# CS107 Lecture 4

## Bits and Bytes; Bitwise Operators

Reading: Bryant & O'Hallaron, Ch. 2.1

Ed Discussion: https://edstem.org/us/courses/28214/discussion/1877377

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Based on slides created by Cynthia Lee, Chris Gregg, Nick Troccoli, Lisa Yan, Jerry Cain and others.

# 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.**

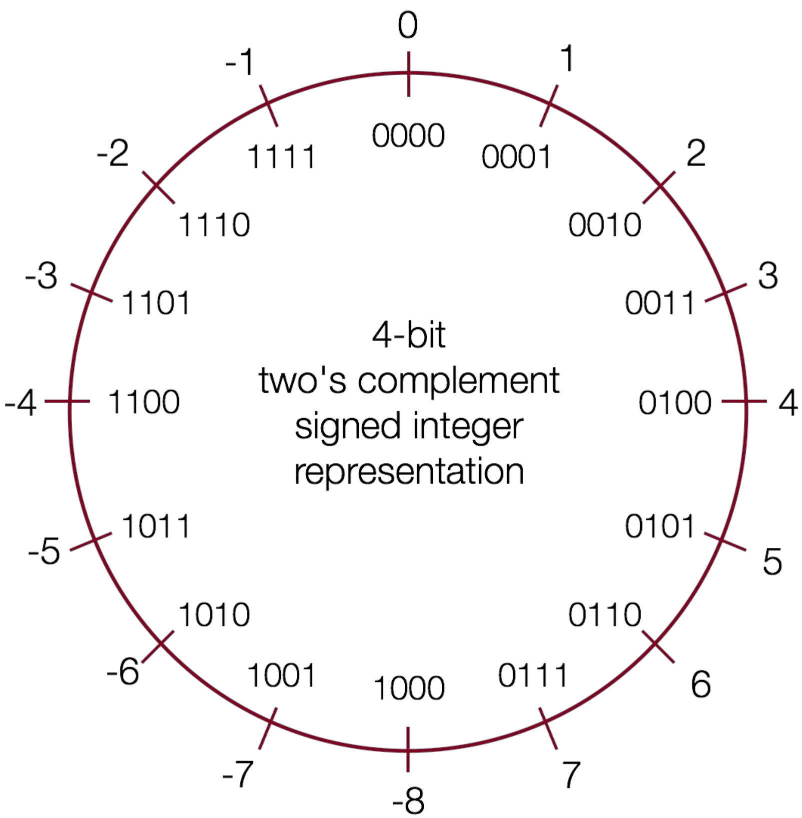
```
int v = -12345;
unsigned int uv = v;
printf("v = %d, uv = %u\n", v, uv);
```

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

The bit representation for -12345 is 0b**11111111111111111100111111000111.**

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

# Casting



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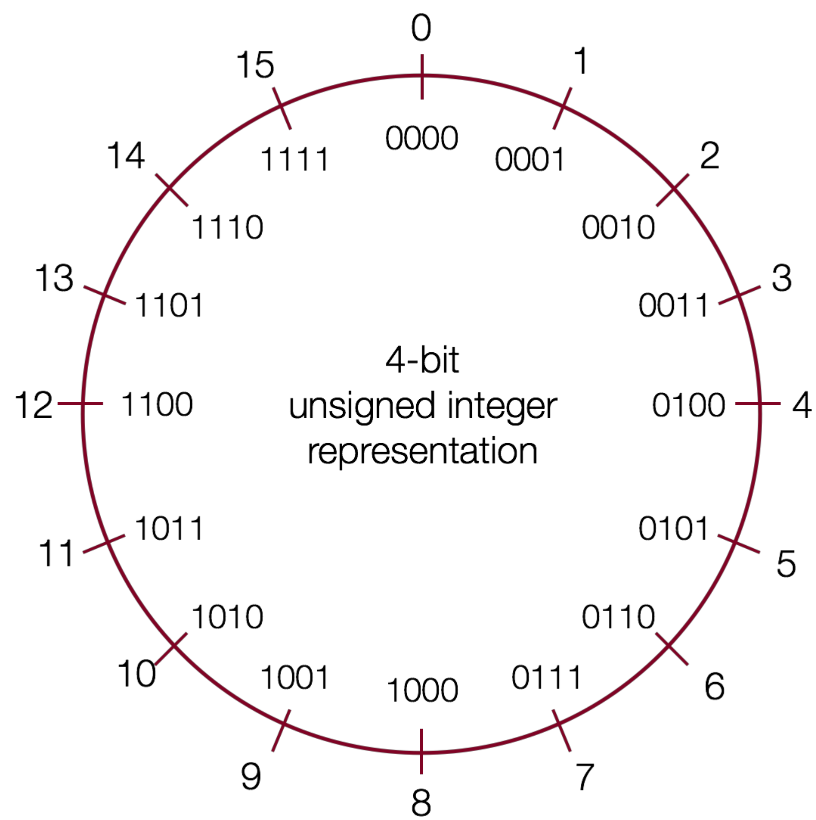
1110
1111

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1111

# Casting

You can cast something to another type by putting that type in parentheses in front of the value:

```
int v = -12345;
...(unsigned int)v...
```

You can also use the **U** suffix after a number literal to treat it as unsigned:

```
-12345U
```

# 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` | Comparison Type? | Evaluates To? | Mathematically correct? |
| --- | --- | --- | --- |
| `0 == 0U` | | | |
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| `0 == 0U` | Unsigned | true | yes |
| `-1 < 0` | | | |
| | | | |
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| `2147483647 > -2147483648` | | | |
| | | | |
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| -1 < 0U | Unsigned | false | No! |
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| 2147483647U > -2147483648 | | | |
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| `-1 > -2` | | | |
| `(unsigned)-1 > -2` | | | |

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| `-1 > -2` | Signed | true | yes |
| `(unsigned)-1 > -2` | Unsigned | true | yes |

# 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 an 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

**Now that we understand values are really stored in binary, how can we manipulate them at the bit level?**

# Bitwise Operators

- You’re already familiar with many operators in C:
  - **Arithmetic operators:** +, -, *, /, %
  - **Comparison operators:** ==, !=, <, >, <=, >=
  - **Logical Operators**: &&, ||, !
- Today, we’re introducing a new category of operators: **bitwise operators:**
  - &, |, ~, ^, <<, >>

# And (&)

AND is a binary operator. The AND of 2 bits is 1 if both bits are 1, and 0 otherwise.

```
output = a & b;
```

| a | b | output |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

& with 1 to let a bit through, & with 0 to zero out a bit

# Or ( | )

OR is a binary operator. The OR of 2 bits is 1 if either (or both) bits is 1.

```
output = a | b;
```

| a | b | output |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

| with 1 to turn on a bit, | with 0 to let a bit go through

# Not (~)

NOT is a unary operator.  The NOT of a bit is 1 if the bit is 0, or 1 otherwise.

```
output = ~a;
```

| a | output |
|---|---|
| 0 | 1 |
| 1 | 0 |

# Exclusive Or (^)

Exclusive Or (XOR) is a binary operator. The XOR of 2 bits is 1 if *exactly* one of the bits is 1, or 0 otherwise.

```
output = a ^ b;
```

| a | b | output |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

^ with 1 to flip a bit, ^ with 0 to let a bit go through

# Operators on Multiple Bits

When these operators are applied to numbers (multiple bits), the operator is applied to the corresponding bits in each number. For example:

AND

```
  0110
& 1100
  ----
  0100
```

OR

```
  0110
| 1100
  ----
  1110
```

XOR

```
  0110
^ 1100
  ----
  1010
```

NOT

```
~ 1100
  ----
  0011
```

# Demo: Bits Playground

# Operators on Multiple Bits

- When these operators are applied to numbers (multiple bits), the operator is applied to the corresponding bits in each number.  For example:

AND

```
  0110
& 1100
  ----
  0100
```

OR

```
  0110
| 1100
  ----
  1110
```

XOR

```
  0110
^ 1100
  ----
  1010
```

NOT

```
~ 1100
  ----
  0011
```

**Note:** these are different from the logical operators AND (&&), OR (||) and NOT (!).

# Operators on Multiple Bits

- When these operators are applied to numbers (multiple bits), the operator is applied to the corresponding bits in each number. For example:

AND

```
  0110
& 1100
  ----
  0100
```

OR

```
  0110
| 1100
  ----
  1110
```

XOR

```
  0110
^ 1100
  ----
  1010
```

NOT

```
~ 1100
  ----
  0011
```

This is different from logical AND (&&). The logical AND returns true if both are nonzero, or false otherwise. With &&, this would be 6 && 12, which would evaluate to **true** (1).

# Operators on Multiple Bits

- When these operators are applied to numbers (multiple bits), the operator is applied to the corresponding bits in each number. For example:

AND

```
  0110
& 1100
  ----
  0100
```

OR

```
  0110
| 1100
  ----
  1110
```

XOR

```
  0110
^ 1100
  ----
  1010
```

NOT

```
~ 1100
  ----
  0011
```

This is different from logical OR (||). The logical OR returns true if either are nonzero, or false otherwise. With ||, this would be 6 || 12, which would evaluate to **true** (1).

# Operators on Multiple Bits

- When these operators are applied to numbers (multiple bits), the operator is applied to the corresponding bits in each number. For example:

AND

```
  0110
& 1100
  ----
  0100
```

OR

```
  0110
| 1100
  ----
  1110
```

XOR

```
  0110
^ 1100
  ----
  1010
```

NOT

```
~ 1100
  ----
  0011
```

This is different from logical NOT (!). The logical NOT returns true if this is zero, and false otherwise. With !, this would be !12, which would evaluate to **false** (0).