CS107 Lecture 5

Bitwise Operators, Continued

reading:

Bryant & O'Hallaron, Ch. 2.1

CS107 Topic 1

How can a computer represent integer numbers?

Why is answering this question important?

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

assign1: implement 3 programs that manipulate binary representations to (1) work around the limitations of arithmetic with addition, (2) simulate a chamber of gas particles, and (3) print Unicode text to the terminal.

Learning Goals

- Learn about the bit shift operators
- Understand when to use one bitwise operator vs. another in your program
- Get practice with writing programs that manipulate binary representations

Lecture Plan

- **Recap**: Bit Operators so far
- Bit Shift Operators
- **Example:** Powers of 2
- **Demo:** GDB

```
cp -r /afs/ir/class/cs107/lecture-code/lect5 .
```

Lecture Plan

- **Recap: Bit Operators so far**
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```

Bits and Bytes So Far

```
// 1. Data is really stored in binary
int x = 5;  // really 0b00…0101 in memory!

// 2. We know what that binary representation is for integers
int y = -5;  // two's complement: 0b111...11011

// 3. We can use/manipulate a binary representation with bit ops
x |= 0x2;  // turn on the 2nd bit from the right: 0b00…0111

// 4. A variable and its binary representation are
// one and the same
printf("%d\n", x); // prints 7!
```

Bitwise OR (|)

| with 1 is useful for turning select bits on.

```
int x = 5; // 0b101

// Turn on the 2nd bit from the right
x |= 0x2; // 0b111
```

| is useful for taking the union of bits.

```
int x = 5;      // 0b00101
int y = 26;     // 0b11010
int z = x | y; // 0b11111
printf("%d\n", z); // 31
```

Bitwise AND (&)

& with 0 is useful for turning select bits off.

```
int x = 5; // 0b101

// Turn off the 3rd bit from the right
x &= -5; // -5 is 0b111...1011
```

& is useful for taking the intersection of bits.

```
int x = 21;      // 0b10101
int y = 27;      // 0b11011
int z = x & y; // 0b10001
printf("%d\n", z); // 17
```

Bitwise XOR (^)

^ with 1 is useful for flipping select bits.

```
int x = 5; // 0b101

// Flip the 2nd bit from the right
x ^= 0x2; // 0b111
```

Bitwise NOT (~)

~ is useful for flipping all bits.

```
int x = 5; // 0b101

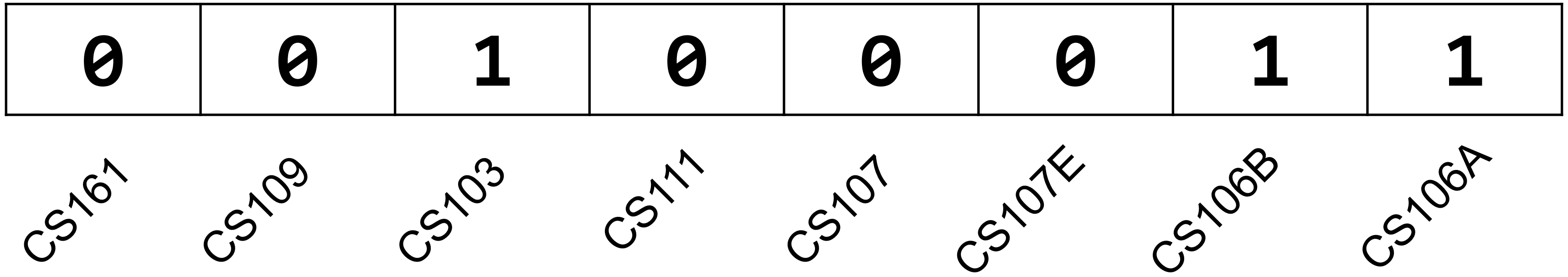
// Flip all bits
x = ~x;  // 0b11111...1010, which is -6

// Take two’s complement (same as negating)
int y = ~x + 1; // same as -x
```

Bit Vectors and Sets

Instead of using arrays of e.g., Booleans in our programs, sometimes it's beneficial to store that information in bits instead – more compact.

- **Example:** we can represent current courses taken using a **`char`** and manipulate its contents using bit operators.



Bit Vectors and Sets

```
#define CS106A 0x1    /* 0000 0001 */
#define CS106B 0x2    /* 0000 0010 */
#define CS107E 0x4    /* 0000 0100 */
#define CS107  0x8    /* 0000 1000 */
#define CS111  0x10   /* 0001 0000 */
#define CS103  0x20   /* 0010 0000 */
#define CS109  0x40   /* 0100 0000 */
#define CS161  0x80   /* 1000 0000 */

char myClasses = ...;
myClasses |= CS107;     // Add CS107
if (myClasses & CS106B) {...
     // taken CS106B!
```

Practice: Bit Masking

Practice: write an expression that, given a 32-bit integer j, flips ("complements") the least-significant byte, and preserves all other bytes.

1. What operator is good for flipping certain bits?
2. What mask do we want?
3. How do we create that mask?

```
j ^ 0xff
```

Lecture Plan

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- **Bit Shift Operators**
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```
cp -r /afs/ir/class/cs107/lecture-code/lect5 .
```

Left Shift (<<)

The LEFT SHIFT operator shifts a bit pattern a certain number of positions to the left. New lower order bits are filled in with 0s, and bits shifted off the end are lost.

```
x << k;     // evaluates to x shifted to the left by k bits
x <<= k;    // shifts x to the left by k bits
```

8-bit examples:

```
00110111 << 2 results in 11011100
01100011 << 4 results in 00110000
10010101 << 4 results in 01010000
```

Right Shift (>>)

The RIGHT SHIFT operator shifts a bit pattern a certain number of positions to the right. Bits shifted off the end are lost.

```
 x >> k;      // evaluates to x shifted to the right by k bits
x >>= k;      // shifts x to the right by k bits
```

Question: how does it fill in the new higher-order bits?

Right Shift (>>)

There are *two kinds* of right shifts, depending on the value and type you are shifting:

- *Unsigned numbers* are right-shifted by filling new high-order bits with 0s ("**logical right shift**").
- *Signed numbers* are right-shifted by filling new high-order bits with the most significant bit ("**arithmetic right shift**"**).**

This way, the sign of the number (if applicable) is preserved!

Right Shift (>>)

The RIGHT SHIFT operator shifts a bit pattern a certain number of positions to the right. Bits shifted off the end are lost.

```
x >> k;     // evaluates to x shifted to the right by k bit
x >>= k;    // shifts x to the right by k bits
```

```
unsigned short x = 2;   // 0000 0000 0000 0010
x >>= 1;                // 0000 0000 0000 0001
printf("%u\n", x); // 1
```

Right Shift (>>)

The RIGHT SHIFT operator shifts a bit pattern a certain number of positions to the right. Bits shifted off the end are lost.

```
x >> k;    // evaluates to x shifted to the right by k bit
x >>= k;   // shifts x to the right by k bits
```

```
short x = 2;  // 0000 0000 0000 0010
x >>= 1;      // 0000 0000 0000 0001
printf("%d\n", x); // 1
```

Right Shift (>>)

The RIGHT SHIFT operator shifts a bit pattern a certain number of positions to the right. Bits shifted off the end are lost.

```
x >> k;    // evaluates to x shifted to the right by k bit
x >>= k;   // shifts x to the right by k bits
```

```
short x = -2; // 1111 1111 1111 1110
x >>= 1;      // 1111 1111 1111 1111
printf("%d\n", x); // -1
```

Shifting and Masking

Suppose we have a 32-bit number.

```
int x = 0b1010010;
```

How can we use bit operators to design a mask that turns on the i-th bit of a number for any i (0, 1, 2, …, 31)?

1. **What operator is good for turning on certain bits?**
2. **What mask do we want?**
3. **How do we create that mask?**

Respond on PollEv for #3: pollev.com/cs107 or text CS107 to 22333 once to join.

What mask would help us turn on the i-th bit of a number?

Nobody has responded yet.

Hang tight! Responses are coming in.

Shifting and Masking

Suppose we have a 32-bit number.

```
int x = 0b1010010;
```

How can we use bit operators to design a mask that turns on the i-th bit of a number for any i (0, 1, 2, …, 31)?

1. **What operator is good for turning on certain bits?**
2. **What mask do we want?**
3. **How do we create that mask?**

`x | (1 << i)`

Shifting and Masking

Suppose we have a 32-bit number.

```
int x = 0b1010010;
```

How can we use bit operators to design a mask that turns on the i-th bit of a number for any i (0, 1, 2, …, 31)?

x | (1 << i)

What if x is a 64-bit number (e.g. long) and i could be 0-63? It turns out there's a problem with this expression…

Bit Operator Pitfalls

- The default type of a number literal in your code is an **int**.
- Let's say you want a long with the index-32 bit as 1:

```
long num = 1 << 32;
```

- This doesn't work! 1 is by default an **int**, and you can't shift an int by 32 because it only has 32 bits. You must specify that you want 1 to be a **long**.

```
long num = 1L << 32;
```

Shifting and Masking

Suppose we have a 64-bit number.

```
long x = 0b1010010;
```

How can we use bit operators to design a mask that turns on the i-th bit of a number for any i (0, 1, 2, ..., 63)?

```
x | (1L << i)
```

Number Literal Suffixes

U makes a literal unsigned, and **L** makes a literal a long.

```
int w = -5 >> 1;  // 0b1111...1101, -5
int x = -5U >> 1; // 0b0111...1101, 2147483645

int y = 1 << 32;  // 0! (technically undefined)
int z = 1L << 32; // 4294967296
```

1L << i

What does **1L << i** represent numerically?

A power of 2! Specifically, 2^i*.*

Lecture Plan

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- **Example: Powers of 2**
- **Demo:** GDB

```
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```

Powers of 2

Challenge: without using loops or math library functions, how could we detect whether a number is a power of 2?

What is true about a power of 2 but not other numbers? 🤔

Powers of 2

Key idea: A power of 2 minus 1 will have all bits below the original bit be 1, and everything else be 0. E.g.

0b10000 – 1 = 0b01111

0b100 – 1 = 0b011

Not true for other non-power-of-2 numbers:

0b10010 – 1 = 0b10001

Cool idea: *no bits overlap* between a power of 2 and a power of 2 minus 1. How is this handy?

Demo: Powers of 2

`is_power_of_2.c`

Lecture Plan

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```
cp -r /afs/ir/class/cs107/lecture-code/lect5 .
```

Introducing GDB

Is there a way to step through the execution of a program and print out its values as it's running? E.g., to view binary representations? **Yes!**

The GDB Debugger

GDB is a **command-line debugger**, a text-based debugger with similar functionality to other debuggers you may have used, such as in Qt Creator

- It lets you put **breakpoints** at specific places in your program to pause there
- It lets you step through execution line by line
- It lets you print out values of variables in various ways (including binary)
- It lets you track down where your program crashed
- And much, much more!

GDB is essential to your success in CS107 this quarter! We'll be building our familiarity with GDB over the course of the quarter.

GDB Guide: cs107.stanford.edu/resources/gdb.html

gdb on a program

- `gdb myprogram` run gdb on executable
- `b` Set breakpoint on a function (e.g., `b main`) or line (`b 42`)
- `r 82` Run with provided args
- `n, s, continue` control forward execution (next, step into, continue)
- `p` print variable (`p varname`) or evaluated expression (`p 3L << 10`)
  - `p/t, p/x` binary and hex formats.
  - `p/d, p/u, p/c`
- `info` `args, locals`

Important: gdb does not run the current line until you hit “next”

Demo: Bitmasks and GDB

`bits_playground.c`

gdb: highly recommended

At this point, setting breakpoints/stepping in gdb may seem like overkill for what could otherwise be achieved by copious **printf** statements.

However, gdb is incredibly useful for assign1 (and all assignments):

- A fast “C interpreter”: p + <expression>
  - Sandbox/try out ideas around bitshift operators, signed/unsigned types, etc.
  - Can print values out in binary!
  - Once you’re happy, then make changes to your C file
- **Tip**: Open two terminal windows and SSH into myth in both
  - Keep one for emacs, the other for gdb/command-line
  - Easily reference C file line numbers and variables while accessing gdb
- **Tip**: Every time you update your C file, **make** and then rerun gdb.

Gdb takes practice! But the payoff is tremendous! ☺

Recap

- **Recap**: Bit Operators so far
- **Bit Operators + GDB Demo:** Courses
- **Demo 2:** Practice and Powers of 2
- Bit Shift Operators

Lecture 5 takeaways: We can use bit operators like &, |, ~, <<, etc. to manipulate the binary representation of values. A number is a bit pattern that can be manipulated arithmetically or bitwise at your convenience!

Next time: *How can a computer represent and manipulate more complex data like text?*

Extra Practice

Shift Operation Pitfalls

1. *Technically*, the C standard does not precisely define whether a right shift for signed integers is logical or arithmetic. However, **almost all compilers/machines** use arithmetic, and you can most likely assume this.
2. Operator precedence can be tricky! For example:

   `1<<2 + 3<<4` means **`1 << (2+3) << 4`** because addition and subtraction have higher precedence than shifts! Always use parentheses to be sure:

   `(1<<2) + (3<<4)`

Color Wheel

- Another application for storing data efficiently in binary is representing **colors**.
- A color representation commonly consists of opacity (how transparent or opaque it is), and how much red/green/blue is in the color.
- **Key idea:** we can encode each of these in 1 byte, in a value from 0-255! Thus, an entire color can be represented in one 4-byte **integer**.

0x 42 53 01 44

42	53	01	44
Opacity	Red	Green	Blue

Demo: Color Wheel

`color_wheel.c`

Bit Masking

Bit masking is also useful for integer representations as well. For instance, we might want to check the value of the most-significant bit, or just one of the middle bytes.

- **Example:** If I have a 32-bit integer **`j`**, what operation should I perform if I want to get *just the lowest byte* in **`j`**?

```
int j = ...;
int k = j & 0xff;        // mask to get just lowest byte
```

Practice: Bit Masking

- **Practice 1:** write an expression that, given a 32-bit integer j, sets its least-significant byte to all 1s, but preserves all other bytes.

- **Practice 2:** write an expression that, given a 32-bit integer j, flips ("complements") all but the least-significant byte, and preserves all other bytes.

Practice: Bit Masking

- **Practice 1:** write an expression that, given a 32-bit integer j, sets its least-significant byte to all 1s, but preserves all other bytes.

```
j | 0xff
```

- **Practice 2:** write an expression that, given a 32-bit integer j, flips ("complements") all but the least-significant byte, and preserves all other bytes.

```
j ^ ~0xff
```

More Exercises

Suppose we have a 64-bit number.

```
long x = 0b1010010;
```

How can we use bit operators, and the constant `1L` or `-1L` to…

- …design a mask that zeros out (i.e., turns off) the bottom i bits (and keeps the rest of the bits the same)?

More Exercises

Suppose we have a 64-bit number.

```
long x = 0b1010010;
```

How can we use bit operators, and the constant `1L` or `-1L` to…

- …design a mask that zeros out (i.e., turns off) the bottom i bits (and keeps the rest of the bits the same)?

x & (-1L << i)