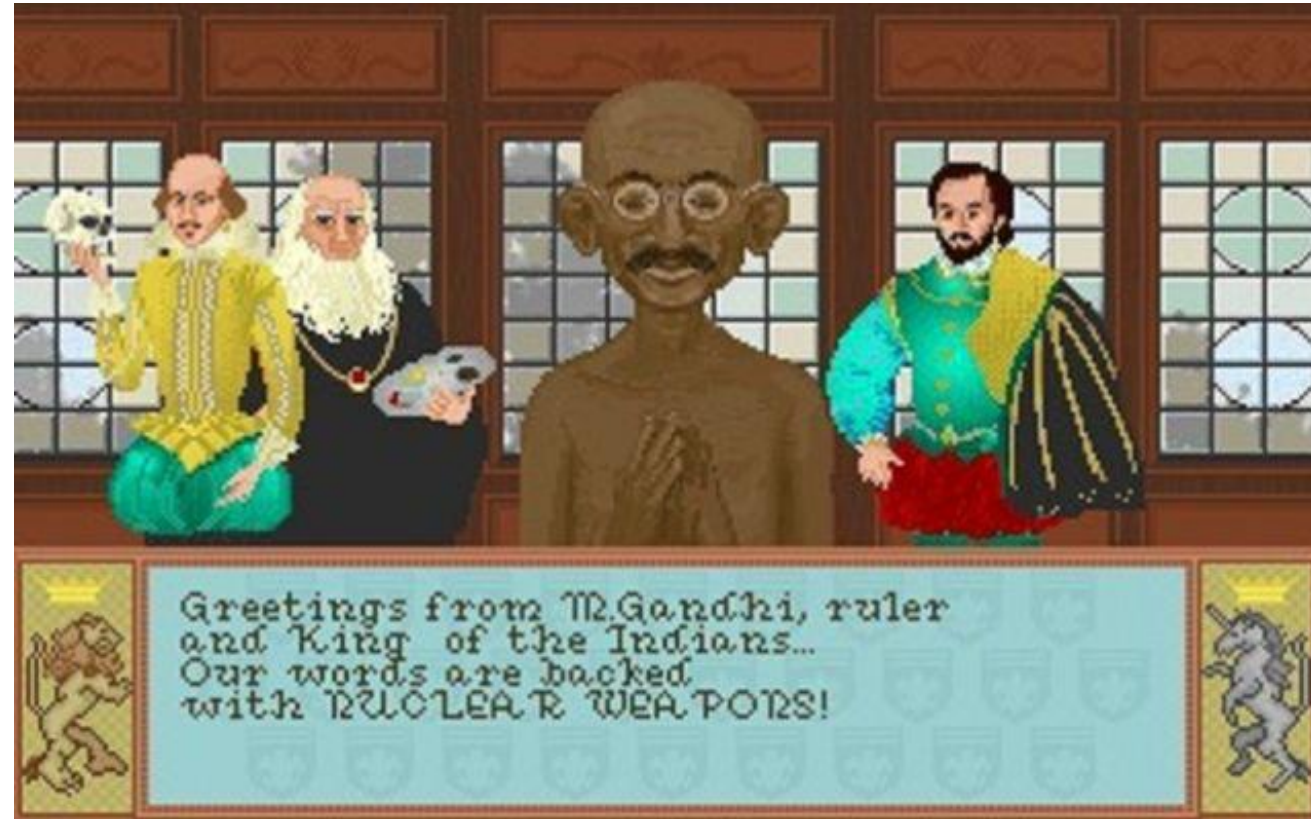
Published on Jul 15, 2012

► Watch HANGOVER feat. Snoop Dogg M/V @ <http://youtu.be/HkMNOIYcpHg>

**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)!"

# Overflow In Practice: Gandhi

- In the game "Civilization", each civilization leader had an "aggression" rating. Gandhi was meant to be peaceful, and had a score of 1.
- If you adopted "democracy", all players' aggression reduced by 2. Gandhi's went from 1 to **255**!
- Gandhi then became a big fan of nuclear weapons.

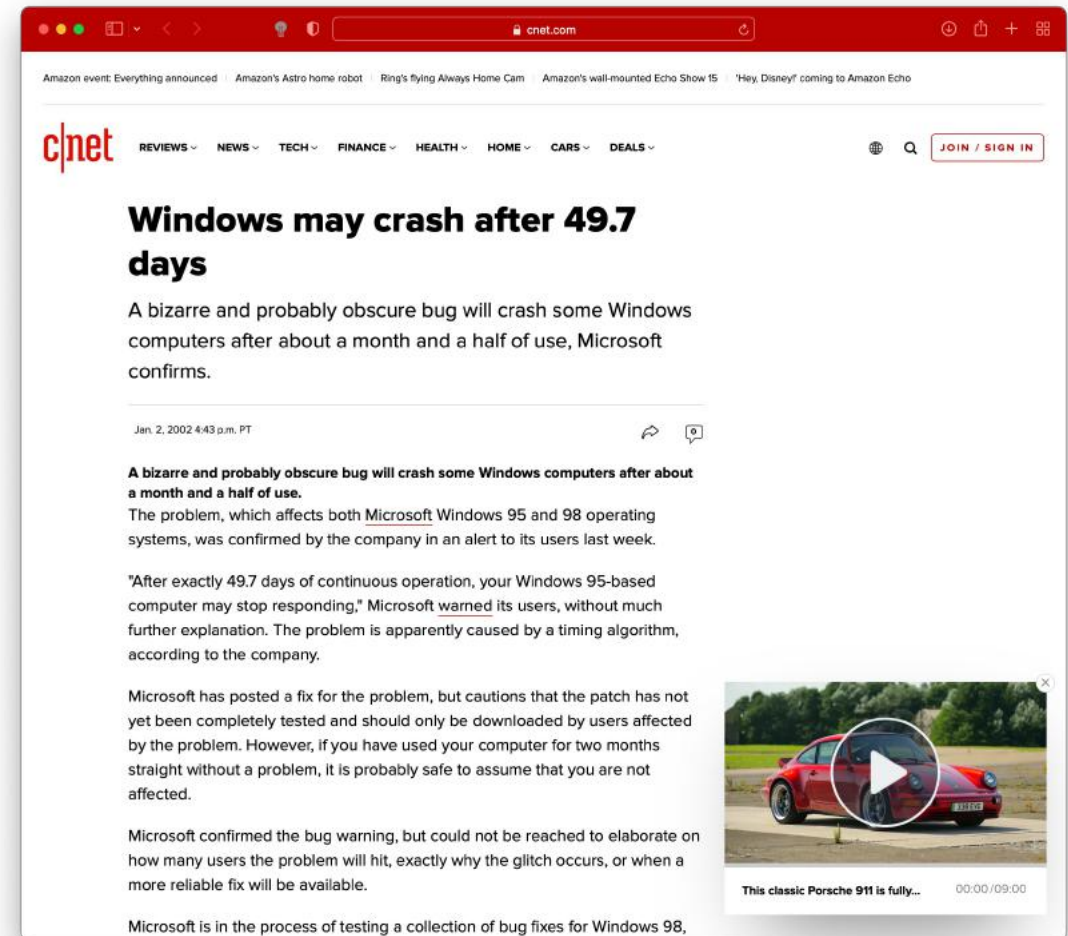


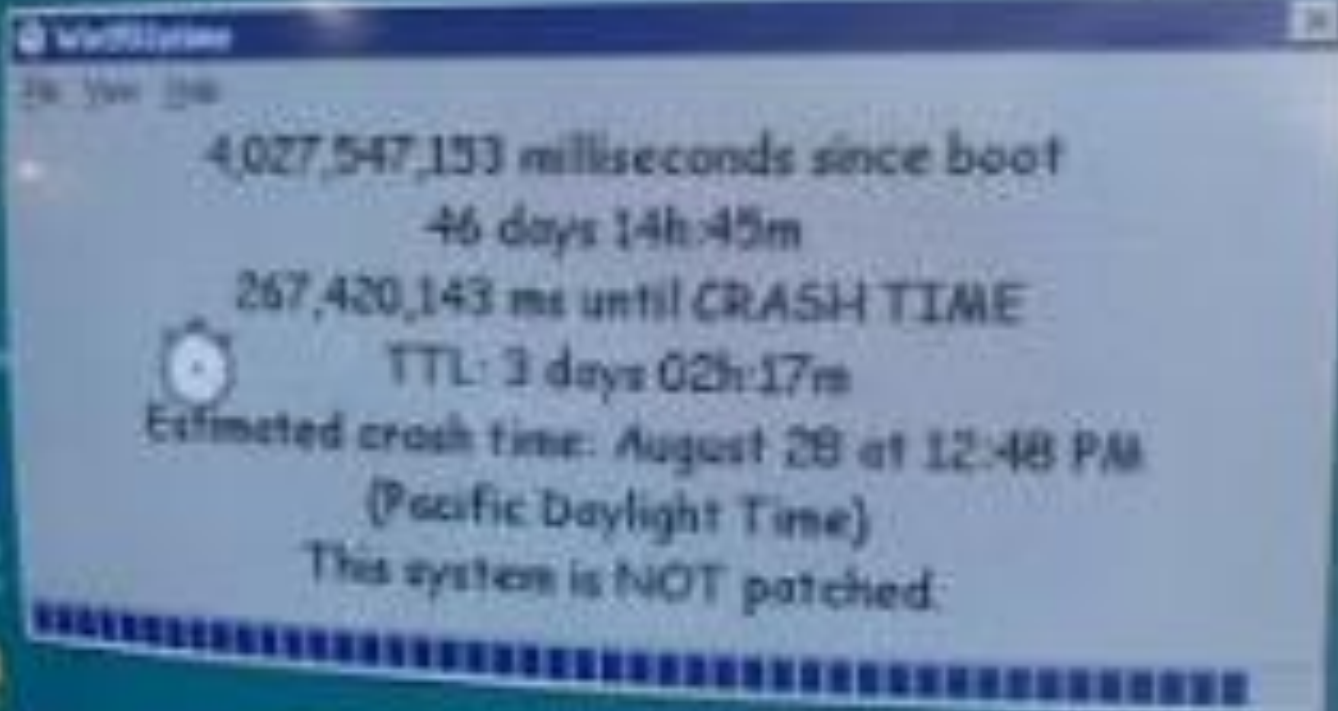
<https://kotaku.com/why-gandhi-is-such-an-asshole-in-civilization-1653818245>



# Windows 95 can only run for 49.7 days before crashing,

- Windows 95 was unable to run longer than 49.7 days of runtime!
- There exists `GetTickCount` function – part of the Windows API – which returns the number of milliseconds which has elapsed since the system has started up as a 32-bit uint.
- And there's 86M ms in a day, i.e.  $1000 * 60 * 60 * 24 = 86,400,000$  and 32 bits is 4,294,967,296 so  $4,294,967,296 / 86,400,000 = 49.7102696$  days!





<https://youtu.be/tdrRoSdBM5M>

# Overflow in Practice:

- [Pacman Level 256](#)
- Make sure to reboot Boeing Dreamliners [every 248 days](#)
- Comair/Delta airline had to [cancel thousands of flights](#) days before Christmas
- [Reported vulnerability CVE-2019-3857](#) in libssh2 may allow a hacker to remotely execute code
- [Donkey Kong Kill Screen](#)

# Demo Revisited: Unexpected Behavior



airline.c

# Lecture Plan

- Bits and Bytes
- Hexadecimal
- Integer Representations
- Unsigned Integers
- Signed Integers
- Overflow
- Casting and Combining Types

# printf and Integers

- There are 3 placeholders for 32-bit integers that we can use:
  - %d: signed 32-bit int
  - %u: unsigned 32-bit int
  - %x: hex 32-bit int
- The placeholder—not the expression filling in the placeholder—dictates what gets printed!

# Casting

- What happens at the byte level when we cast between variable types? The bytes remain the same! **This means they may be interpreted differently depending on the type.**

```
int v = -12345;  
unsigned int uv = v;  
printf("v = %d, uv = %u\n", v, uv);
```

This prints out: "v = -12345, uv = 4294954951". Why?

# Casting

- What happens at the byte level when we cast between variable types? The bytes remain the same! **This means they may be interpreted differently depending on the type.**

```
int v = -12345;  
unsigned int uv = v;  
printf("v = %d, uv = %u\n", v, uv);
```

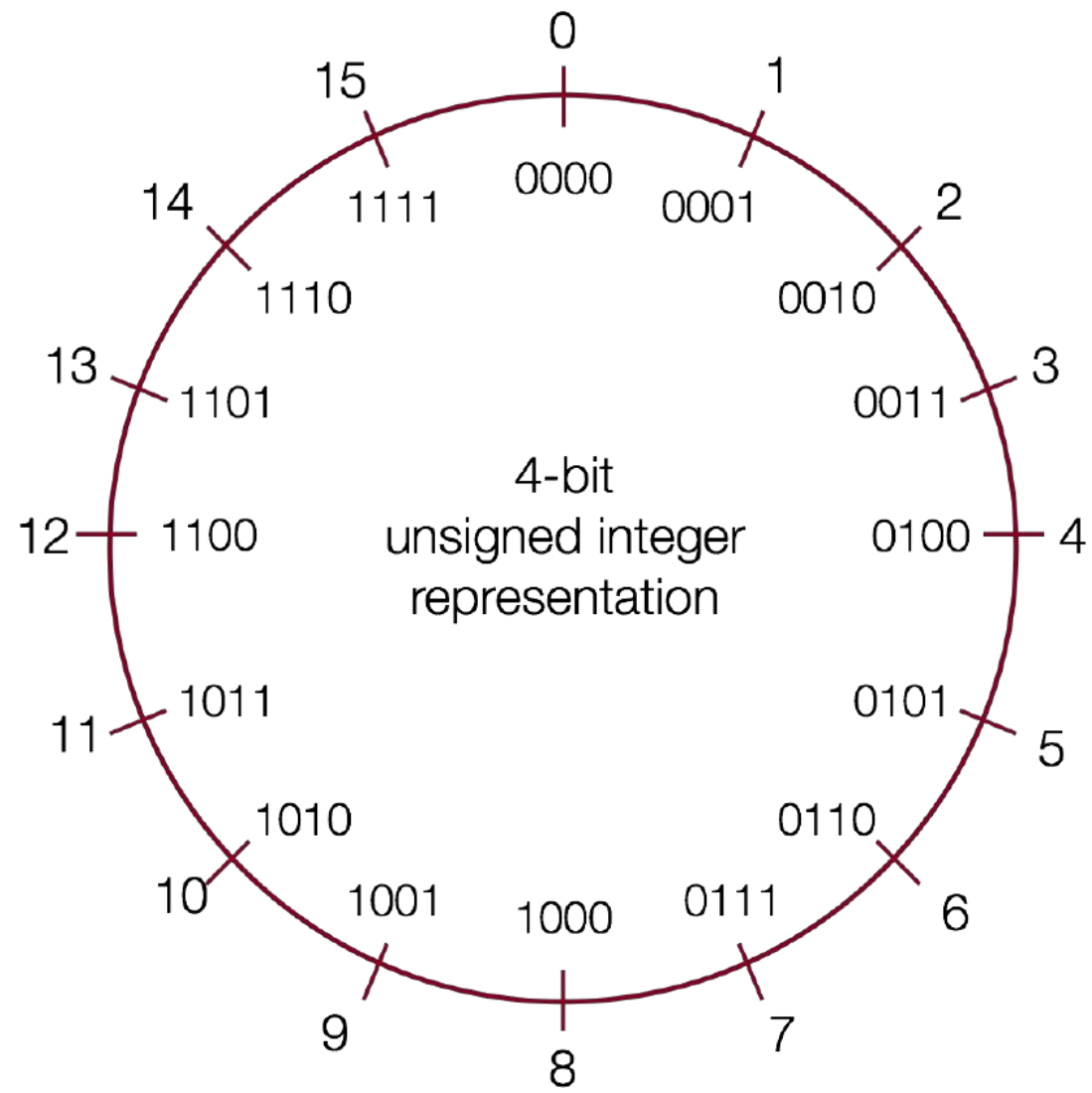
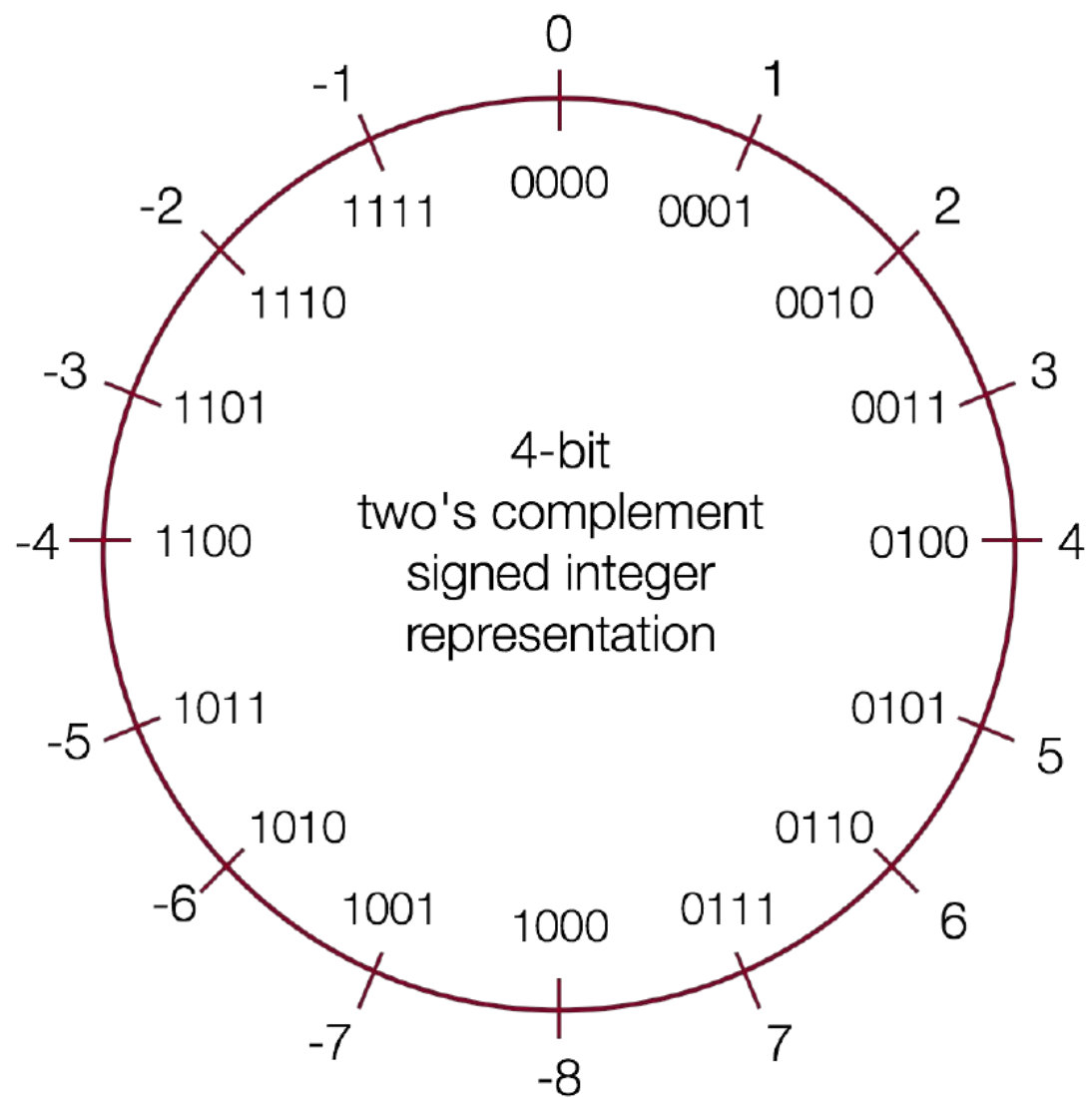
The bit representation for -12345 is

0b**11111111111111111111111100111111000111**.

If we treat this binary representation as a positive number, it's *huge*!



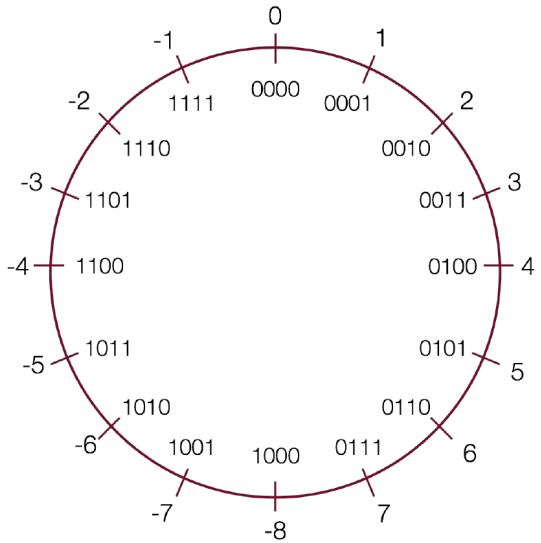
# Casting



# Comparisons Between Different Types

- **Be careful** when comparing signed and unsigned integers. **C will implicitly cast** the signed argument to unsigned, and then performs the operation assuming both numbers are non-negative.

Expression	Type	Evaluation	Correct?
0 == 0U	Unsigned	1	yes
-1 < 0	Signed	1	yes
-1 < 0U	Unsigned	0	No!
2147483647 > -2147483647 - 1	Signed	1	yes
2147483647U > -2147483647 - 1	Unsigned	0	No!
2147483647 > (int)2147483648U	Signed	1	No!
-1 > -2	Signed	1	yes
(unsigned)-1 > -2	Unsigned	1	yes



Type	Size (Bytes)	Minimum	Maximum
int	4	-2147483648	2147483647
unsigned int	4	0	4294967295

# Comparisons Between Different Types

Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

**s3 > u3**

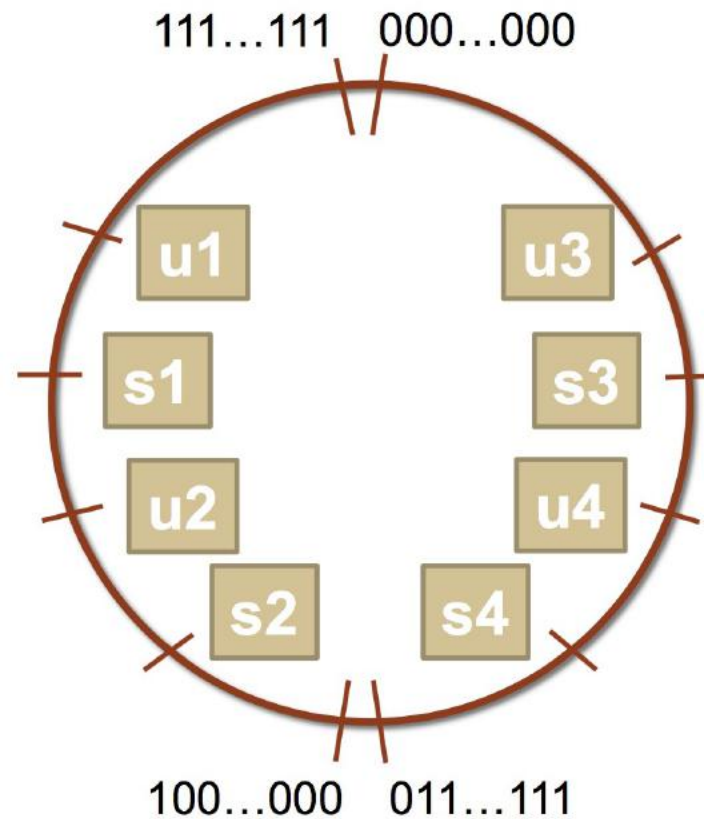
**u2 > u4**

**s2 > s4**

**s1 > s2**

**u1 > u2**

**s1 > u3**



# Comparisons Between Different Types

Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

**s3 > u3 - true**

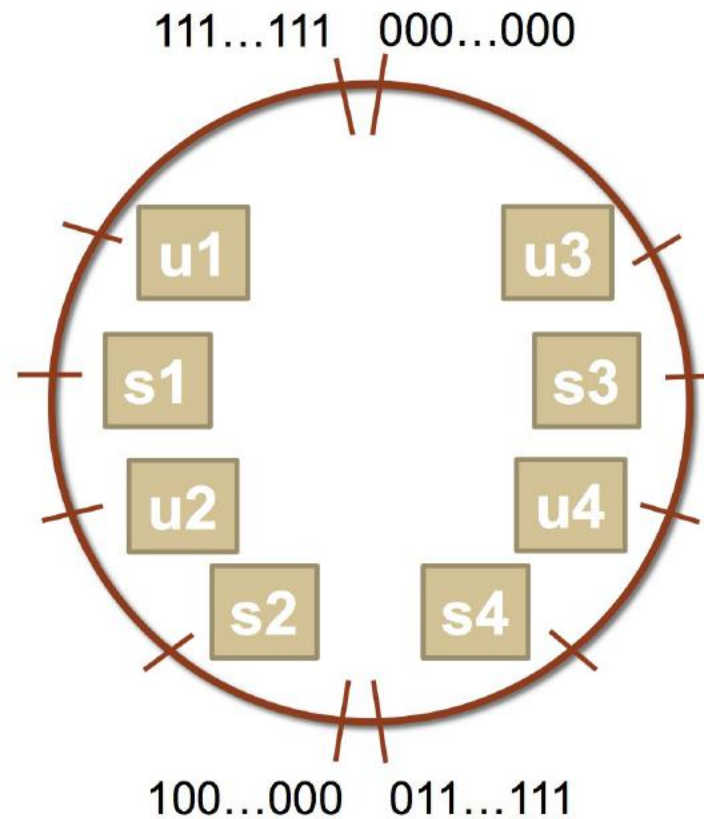
u2 > u4

s2 > s4

s1 > s2

u1 > u2

s1 > u3



# Comparisons Between Different Types

Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

**s3 > u3 - true**

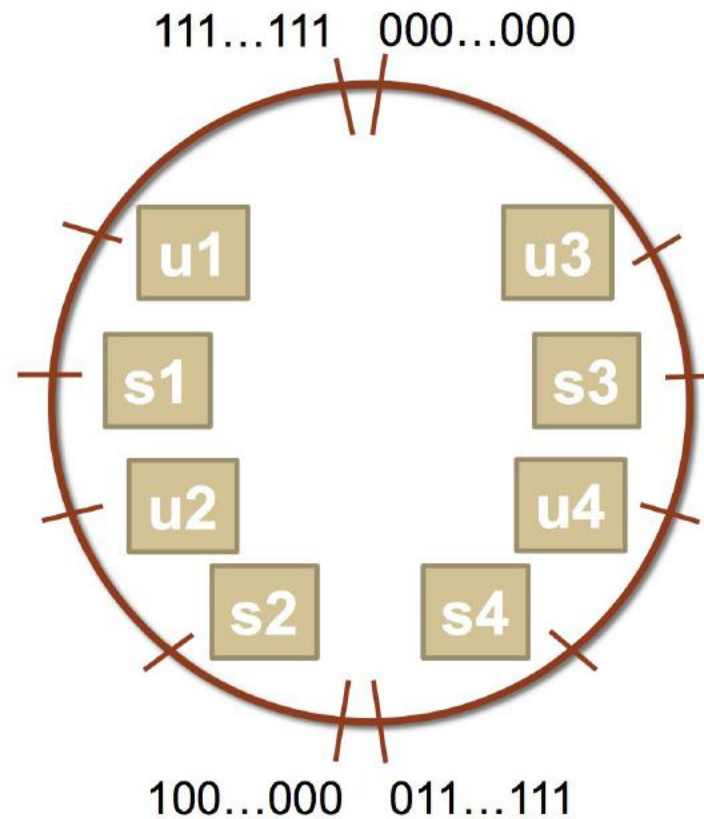
**u2 > u4 - true**

**s2 > s4**

**s1 > s2**

**u1 > u2**

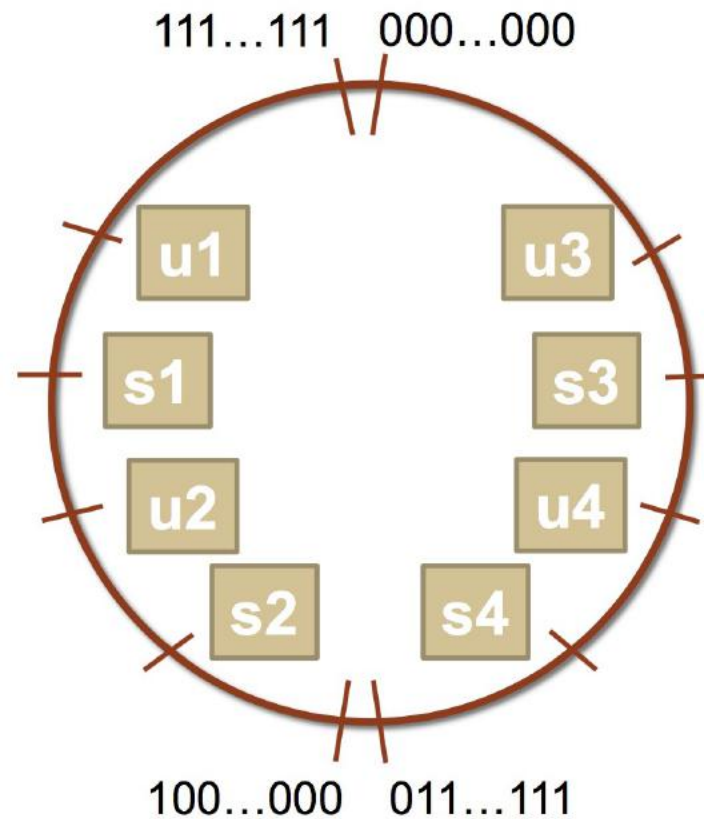
**s1 > u3**



# Comparisons Between Different Types

Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

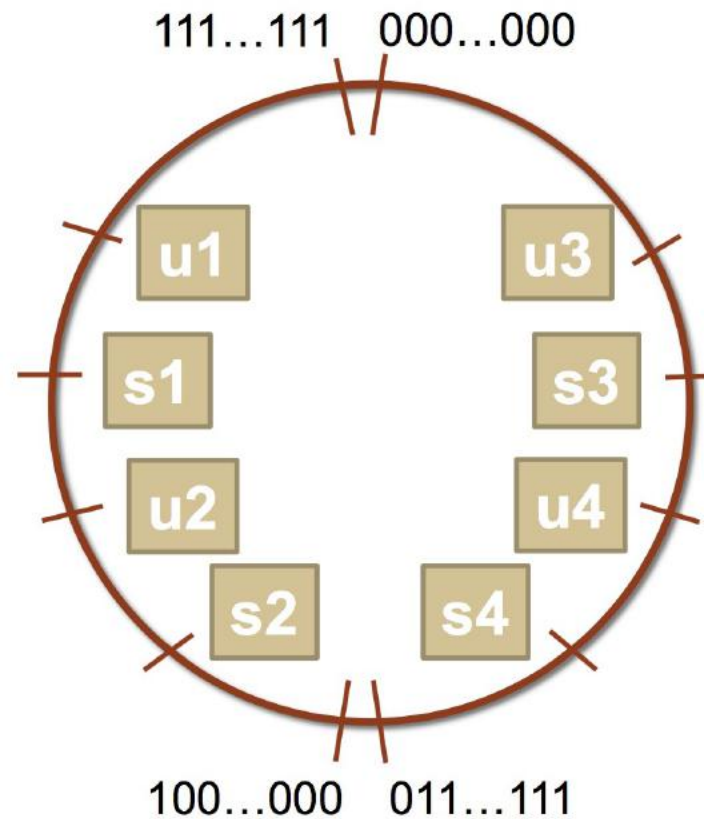
**s3 > u3 - true**  
u2 > u4 - true  
s2 > s4 - false  
s1 > s2  
u1 > u2  
s1 > u3



# Comparisons Between Different Types

Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

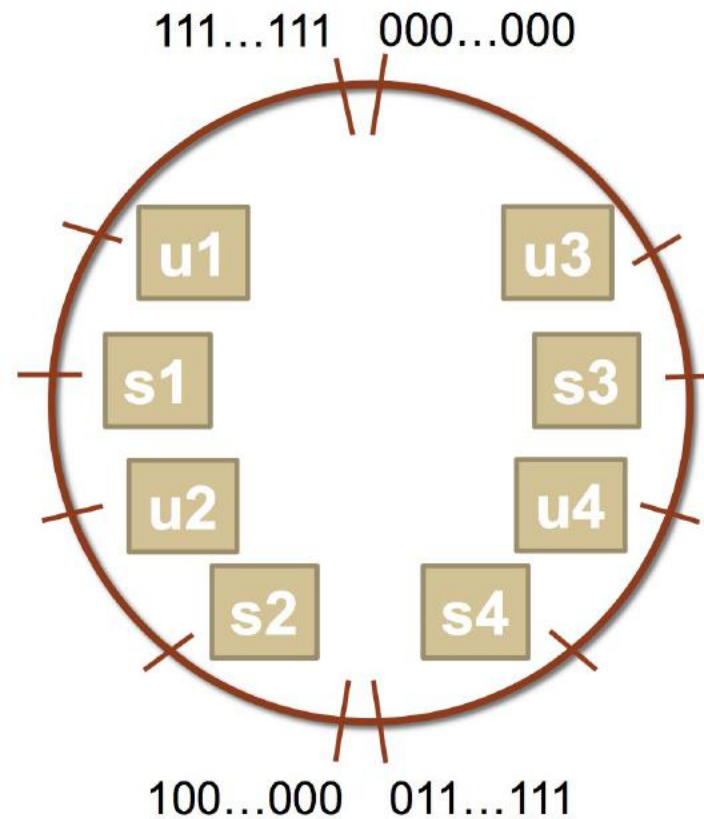
**s3 > u3 - true**  
u2 > u4 - true  
s2 > s4 - false  
s1 > s2 - true  
u1 > u2  
s1 > u3



# Comparisons Between Different Types

Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

**s3 > u3 - true**  
u2 > u4 - true  
s2 > s4 - false  
s1 > s2 - true  
u1 > u2 - true  
s1 > u3

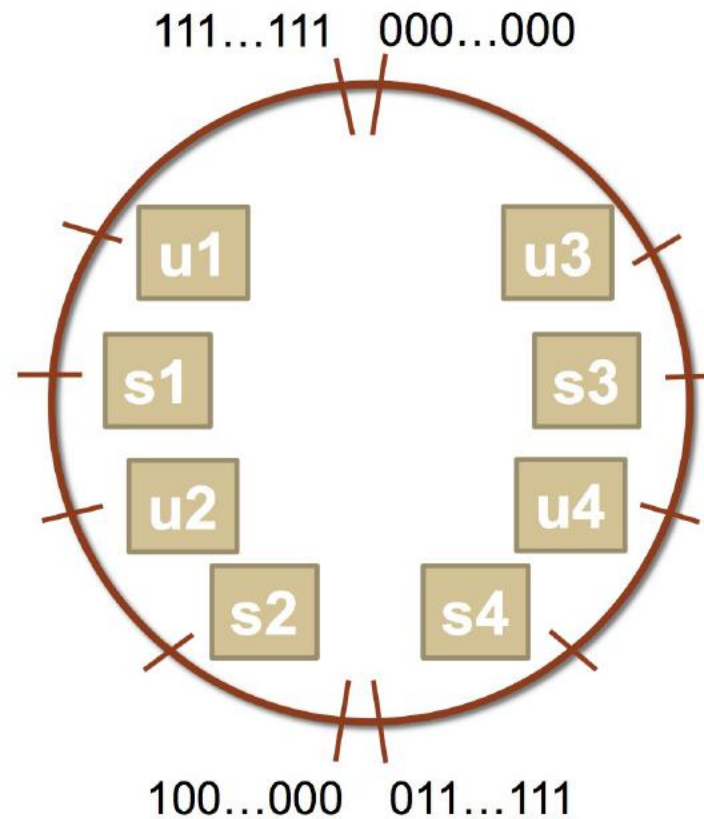




# Comparisons Between Different Types

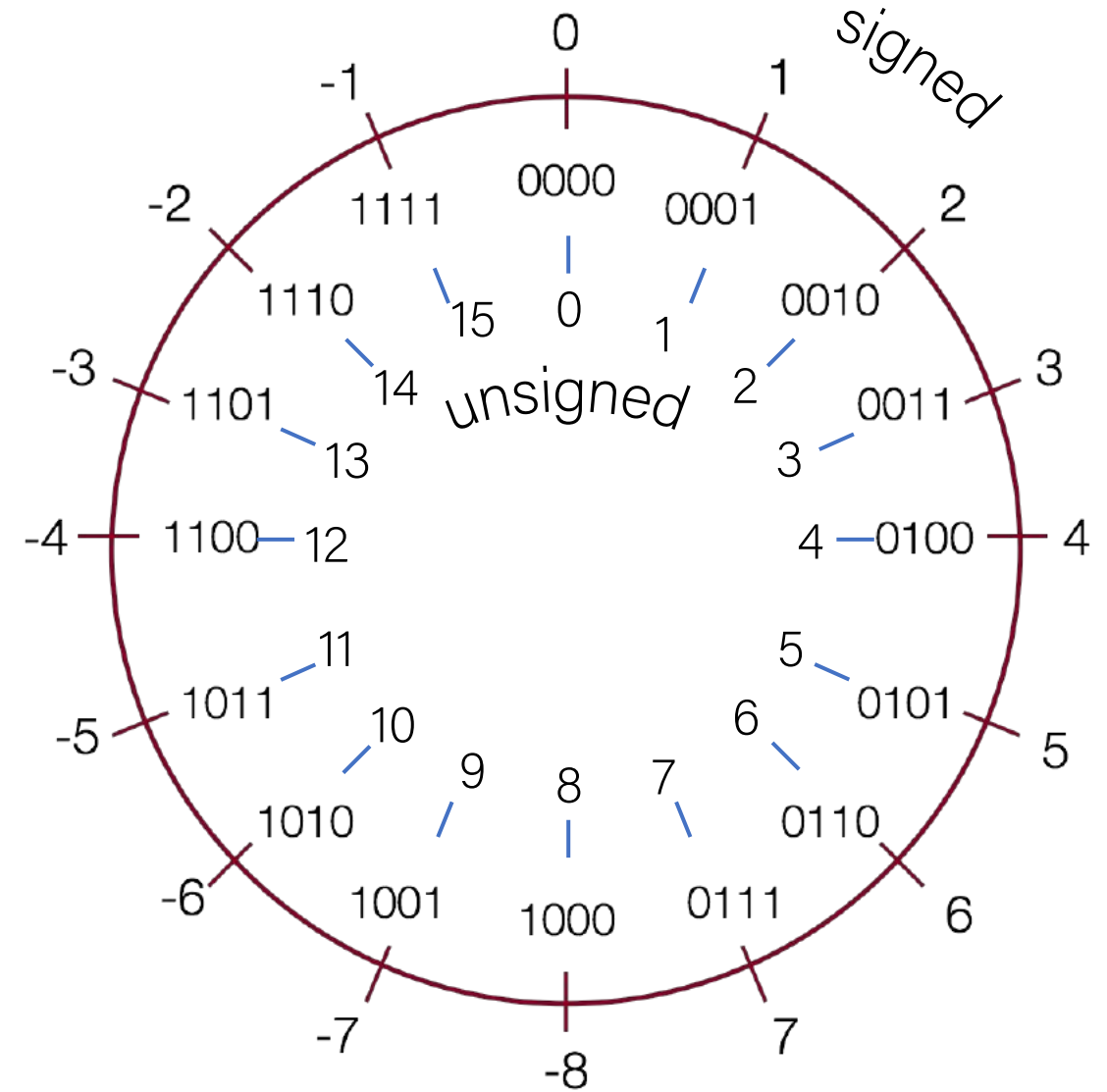
Which many of the following statements are true? (*assume that variables are set to values that place them in the spots shown*)

**s3 > u3 - true**  
u2 > u4 - true  
s2 > s4 - false  
s1 > s2 - true  
u1 > u2 - true  
**s1 > u3 - true**



# Recap

- Getting Started With C
- Bits and Bytes
- Hexadecimal
- Integer Representations
- Unsigned Integers
- Signed Integers
- Overflow



**Next time:** How can we manipulate individual bits and bytes? How can we represent floating point numbers?