CS107 Winter 2020, Lecture 2
Bits and Bytes; Integer Representations

reading:

Bryant & O'Hallaron, Ch. 2.2-2.3

Slides by Jerry Cain and Lisa Yan, who leveraged prior work by Nick Troccoli, Julie Zelenski, Marty Stepp, Cynthia Lee, Chris Gregg, and others.

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

Demo: Unexpected Behavior

```
cp -r /afs/ir/class/cs107/samples/lectures/lect2 .
```

Plan For Today

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

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Introducing 0

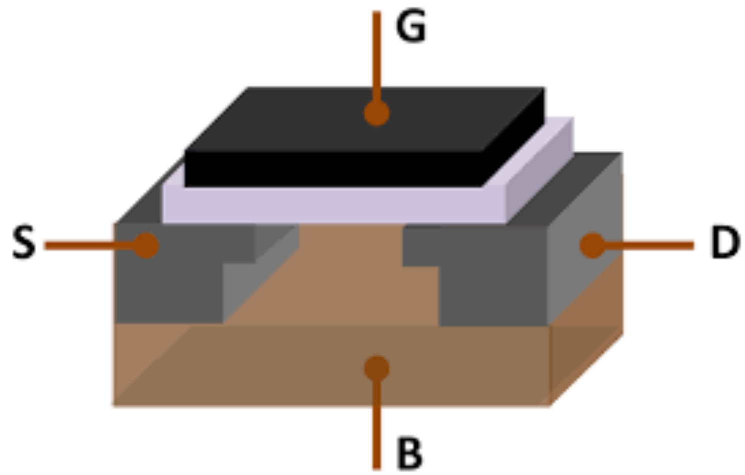
0

Introducing 0’s Sidekick: 1

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, as 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!
  - Text
  - Images
  - Audio
  - Video
  - 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

$\mathbf{2}^{X}$: 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

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

Base 10 to Base 2

Question: What is 6 in base 2?

- Strategy:
  - What is the largest power of 2 $\leq$ 6?

Base 10 to Base 2

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- Strategy:
  - What is the largest power of 2 ≤ 6? **2^2=4**

0	1	_	_
2^3	2^2	2^1	2^0

Base 10 to Base 2

Question: What is 6 in base 2?

- Strategy:
  - What is the largest power of 2 ≤ 6? **2^2=4**
  - Now, what is the largest power of 2 ≤ 6 – 2^2?

0	1	___	___
2^3	2^2	2^1	2^0

Base 10 to Base 2

Question: What is 6 in base 2?

- Strategy:
  - What is the largest power of 2 ≤ 6? $\mathbf{2^2=4}$
  - Now, what is the largest power of 2 ≤ 6 – 2^2? $\mathbf{2^1=2}$

0	1	1	_
2^3	2^2	2^1	2^0

Base 10 to Base 2

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  - Now, what is the largest power of 2 ≤ 6 – 2^2? $\mathbf{2^1=2}$
  - 6 – 2^2 – 2^1 = 0!

0	1	1	_
2^3	2^2	2^1	2^0

Base 10 to Base 2

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

Base 10 to Base 2

Question: What is 6 in base 2?

- Strategy:
  - What is the largest power of 2 ≤ 6? $\mathbf{2^2=4}$
  - Now, what is the largest power of 2 ≤ 6 – 2^2? $\mathbf{2^1=2}$
  - $6 - 2^2 - 2^1 = 0$!

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

= **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?

Byte Values

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Byte Values

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

Byte Values

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

11111111

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

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

Byte Values

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

11111111

2^x: 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 x 10 = 1450**0**

1100_2 x 2 = 1100**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!

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Hexadecimal

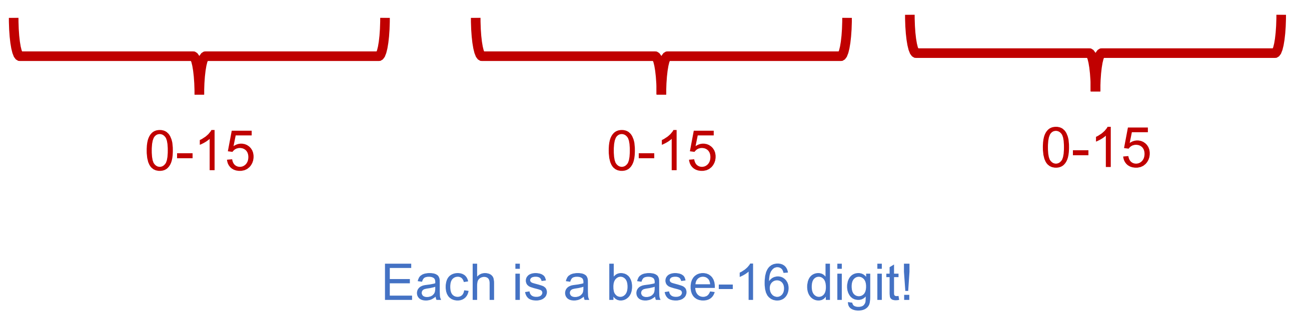
- When working with bits, often times we have large numbers with 32 or 64 bits.
- Instead, we'll represent bits in *base-16* instead*;* this is called **hexadecimal**.

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**.



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

Practice: Hexadecimal to Binary

What is **`0x173A`** in binary?

Hexadecimal	**1**	**7**	**3**	**A**
Binary	**0001**	**0111**	**0011**	**1010**

Practice: Hexadecimal to Binary

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

Binary	**11**	**1100**	**1010**
Hexadecimal	**3**	**C**	**A**

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Number Representations

- **Unsigned Integers**: positive integers, and 0. (e.g. 0, 1, 2, … 99999…
- **Signed Integers:** negative, positive and 0. (e.g. …-2, -1, 0, 1,… 9999…)

- **Floating Point Numbers:** real numbers. (e,g. 0.1, -12.2, $1.5\text{x}10^{12}$)

Number Representations

- **Unsigned Integers**: positive integers, and 0. (e.g. 0, 1, 2, … 99999…
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- **Floating Point Numbers:** real numbers. (e,g. 0.1, -12.2, 1.5×10^{12})

→ Stay tuned until week 5!

Number Representations

C Declaration	Size (Bytes)
`int`	4
`double`	8
`float`	4
`char`	1
`char *`	8
`short`	2
`long`	8

In The Days Of Yore…

C Declaration	Size (Bytes)
`int`	4
`double`	8
`float`	4
`char`	1
`char *`	4
`short`	2
`long`	4

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 some fundamental datatypes got bigger; pointers, for instance, needed to be **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 up to **1024*1024*1024 GB** of memory (RAM)!

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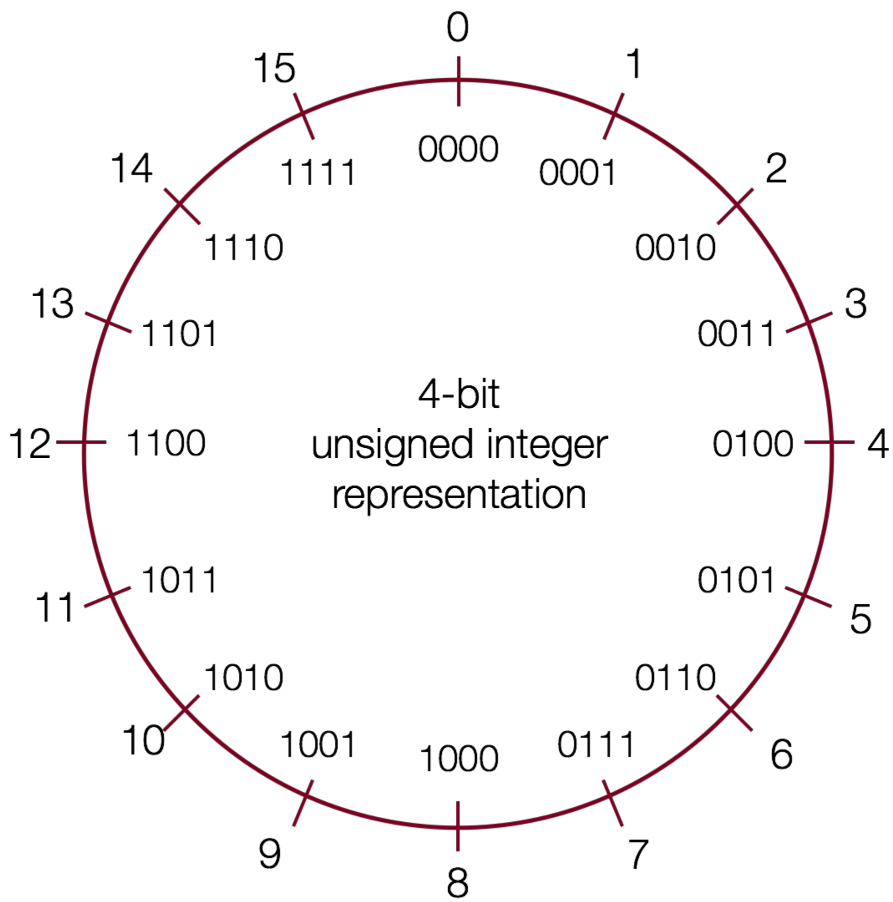
Unsigned Integers

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

```
0b0001 = 1
0b0101 = 5
0b1011 = 11
0b1111 = 15
```

- The range of an unsigned number is 0 → 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



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Announcements

- Sign up for Piazza on the Help page if you haven't already!
- Lab signups opened this morning at 10:30am, and they start next week.
  - Lab materials posted on the course website at the start of each week
- Helper Hours started earlier this week
- Assignment 0 due Monday evening.
  - No grace period for this one. We want to grade it immediately!
- Assignment 1 goes out this coming Monday, will exercise material from today and this coming Monday.

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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

0110

positive 6

1011

negative 3

Sign Magnitude Representation

0000

positive 0

1000

negative 0

Sign Magnitude Representation

1 000 = -0	0 000 = 0
1 001 = -1	0 001 = 1
1 010 = -2	0 010 = 2
1 011 = -3	0 011 = 3
1 100 = -4	0 100 = 4
1 101 = -5	0 101 = 5
1 110 = -6	0 110 = 6
1 111 = -7	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 should just work regardless of whether the numbers are positive or negative.

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

A Better Idea

- Ideally, binary addition should just work regardless of whether the numbers are positive or negative.

```
  0101
+ 1011
------
  0000
```

A Better Idea

- Ideally, binary addition should just work regardless of whether the numbers are positive or negative.

```
  0011
+ ????
------
  0000
```

A Better Idea

- Ideally, binary addition should just work regardless of whether the numbers are positive or negative.

```
  0011
+ 1101
------
  0000
```

A Better Idea

- Ideally, binary addition should just work regardless of whether the numbers are positive or negative.

```
  0000
+ ????
  ----
  0000
```

A Better Idea

- Ideally, binary addition should just work regardless of whether the numbers are positive or negative.

```
  0000
+ 0000
  ----
  0000
```

There Seems Like a Pattern Here…

0101	0011	0000
+ 1011	+ 1101	+ 0000
0000	0000	0000

- 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.

```
  0101
+ 1010
  ----
  1111
```

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

```
  1111
+ 0001
  ----
  0000
```

Another Trick

- To compute the negative 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.

```
  100100
+ ??????
  ------
  000000
```

Another Trick

- To compute the negative 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.

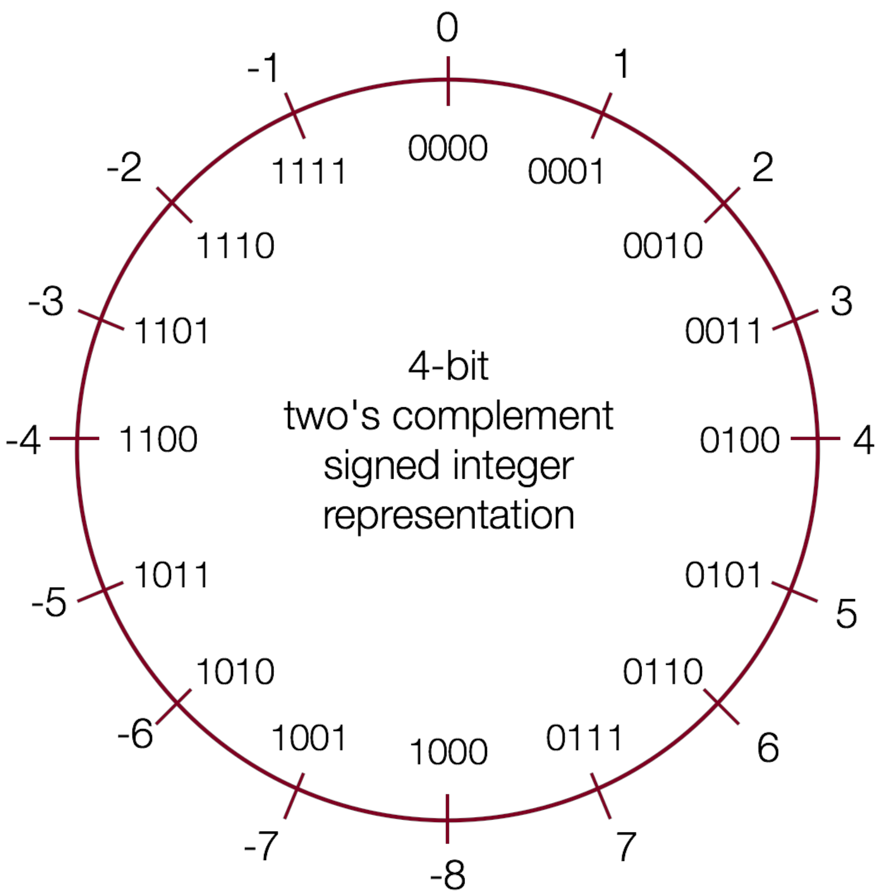
$$
\begin{array}{r}
100100 \\
+\;???100 \\
\hline
000000
\end{array}
$$

Another Trick

- To compute the negative 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.

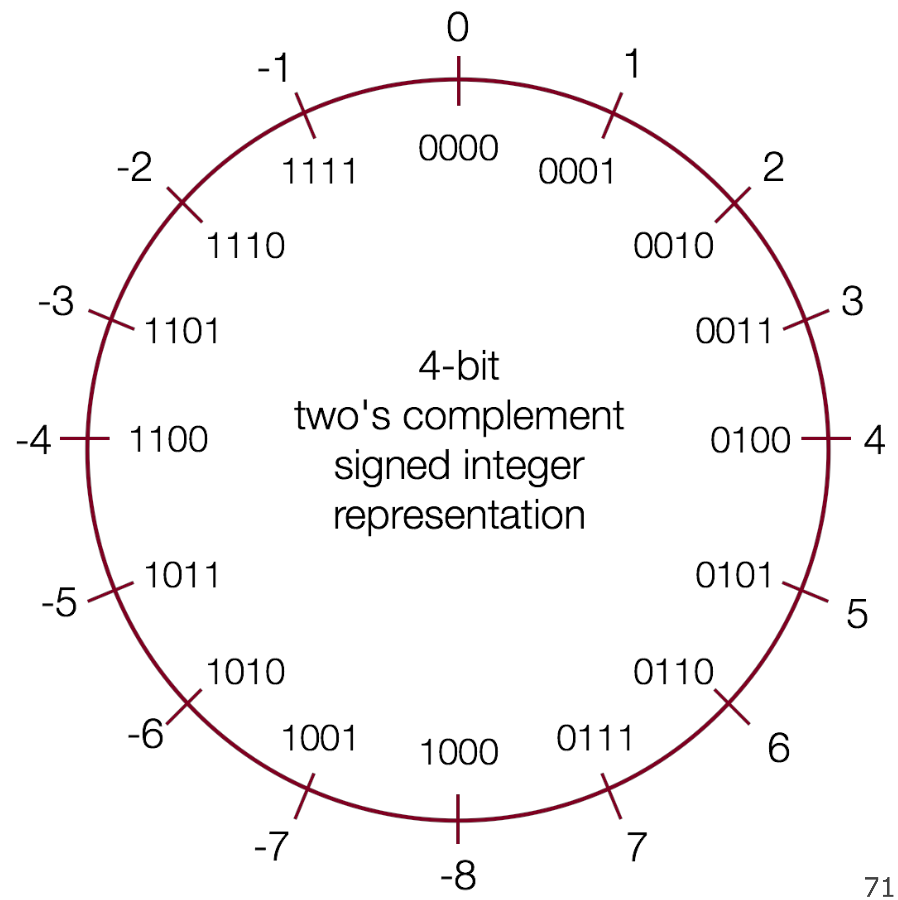
$$
\begin{array}{r}
100100 \\
+\ 011100 \\
\hline
000000
\end{array}
$$

Two’s Complement



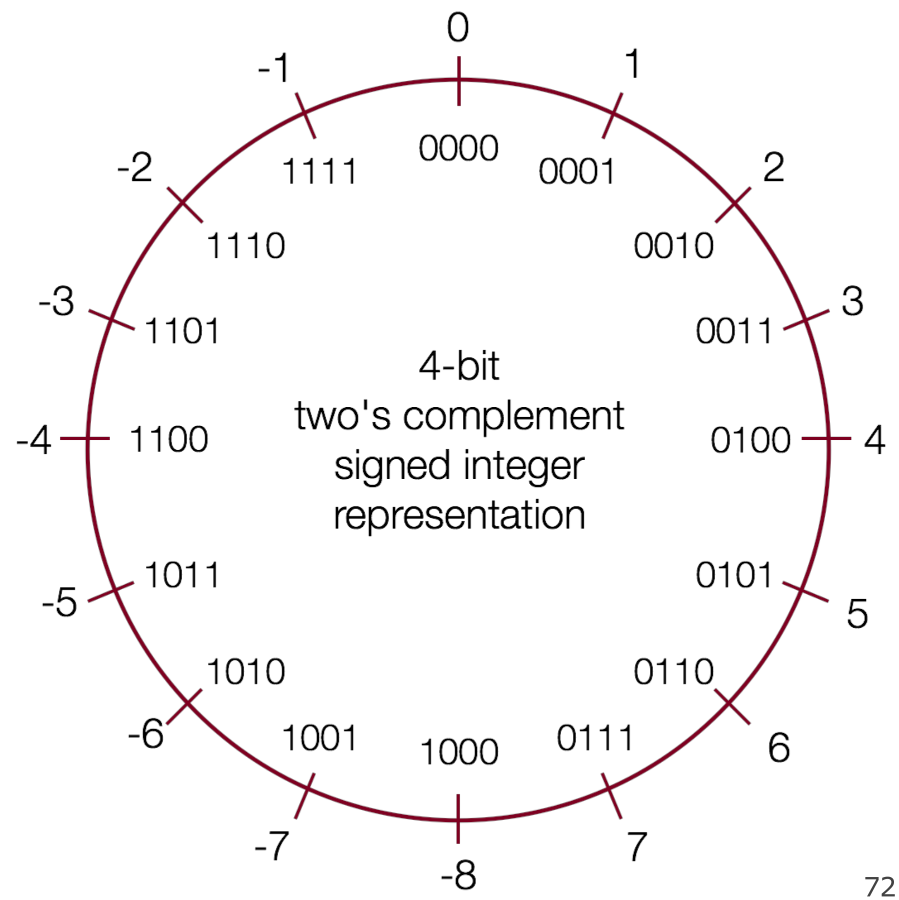
Two’s Complement

- 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?

	0010	2
+	1011	-5
	1101	-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
			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)

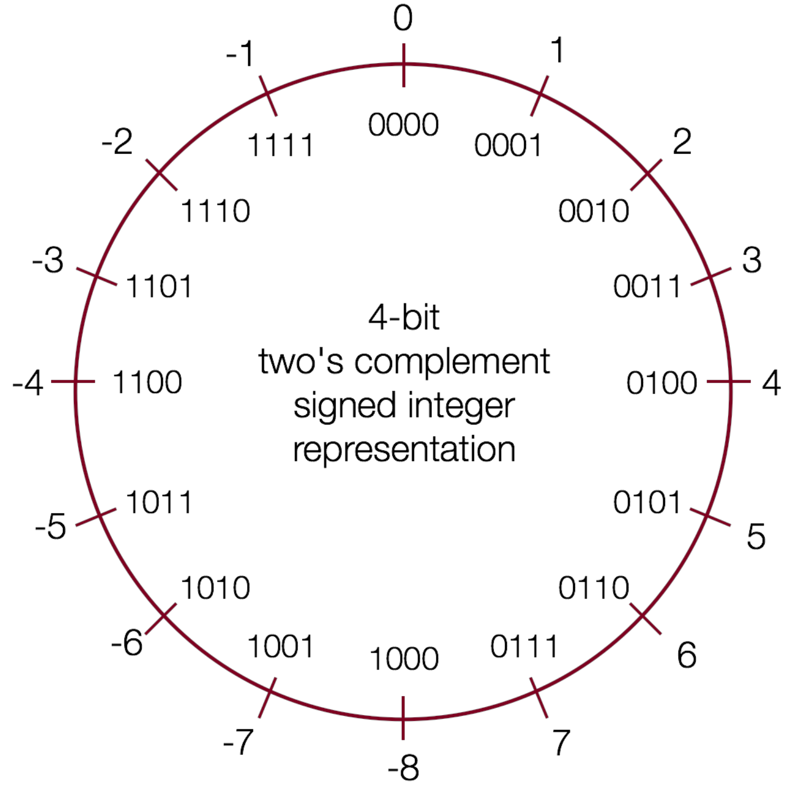
Practice: Two's Complement

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

a) -4 (1100)

b) 7 (0111)

c) 3 (0011)



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- **Overflow**

Overflow

- If you exceed the **maximum** value of your bit representation, you *wrap around* or *overflow* back to the **smallest** bit representation. (Assume unsigned 4-bit numbers).

```
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
```

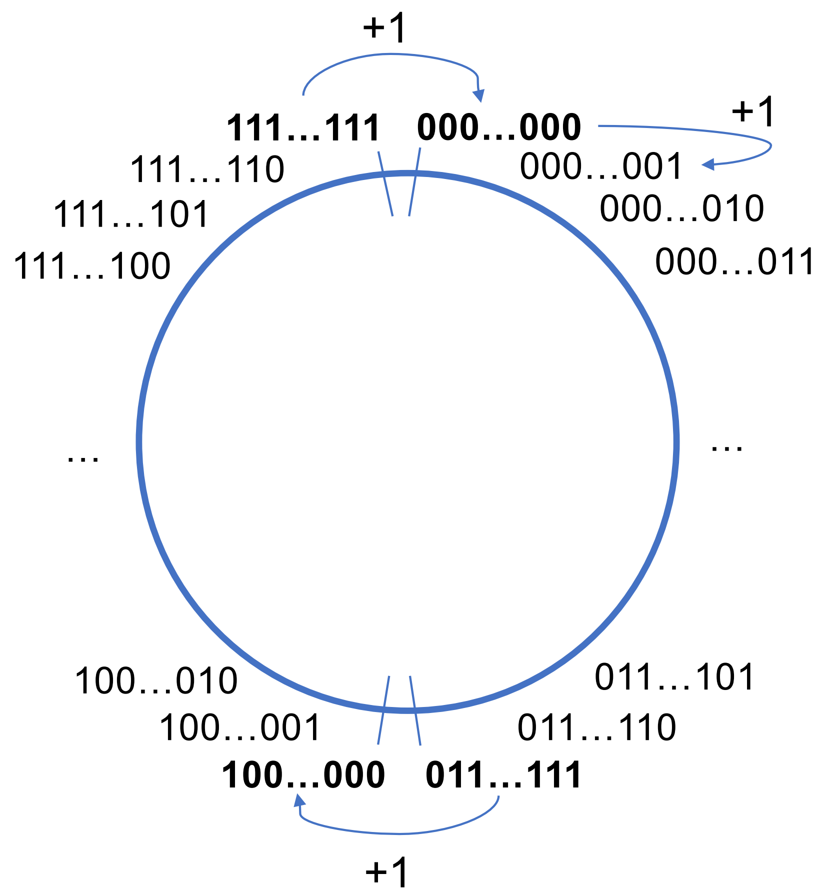
Min and Max Integer Values

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,` …

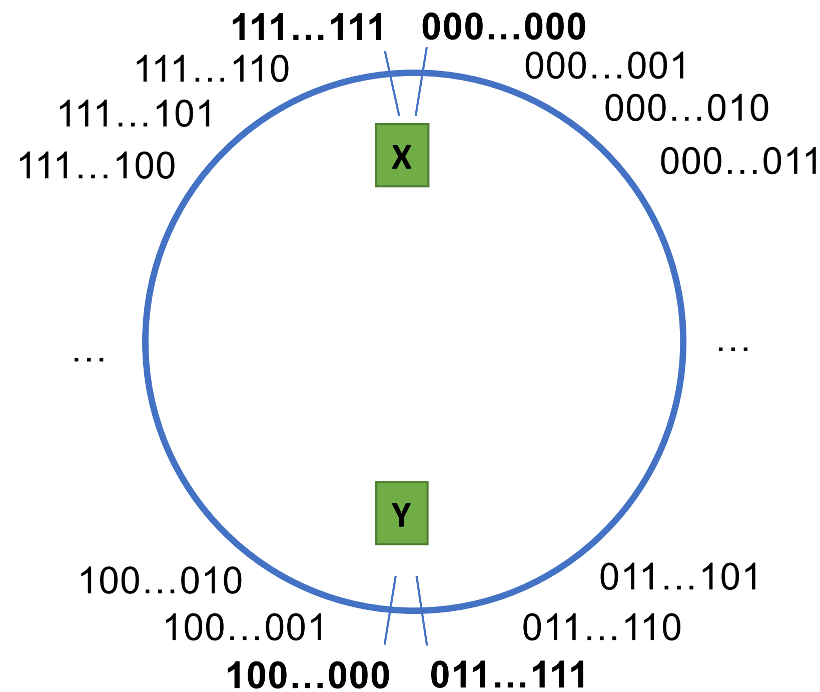
Overflow


+1
111…111
000…000
+1
111…110
000…001
111…101
000…010
111…100
000…011
…
…
100…010
011…101
100…001
011…110
100…000
011…111
+1

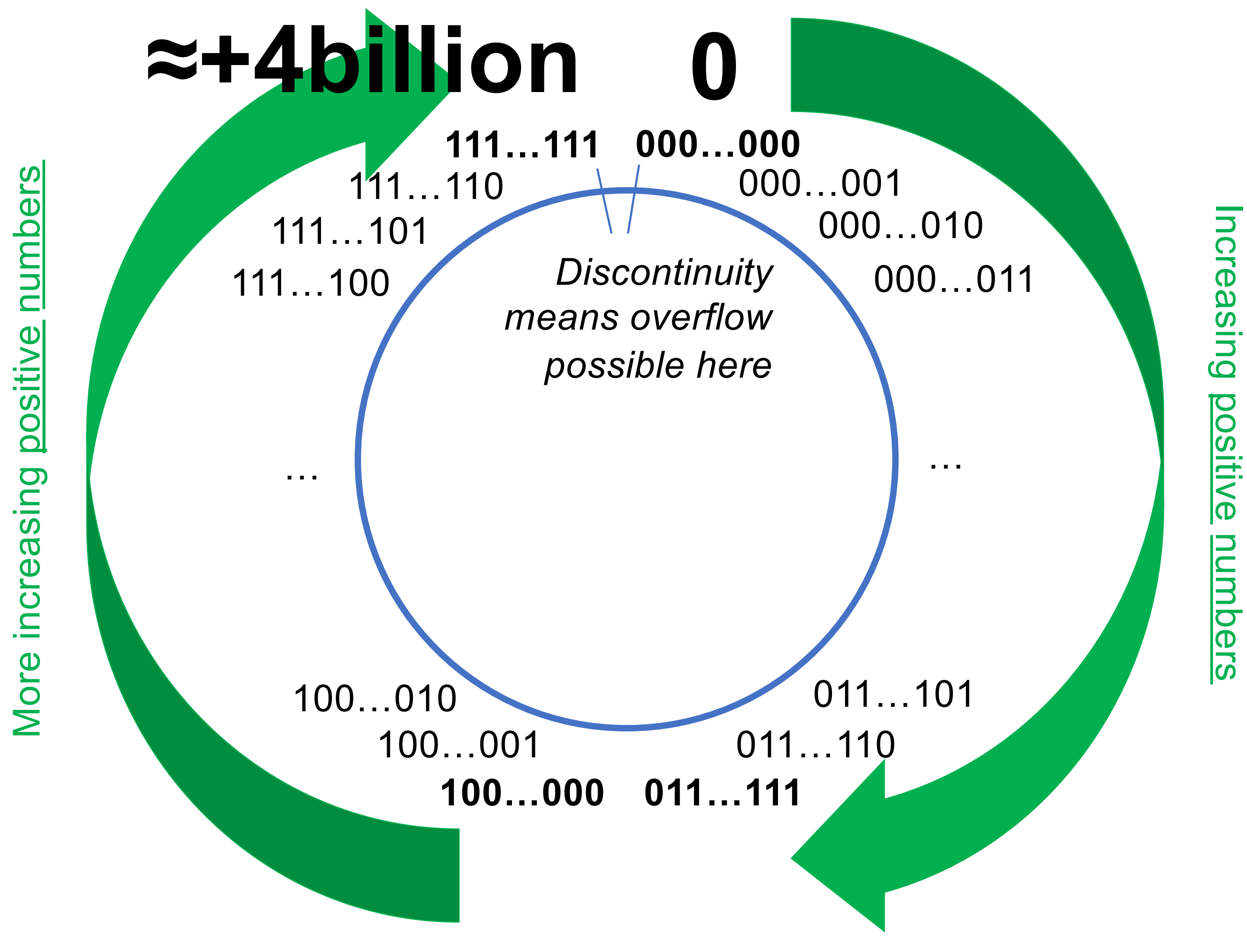
Overflow

At which points can overflow occur for signed and unsigned int?

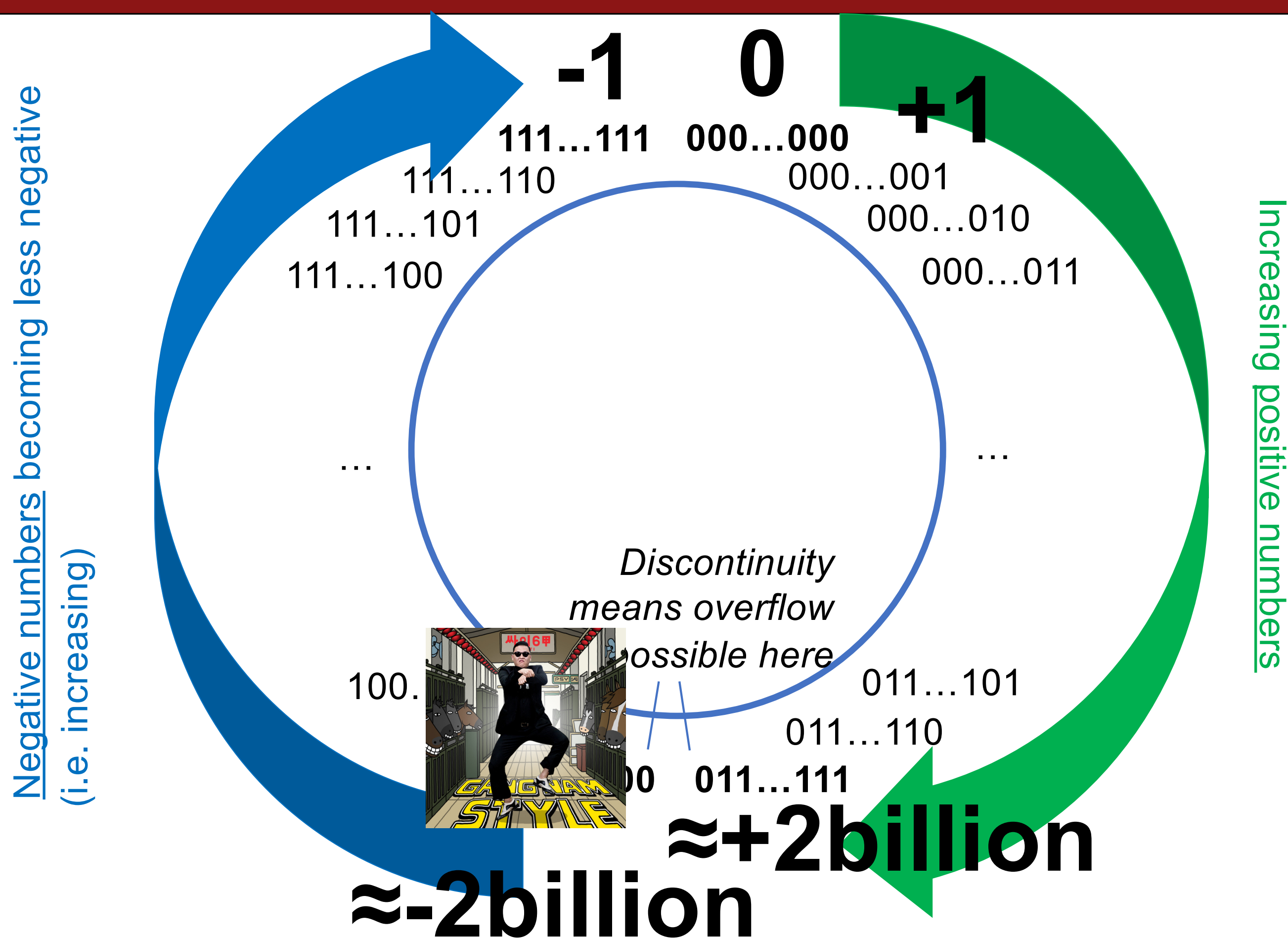
A. Signed and unsigned can both overflow at points X and Y
B. Signed can overflow only at X, unsigned only at Y
C. Signed can overflow only at Y, unsigned only at X
D. Signed can overflow at X and Y, unsigned only at X
E. Other



Unsigned Integers



Signed Numbers



Overflow In Practice: PSY

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: 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 January 13, 2038!

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

Recap

- Bits and Bytes
- Hexadecimal
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- **Surprise Bonus Topic If We Have Time: 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

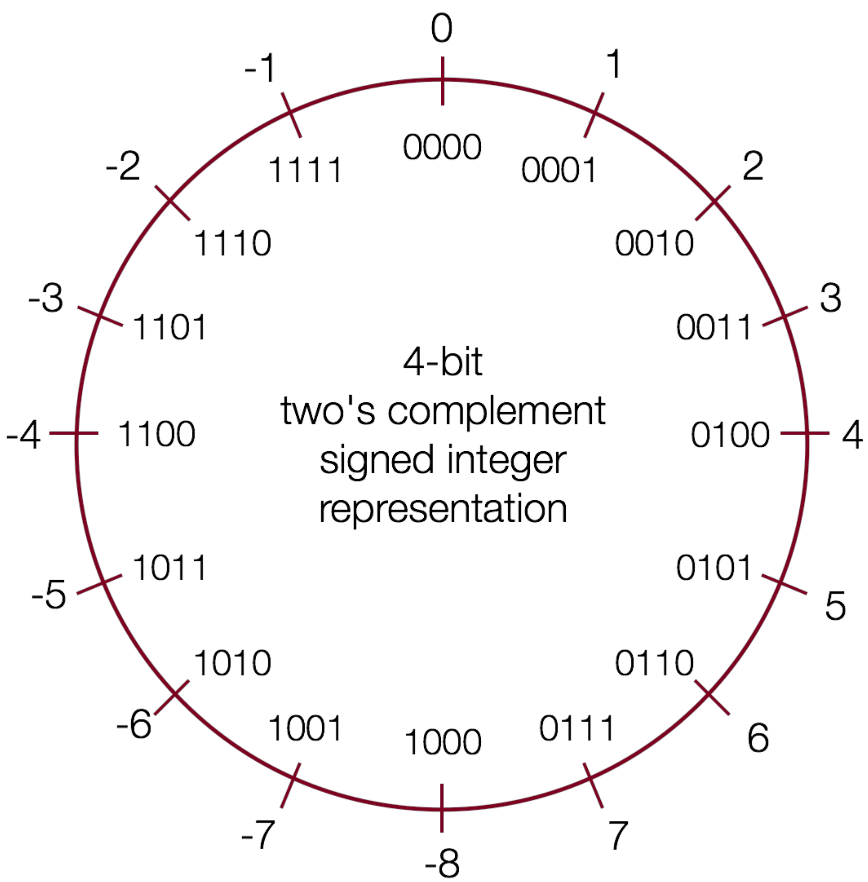
- What happens at the byte level when we cast between variable types? **The bytes remain the same. This means they may be interpreted differently depending on the type.**

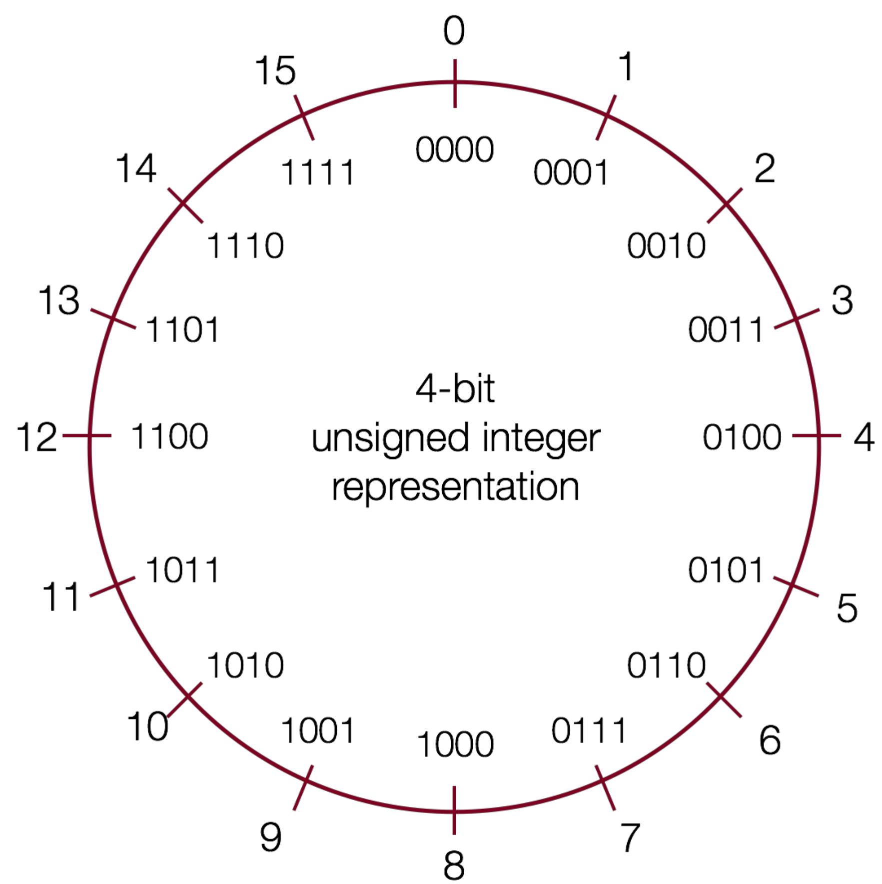
```
int v = -12345;
unsigned int uv = v;
printf("v = %d, uv = %u\n", v, uv);
```

The bit representation for -12345 is **`0b11001111111000111.`**

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

Casting

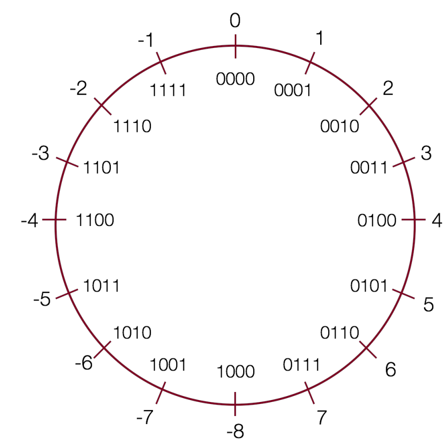

0
1
2
3
4
5
6
7
-8
-7
-6
-5
-4
-3
-2
-1
0000
0001
0010
0011
0100
0101
0110
0111
1000
1001
1010
1011
1100
1101
1110
1111
4-bit
two's complement
signed integer
representation


0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0000
0001
0010
0011
0100
0101
0110
0111
1000
1001
1010
1011
1100
1101
1110
1111
4-bit
unsigned integer
representation

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			
-1 < 0			
-1 < 0U			
2147483647 > -2147483647 - 1			
2147483647U > -2147483647 - 1			
2147483647 > (int)2147483648U			
-1 > -2			
(unsigned)-1 > -2			



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`			
`-1 < 0U`			
`2147483647 >` `-2147483647 - 1`			
`2147483647U >` `-2147483647 - 1`			
`2147483647 >` `(int)2147483648U`			
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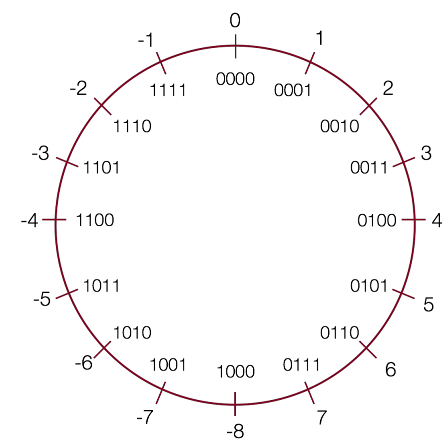

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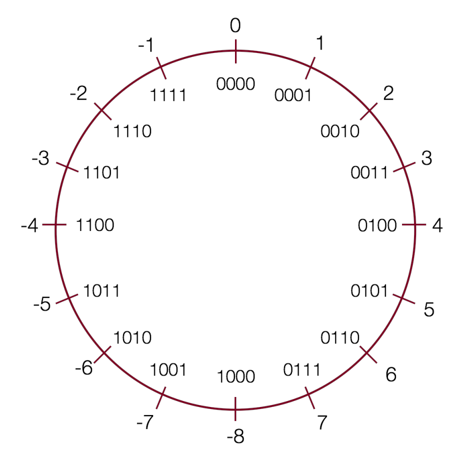

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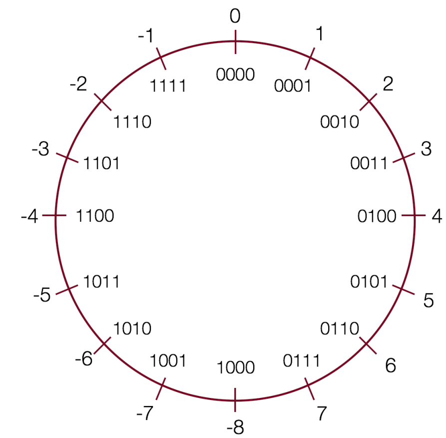

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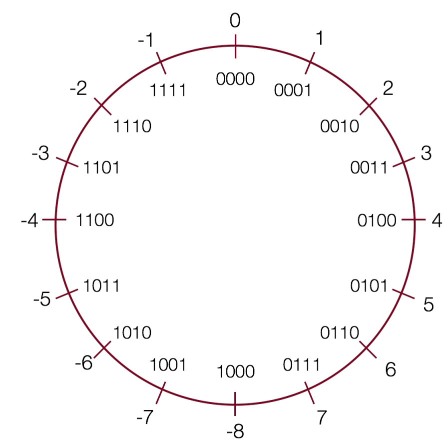

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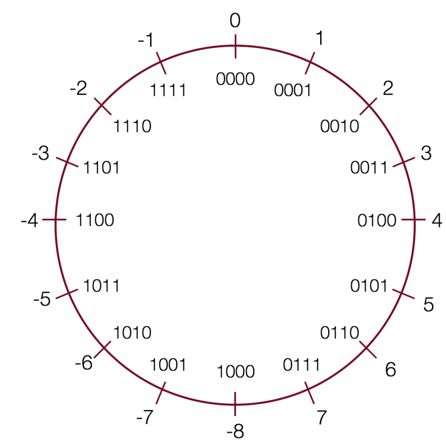

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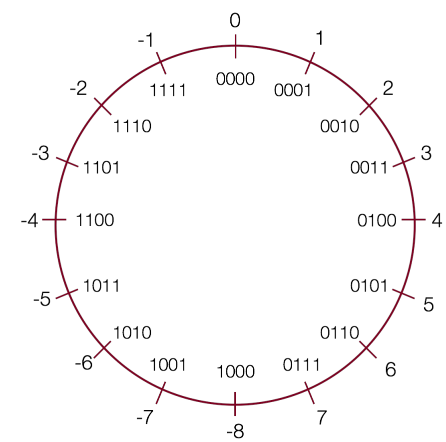

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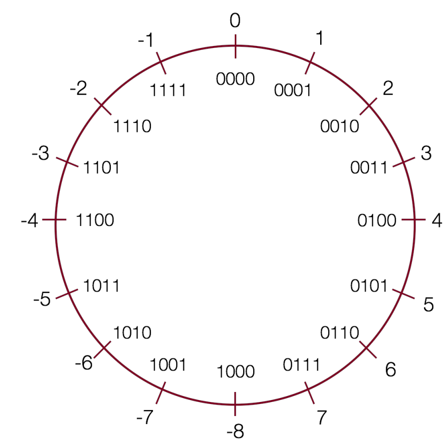

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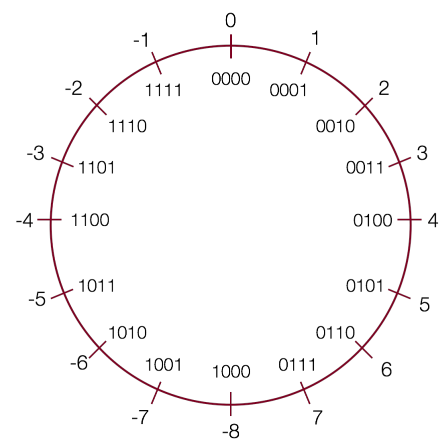
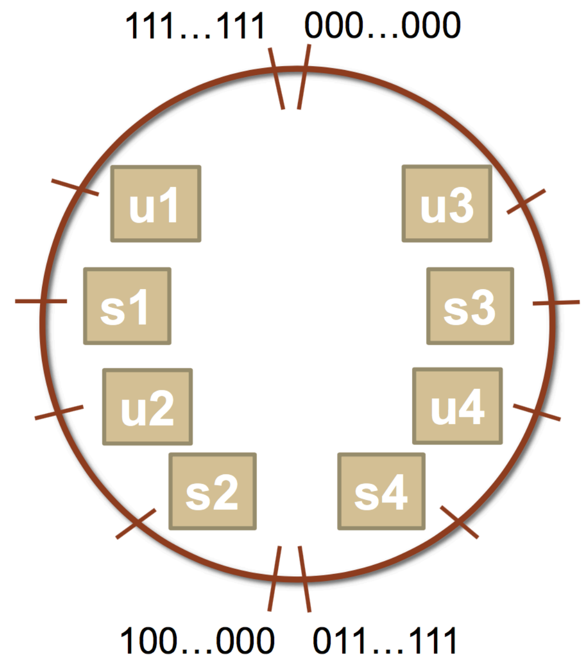


Comparisons Between Different Types

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

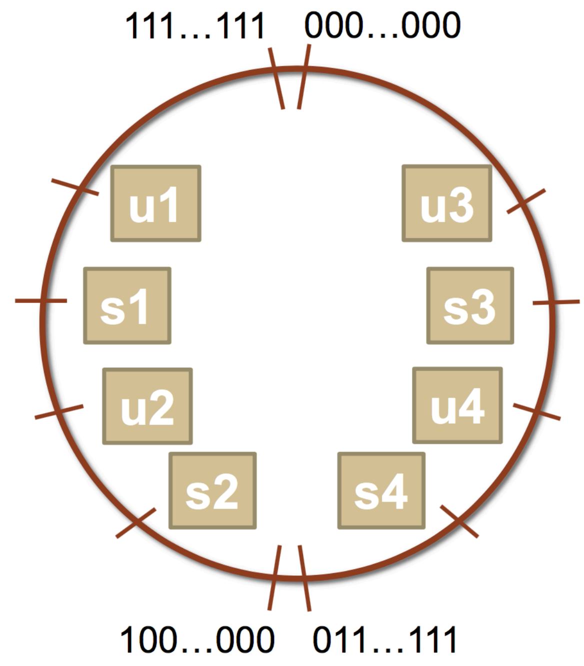
s3 > u3
u2 > u4
s2 > s4
s1 > s2
u1 > u2
s1 > u3



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
```



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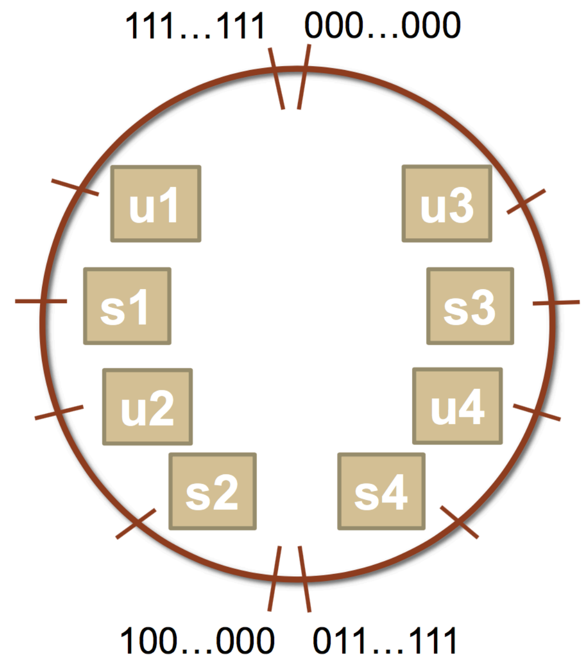
s1 > s2
u1 > u2
s1 > u3
```



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s1 > u3
```

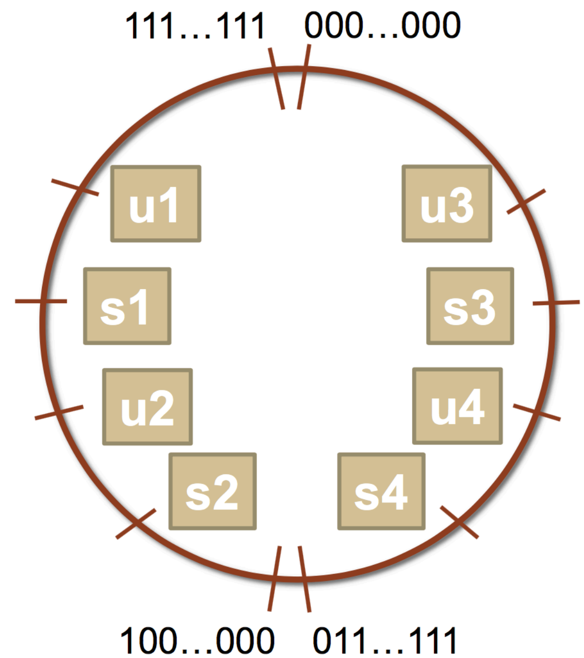

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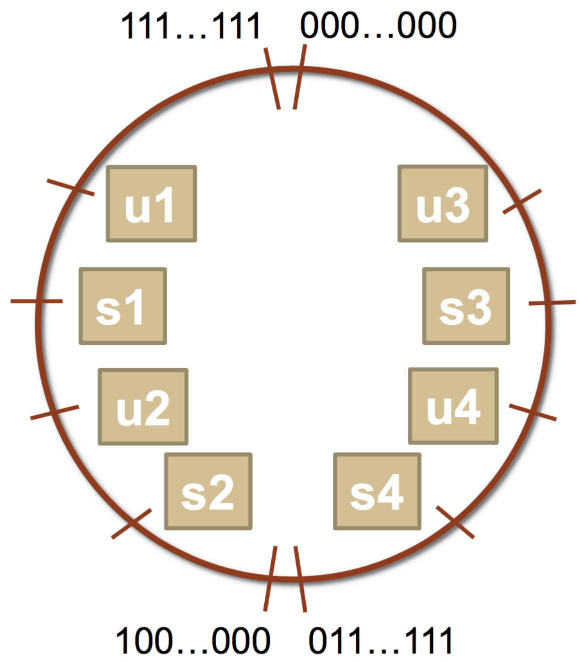

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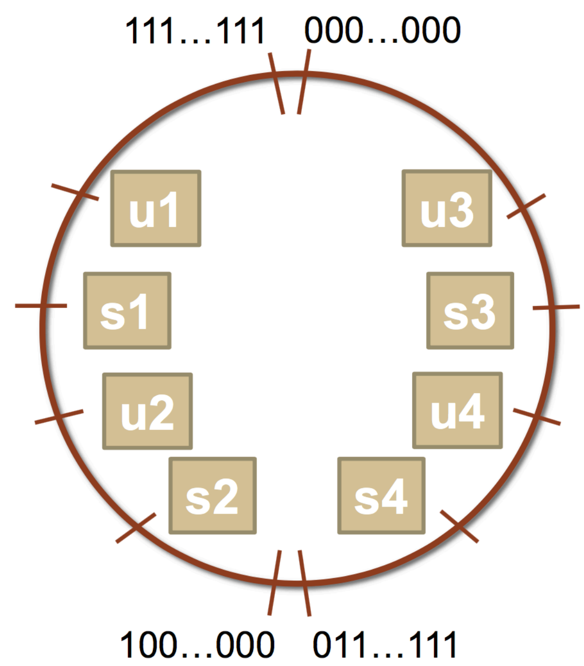
u1 > u2 - true
s1 > u3
```



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u1 > u2 - true
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```

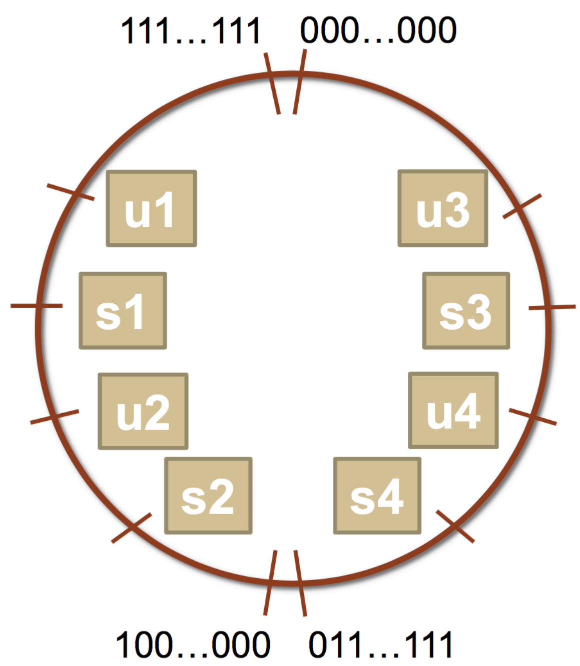

Expanding Bit Representations

- Sometimes, we want to convert between two integers of different sizes (e.g. **`short`** to **`int`**, or **`int`** to **`long`**).
- We might not be able to convert from a bigger data type to a smaller data type, but we do want to always be able to convert from a **smaller** data type to a **bigger** data type.
- For **unsigned** values, we can add leading zeros to the representation ("zero extension")
- For **signed** values, we can repeat the sign of the value for new digits ("sign extension"
- Note: when doing <, >, <=, >= comparison between different size types, it will promote to the larger type.

Expanding Bit Representation

```
unsigned short s = 4;
// short is a 16-bit format, so                    s = 0000 0000 0000 0100b

unsigned int i = s;
// conversion to 32-bit int, so i = 0000 0000 0000 0000 0000 0000 0000 0100b
```

Expanding Bit Representation

```
short s = 4;
// short is a 16-bit format, so                     s = 0000 0000 0000 0100b

int i = s;
// conversion to 32-bit int, so i = 0000 0000 0000 0000 0000 0000 0000 0100b
```

— or —

```
short s = -4;
// short is a 16-bit format, so                     s = 1111 1111 1111 1100b

int i = s;
// conversion to 32-bit int, so i = 1111 1111 1111 1111 1111 1111 1111 1100b
```

Truncating Bit Representation

If we want to **reduce** the bit size of a number, C **truncates** the representation and discards the more significant bits.

```
int x = 53191;
short sx = x;
int y = sx;
```

What happens here? Let's look at the bits in x (a 32-bit int), 53191:

0000 0000 0000 0000 1100 1111 1100 0111

When we cast x to a short, it only has 16-bits, and C *truncates* the number:

1100 1111 1100 0111

This is -12345! And when we cast sx back to int, we sign-extend the number.

1111 1111 1111 1111 1100 1111 1100 0111 // still -12345

Truncating Bit Representation

If we want to **reduce** the bit size of a number, C **truncates** the representation and discards the more significant bits.

```
int x = -3;
short sx = x;
int y = sx;
```

What happens here? Let's look at the bits in x (a 32-bit int), -3:

1111 1111 1111 1111 1111 1111 1111 1101

When we cast x to a short, it only has 16-bits, and C *truncates* the number:

1111 1111 1111 1101

This is -3! **If the number does fit, it will convert fine.** y looks like this:

1111 1111 1111 1111 1111 1111 1111 1101 // still -3

Truncating Bit Representation

If we want to **reduce** the bit size of a number, C **truncates** the representation and discards the more significant bits.

```
unsigned int x = 128000;
unsigned short sx = x;
unsigned int y = sx;
```

What happens here? Let's look at the bits in x (a 32-bit unsigned int), 128000:

`0000 0000 0000 0001 1111 0100 0000 0000`

When we cast x to a short, it only has 16-bits, and C *truncates* the number:

`1111 0100 0000 0000`

This is 62464! **Unsigned numbers can lose info too.** Here is what y looks like:

`0000 0000 0000 0000 1111 0100 0000 0000` // still 62464

The `sizeof` Operator

```
long sizeof(type);

    // Example
    long int_size_bytes = sizeof(int);   // 4
    long short_size_bytes = sizeof(short); // 2
    long char_size_bytes = sizeof(char);   // 1
```

`sizeof` takes a variable type as a parameter and returns the size of that type, in bytes.