ECE/CS 250
Computer Architecture
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From C to Binary

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Slides are derived from work by
Daniel J. Sorin (Duke), Andrew Hilton (Duke), Alvy Lebeck (Duke),
Benjamin Lee (Duke), Amir Roth (Penn)

Also contains material adapted from CSC230: C and Software Tools developed by
the NC State Computer Science Faculty
• Previously:
  • Computer is machine that does what we tell it to do

• Next:
  • How do we tell computers what to do?
  • How do we represent data objects in binary?
  • How do we represent data locations in binary?
Representing High Level Things in Binary

- Computers represent everything in binary
- Instructions are specified in binary
- Instructions must be able to describe
  - Operation types (add, subtract, shift, etc.)
  - Data objects (integers, decimals, characters, etc.)
  - Memory locations
- Example:
  ```
  int x, y;       // Where are x and y? How to represent an int?
  bool decision; // How do we represent a bool? Where is it?
  y = x + 7;      // How do we specify “add”? How to represent 7?
  decision=(y>18); // Etc.
  ```
Representing Operation Types

• How do we tell computer to add? Shift? Read from memory? Etc.

• Arbitrarily! 😊

• Each Instruction Set Architecture (ISA) has its own binary encodings for each operation type

• E.g., in MIPS:
  • Integer add is: 00000 010000
  • Read from memory (load) is: 010011
  • Etc.
Representing Data Types


• Same as before: binary!

• **Data and interpretation are separate:**
  • The same 32 bits might mean one thing if interpreted as an integer, but another thing if interpreted as a floating point number
Basic Data Types

**Bit (bool):** 0, 1

**Bit String:** sequence of bits of a particular length
- 4 bits is a nibble
- 8 bits is a byte
- 16 bits is a half-word (for MIPS32)
- 32 bits is a word (for MIPS32)
- 64 bits is a double-word (for MIPS32)
- 128 bits is a quad-word (for MIPS32)

**Integers (char, short, int, long):**
“2’s Complement” (32-bit or 64-bit representation)

**Floating Point (float, double):**
- Single Precision (32-bit representation)
- Double Precision (64-bit representation)
- Extended (Quad) Precision (128-bit representation)

**Character (char):**
- ASCII 7-bit code

What is a **word**?
The standard unit of manipulation for a particular system. E.g.:
- MIPS32: 32 bits
- Intel x86_64 (modern): 64 bit
- Original Nintendo: 8 bit
- Super Nintendo: 16 bit
- Intel x86 (classic): 32 bit
- Nintendo 64: 64 bit

---

All pink arrows are true for a MIPS32 and Intel x86
Basic Binary

• Advice: memorize the following
  • \(2^0 = 1\)
  • \(2^1 = 2\)
  • \(2^2 = 4\)
  • \(2^3 = 8\)
  • \(2^4 = 16\)
  • \(2^5 = 32\)
  • \(2^6 = 64\)
  • \(2^7 = 128\)
  • \(2^8 = 256\)
  • \(2^9 = 512\)
  • \(2^{10} = 1024\)
Bits vs things

- If you have $N$ bits, you can represent $2^N$ things.

- If you have $T$ things, you need $\log_2 T$ bits to pick one.

You will have to answer questions of this form roughly a thousand times in this course – note it now!

Exercises:
- I have 8 bits, how many integers can I represent?
  - $2^8 = 256$
- I need to represent 32 cache sets. How many bits do I need?
  - $\log_2 32 = 5$
- I have 4GB of RAM. How many bits do I need to pick one byte of it?
  - $\log_2 4G = \ldots$?
The binary metric system:

- $2^{10} = 1024$.
- This is *basically* 1000, so we can have an alternative form of metric units based on base 2.
- $2^{10}$ bytes = 1024 bytes = 1kB.
  - Sometimes written as 1kiB (pronounced “kibibyte” where the ‘bi’ means ‘binary’) (but nobody says “kibibyte” out loud because it sounds stupid)
- $2^{20}$ bytes = 1MB, $2^{30}$ bytes = 1GB, $2^{40}$ bytes = 1TB, etc.
- Easy rule to convert between exponent and binary metric number:

$$2^{x} \cdot 2^y = 2^{x+y}\text{<X_prefix>}B$$

2\text{13} bytes = 2^3 kB = 8 kB
2\text{39} bytes = 2^9 GB = 512 GB
2\text{05} bytes = 2^5 B = 32 B

From last slide: \[ \log_2 4G = 32 \]
What does it mean to say base 10 or base 2?

- **Integers in regular base 10:**
  - 6253 = 6000 + 200 + 50 + 3
    = 6*10^3 + 2*10^2 + 5*10^1 + 3*10^0

- **Integers in base 2:**
  - 1101 = 1000 + 100 + 00 + 1
    = 1*2^3 + 1*2^2 + 0*2^1 + 1*2^0
    = 8 + 4 + 1
    = 13

<table>
<thead>
<tr>
<th>Digit</th>
<th>Base</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1101</td>
<td>1</td>
</tr>
</tbody>
</table>

- **1 1 0 1**
  - Bit 3 8's place
  - Bit 2 4's place
  - Bit 1 2's place
  - Bit 0 1's place
Decimal to binary using remainders

<table>
<thead>
<tr>
<th>?</th>
<th>Quotient</th>
<th>Remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>457</td>
<td>228</td>
<td>1</td>
</tr>
<tr>
<td>228</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>114</td>
<td>57</td>
<td>0</td>
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<td>57</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>28</td>
<td>14</td>
<td>0</td>
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<tr>
<td>14</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
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</tr>
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<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

111001001
## Decimal to binary using comparison

### Table

<table>
<thead>
<tr>
<th>Num</th>
<th>Compare $2^n$</th>
<th>$\geq ?$</th>
</tr>
</thead>
<tbody>
<tr>
<td>457</td>
<td>256</td>
<td>1</td>
</tr>
<tr>
<td>201</td>
<td>128</td>
<td>1</td>
</tr>
<tr>
<td>73</td>
<td>64</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
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</tr>
<tr>
<td>9</td>
<td>8</td>
<td>1</td>
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<tr>
<td>1</td>
<td>4</td>
<td>0</td>
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<tr>
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<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The binary representation is 111001001.
# Hexadecimal

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

Indicates a hex number

One hex digit represents 4 bits. Two hex digits represent a byte (8 bits).
Binary to/from hexadecimal

- 0101101100100111₂ -->
- 0101 1011 0010 0011₂ -->
- 5 B 2 3₁₆

1 F 4 B₁₆ -->

0001 1111 0100 1011₂ -->

0001111101001011₂
BitOps: Unary

- Bit-wise complement (~)
  - Flips every bit.

\[
\begin{align*}
\text{~0x0d} & \quad \text{// (binary 00001101)} \\
\text{== 0xf2} & \quad \text{// (binary 11110010)}
\end{align*}
\]

Not the same as Logical NOT (!) or sign change (−)

```
char i, j1, j2, j3;
i = 0x0d;        // binary 00001101
j1 = ~i;        // binary 11110010
j2 = -i;        // binary 11110011
j3 = !i;        // binary 00000000
```
BitOps: Two Operands

- Operate **bit-by-bit** on operands to produce a result operand of the same length
- And (\&): result 1 if both inputs 1, 0 otherwise
- Or (\|): result 1 if either input 1, 0 otherwise
- Xor (^): result 1 if one input 1, but not both, 0 otherwise

**Useful identities (applied per-bit):**

- \(X \& 1 = X\) \(\text{ANDing with 1 does nothing}\)
- \(X \& 0 = 0\) \(\text{ANDing with 0 gives zero}\)
- \(X \| 0 = X\) \(\text{ORing with 0 does nothing}\)
- \(X \| 1 = 1\) \(\text{ORing with 1 gives one}\)
- \(X ^ 0 = X\) \(\text{XORing with 0 does nothing}\)
- \(X ^ 1 = \neg X\) \(\text{XORing with 1 flips the bit}\)
Two Operands... (cont’d)

- **Examples**

```
0011 1000 & 1101 1110
---------
0001 1000

0011 1000 | 1101 1110
---------
1111 1110

0011 1000 ^ 1101 1110
---------
1110 0110
```
Shift Operations

• $x \ll y$ is left (logical) shift of $x$ by $y$ positions
  • $x$ and $y$ must both be integers
  • $x$ should be unsigned or positive
  • $y$ leftmost bits of $x$ are discarded
  • zero fill $y$ bits on the right

\[
\begin{array}{c}
01111001 \ll 3 \\
\hline
11001000
\end{array}
\]

these 3 bits are discarded

these 3 bits are zero filled
• $x >> y$ is right (logical) shift of $x$ by $y$ positions
  • $y$ rightmost bits of $x$ are discarded
  • zero fill $y$ bits on the left

01111001 >> 3

---

00001111

these 3 bits are zero filled

these 3 bits are discarded
Bitwise Recipes

• Set a certain bit to 1?
  • Make a MASK with a **one** at every position you want to *set*:
    \[ m = 0x02; \quad // \quad 00000010_2 \]
  • OR the mask with the input:
    \[ v = 0x41; \quad // \quad 01000001_2 \]
    \[ v |= m; \quad // \quad 01000011_2 \]

• Clear a certain bit to 0?
  • Make a MASK with a **zero** at every position you want to *clear*:
    \[ m = 0xFD; \quad // \quad 11111101_2 \quad (could\ also\ write\ ~0x02) \]
  • AND the mask with the input:
    \[ v = 0x27; \quad // \quad 00100111_2 \]
    \[ v &= m; \quad // \quad 00100101_2 \]

• Get a substring of bits (such as bits 2 through 5)?
  *Note: bits are numbered right-to-left starting with zero.*
  • Shift the bits you want all the way to the right then AND them with an appropriate mask:
    \[ v = 0x67; \quad // \quad 01100111_2 \]
    \[ v >>= 2; \quad // \quad 00010011_2 \]
    \[ v &= 0x0F; \quad // \quad 00001001_2 \]
Binary Math : Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
00101011
\end{array}
\]

• How do we do this?
Binary Math : Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
00100101
\end{array}
\]

695

+ 232

• How do we do this?
  • Let’s revisit decimal addition
  • Think about the process as we do it
Binary Math: Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
00101011
\end{array}
\quad
\begin{array}{c}
695 \\
+ 232 \\
\hline
7
\end{array}
\]

• First add one’s digit 5+2 = 7
Binary Math: Addition

- Suppose we want to add two numbers:

```
  00011101
+ 00101011
  00101011
```

- First add one’s digit $5+2 = 7$
- Next add ten’s digit $9+3 = 12$ (2 carry a 1)
Binary Math : Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
001001001 \\
\end{array}
\]

= 695 + 232 = 927

• First add one’s digit 5+2 = 7
• Next add ten’s digit 9+3 = 12 (2 carry a 1)
• Last add hundred’s digit 1+6+2 = 9
Binary Math : Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
00101011
\end{array}
\]

• Back to the binary:

• First add 1’s digit 1+1 = ...?
Binary Math: Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
1 \\
00011101 \\
+ 00101011 \\
\hline
01010111 \\
\end{array}
\]

• Back to the binary:
• First add 1’s digit 1+1 = 2 (0 carry a 1)
Binary Math : Addition

• Suppose we want to add two numbers:

\[
\begin{array}{c}
11 \\
00011101 \\
+ 00101011 \\
\hline
00
\end{array}
\]

• Back to the binary:
• First add 1’s digit 1+1 = 2 (0 carry a 1)
• Then 2’s digit: 1+0+1 = 2 (0 carry a 1)
• You all finish it out....
Binary Math: Addition

- Suppose we want to add two numbers:

  111111
  00011101 = 29
  + 00101011 = 43

  01001000 = 72

- Can check our work in decimal
Issues for Binary Representation of Numbers

• **How to represent negative numbers?**

• There are many ways to represent numbers in binary
  • Binary representations are encodings → many encodings possible
  • What are the issues that we must address?

• Issue #1: Complexity of arithmetic operations

• Issue #2: Negative numbers

• Issue #3: Maximum representable number

• Choose representation that makes these issues easy for machine, even if it’s not easy for humans (i.e., ECE/CS 250 students)
  • Why? Machine has to do all the work!
Sign Magnitude

- Use leftmost bit for + (0) or − (1):
- 6-bit example (1 sign bit + 5 magnitude bits):
  - +17 = 010001
  - -17 = 110001

Pros:
  - Conceptually simple
  - Easy to convert

Cons:
  - Harder to compute (add, subtract, etc) with
  - Positive and negative 0: 000000 and 100000

NOBODY DOES THIS
1’s Complement Representation for Integers

- Use largest positive binary numbers to represent negative numbers
- To negate a number, invert ("not") each bit:
  - $0 \rightarrow 1$
  - $1 \rightarrow 0$
- Cons:
  - Still two 0s (yuck)
  - Still hard to compute with

<table>
<thead>
<tr>
<th>Binary</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
</tr>
<tr>
<td>0011</td>
<td>3</td>
</tr>
<tr>
<td>0100</td>
<td>4</td>
</tr>
<tr>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>1000</td>
<td>-7</td>
</tr>
<tr>
<td>1001</td>
<td>-6</td>
</tr>
<tr>
<td>1010</td>
<td>-5</td>
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<tr>
<td>1011</td>
<td>-4</td>
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<tr>
<td>1100</td>
<td>-3</td>
</tr>
<tr>
<td>1101</td>
<td>-2</td>
</tr>
<tr>
<td>1110</td>
<td>-1</td>
</tr>
<tr>
<td>1111</td>
<td>0</td>
</tr>
</tbody>
</table>

NOBODY DOES THIS EITHER
2’s Complement Integers

- Use large positives to represent negatives
- \((-x) = 2^n - x\)
- This is 1’s complement + 1
- So, to negate, **just invert bits and add 1**

6-bit examples:

- \(010110_2 = 22_{10} ; 101010_2 = -22_{10}\)
- \(1_{10} = 000001_2 ; -1_{10} = 111111_2\)
- \(0_{10} = 000000_2 ; -0_{10} = 000000_2 \rightarrow \text{good!}\)

EVERYBODY DOES THIS
Another way to think about 2’s complement

- Regular base 10:
  - 6253 = 6000 + 200 + 50 + 3
    = 6*10^3 + 2*10^2 + 5*10^1 + 3*10^0

- Unsigned base 2:
  - 1101 = 1000 + 100 + 00 + 1
    = 1*2^3 + 1*2^2 + 0*2^1 + 1*2^0
    = 8 + 4 + 1
    = 13

- Signed base 2:
  - 1101 = -1000 + 100 + 00 + 1
    = 1*-2^3 + 1*2^2 + 0*2^1 + 1*2^0
    = -8 + 4 + 1
    = -3

Alternately, flip the bits and add 1:

Flip: 0010
+1: 0011

That’s 3 in binary, so the number is indeed -3

Two’s complement is like making the highest order bit apply a negative value!
Pros and Cons of 2’s Complement

• Advantages:
  • Only one representation for 0 (unlike 1’s comp): \( 0 = 000000 \)
  • Addition algorithm is much easier than with sign and magnitude
    • Independent of sign bits

• Disadvantage:
  • One more negative number than positive
  • Example: 6-bit 2’s complement number
    \( 100000_2 = -32_{10} \); but \( 32_{10} \) could not be represented

All modern computers use 2’s complement for integers
Integer ranges

- If I have an n-bit integer:
  - And it’s **unsigned**, then I can represent \{0 .. 2^n – 1\}
  - And it’s **signed**, then I can represent \{-2^{n-1} .. 2^{n-1} – 1\}

- Result:

<table>
<thead>
<tr>
<th>Size in bits</th>
<th>Size in bytes</th>
<th>Datatype</th>
<th>Unsigned range</th>
<th>Signed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>char</td>
<td>0 .. 255</td>
<td>-128 .. 127</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>short</td>
<td>0 .. 65,535</td>
<td>-32,768 .. 32,767</td>
</tr>
<tr>
<td>32</td>
<td>4</td>
<td>int</td>
<td>0 .. 4,294,967,295</td>
<td>-2,147,483,648 .. 2,147,483,647</td>
</tr>
<tr>
<td>64</td>
<td>8</td>
<td>long long</td>
<td>18,446,744,073,709,600,000</td>
<td>-9,223,372,036,854,780,000 .. 9,223,372,036,854,780,000</td>
</tr>
</tbody>
</table>

Remember: if you have N bits, you can represent 2^N things

How to get unsigned integers in C? Just say **unsigned**:

```c
int x;       // defaults to signed
unsigned int y; // explicitly unsigned
```
2’s Complement Precision Extension

- Most computers today support 32-bit (int) or 64-bit integers
  - Specify 64-bit using gcc C compiler with long long
- To extend precision, use sign bit extension
  - Integer precision is number of bits used to represent a number

Examples

14_{10} = 001110_{2} in 6-bit representation.
14_{10} = 000000001110_{2} in 12-bit representation

-14_{10} = 110010_{2} in 6-bit representation
-14_{10} = 111111110010_{2} in 12-bit representation.
Binary Math : Addition

- Let’s look at another binary addition:

\[
\begin{array}{c}
01011101 \\
+ 01101011 \\
\hline
01101011
\end{array}
\]
• What about this one:

\[
\begin{array}{c}
11111111 \\
01011101 \quad = \quad 93 \\
+ \quad 01101011 \quad = \quad 107 \\
\hline
11001000 \quad = \quad -56
\end{array}
\]

• But... that can’t be right?
  • What do you expect for the answer?
  • What is it in 8-bit signed 2’s complement?
Integer Overflow

- Answer should be 200
  - Not representable in 8-bit signed representation
    - No right answer
- This is called integer **Overflow**
- Real problem in programs
- How to solve?

It hurts when I add two ints and it overflows

Then don't do that
Adding works for unsigned and signed

- Addition works the same way for unsigned and signed numbers. WOW!!
- But watch out for overflow...
  (And overflow for unsigned is different than overflow for signed)

<table>
<thead>
<tr>
<th>Signed</th>
<th>Unsigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>+ 0001</td>
<td>1</td>
</tr>
<tr>
<td>------</td>
<td>0110</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signed</th>
<th>Unsigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1111</td>
<td>1101</td>
</tr>
<tr>
<td></td>
<td>-3</td>
</tr>
<tr>
<td>+ 1111</td>
<td>-1</td>
</tr>
<tr>
<td>------</td>
<td>1100</td>
</tr>
<tr>
<td>-4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signed</th>
<th>Unsigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>+ 0100</td>
<td>4</td>
</tr>
<tr>
<td>------</td>
<td>1001</td>
</tr>
<tr>
<td>9 -7???</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signed</th>
<th>Unsigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>0101</td>
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<tr>
<td>+ 1111</td>
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<tr>
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<td>0101</td>
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<tr>
<td></td>
<td>5</td>
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<tr>
<td>+ 1111</td>
<td>-1</td>
</tr>
<tr>
<td>------</td>
<td>0100</td>
</tr>
</tbody>
</table>
| 4      | 20 4???
Subtraction

2’s complement makes subtraction easy:
- Remember: \( A - B = A + (-B) \)
- And: \( -B = \neg B + 1 \)
  - that means flip bits ("not")
- So we just flip the bits and start with carry-in (CI) = 1
- Later: No new circuits to subtract (re-use adder hardware!)

\[
\begin{array}{c}
1 \\
0110101 \rightarrow 0110101 \\
- 1010010 \\
+ 0101101
\end{array}
\]
What About Non-integer Numbers?

- There are infinitely many real numbers between two integers
- Many important numbers are real
  - Speed of light $\sim= 3\times10^8$
  - $\pi = 3.1415...$
- Fixed number of bits limits range of integers
  - Can’t represent some important numbers
- Humans use Scientific Notation
  - $1.3\times10^4$
Option 1: Fixed point

- Use normal integers, but \((X \times 2^K)\) instead of \(X\)
  - Example: 32 bit int, but use \(X \times 65536\)
    - \(3.1415926 \times 65536 = 205887\)
    - \(0.5 \times 65536 = 32768\), etc..

- Pros:
  - Addition/subtraction just like integers ("free")

- Cons:
  - Mul/div require renormalizing (divide by 64K)
  - Range limited (no good rep for large + small)

- Can be good in specific situations
Can we do better?

• Think about scientific notation for a second:
• For example:
  
  6.02 * 10^{23}

• Real number, but comprised of ints:
  • 6 generally only 1 digit here
  • 02 any number here
  • 10 always 10 (base we work in)
  • 23 can be positive or negative

• Can we do something like this in binary?
Option 2: Floating Point

- How about:
  \[+/- \ X.YYYYYY \times 2^{+/-N}\]

- Big numbers: large positive N
- Small numbers (<1): negative N
- Numbers near 0: small N

- This is “floating point”: most common way
IEEE single precision floating point

• Specific format called IEEE single precision: 
  +/-  1.YYYYY \times 2^{(N-127)} 

• “float” in Java, C, C++, ...

• Assume first bit is always 1 (saves us a bit)
• 1 sign bit (+ = 0, 1 = -)
• 8 bit biased exponent (do N-127)
• Implicit 1 before binary point
• 23-bit mantissa (YYYYY)
Binary fractions

- 1.YYYY has a binary point
  - Like a decimal point but in binary
  - After a decimal point, you have
    - tenths
    - hundredths
    - thousandths
    - ...

- So after a binary point you have...
  - Halves
  - Quarters
  - Eighths
  - ...
Floating point example

- Binary fraction example:
  \[ 101.101 = 4 + 1 + \frac{1}{2} + \frac{1}{8} = 5.625 \]
- For floating point, needs normalization:
  \[ 1.01101 \times 2^2 \]
- Sign is +, which = 0
- Exponent = 127 + 2 = 129 = 1000 0001
- Mantissa = 1.011 0100 0000 0000 0000 0000

Can use hex to represent those bits in a less annoying way:

\[
\begin{array}{cccccccccc}
31 & 30 & 29 & 28 & 27 & 26 & 25 & 24 & 23 & 22 & 0 \\
0 & 1000 & 0001 & 011 & 0100 & 0000 & 0000 & 0000 & 0000 & 0000 & 0
\end{array}
\]

\[
\begin{array}{cccccccccc}
0 & 1000 & 0000 & 1011 & 0100 & 0000 & 0000 & 0000 & 0000 & 0000 & 0
\end{array}
\]
Example:
What floating-point number is: 
\texttt{0xC1580000}?
What floating-point number is 0xC1580000?

\[
\begin{array}{cccccc}
31 & 30 & 23 & 22 & 0 \\
X &=& 1 & 1000 & 0010 & 101 & 1000 & 0000 & 0000 & 0000 & 0000 \\
s & E & F
\end{array}
\]

Sign = 1 which is negative

Exponent = (128+2)-127 = 3

Mantissa = 1.1011

\[-1.1011 \times 2^3 = -1101.1 = -13.5\]
Trick question

• How do you represent 0.0?
  • Why is this a trick question?
  • 0.0 = 0.00000
  • But need 1.XXXXX representation?

• Exponent of 0 is denormalized
  • Implicit 0. instead of 1. in mantissa
  • Allows 0000....0000 to be 0
  • Helps with very small numbers near 0

• Results in +/- 0 in FP (but they are “equal”)
Other Weird FP numbers

- Exponent = 1111 1111 also not standard
  - All 0 mantissa: +/- \infty
    - 1/0 = +\infty
    - -1/0 = -\infty
  - Non zero mantissa: Not a Number (NaN)
    - \sqrt{-42} = NaN
Floating Point Representation

- Double Precision Floating point:

  64-bit representation:
  - 1-bit sign
  - 11-bit (biased) exponent
  - 52-bit fraction (with implicit 1).

- “double” in Java, C, C++, ...

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<th>Exp</th>
<th>Mantissa</th>
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<tbody>
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<td>1</td>
<td>11-bit</td>
<td>52-bit</td>
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</table>


What About Strings?

- Many important things stored as strings...
  - E.g., your name
- How should we store strings?
<table>
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<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
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<td> </td>
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<td>041</td>
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<td>2</td>
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<td>STX</td>
<td>(start of text)</td>
<td>34</td>
<td>22</td>
<td>042</td>
<td>&amp;#34;</td>
<td>&quot;</td>
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<tr>
<td>3</td>
<td>3</td>
<td>003</td>
<td>ETX</td>
<td>(end of text)</td>
<td>35</td>
<td>23</td>
<td>043</td>
<td>&amp;#35;</td>
<td>#</td>
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<tr>
<td>4</td>
<td>4</td>
<td>004</td>
<td>EOT</td>
<td>(end of transmission)</td>
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Source: www.LookupTables.com
One Interpretation of 128-255

| 128 | Ç | 144 | É | 161 | i | 177 | 193 | 209 | 225 | 241 | ± |
| 129 | ü | 145 | æ | 162 | ó | 178 | 194 | 210 | 226 | Γ | 242 |
| 130 | é | 146 | Æ | 163 | ú | 179 | 195 | 211 | 227 | π | 243 |
| 131 | à | 147 | ò | 164 | ñ | 180 | 196 | 212 | 228 | Σ | 244 |
| 132 | à | 148 | ö | 165 | ñ | 181 | 197 | 213 | 229 | θ | 245 |
| 133 | á | 149 | ø | 166 | Å | 182 | 198 | 214 | 230 | τ | 246 |
| 134 | å | 150 | ú | 167 | · | 183 | 199 | 215 | 231 | ρ | 247 |
| 135 | ç | 151 | ˚ | 168 | ¿ | 184 | 200 | 216 | 232 | Φ | 248 |
| 136 | è | 152 | _ | 169 | _ | 185 | 201 | 217 | 233 | ⊙ | 249 |
| 137 | ë | 153 | Ö | 170 | - | 186 | 202 | 218 | 234 | Ω | 250 |
| 138 | ñ | 154 | Ü | 171 | ½ | 187 | 203 | 219 | 235 | δ | 251 |
| 139 | i | 156 | £ | 172 | ¼ | 188 | 204 | 220 | 236 | ∞ | 252 |
| 140 | i | 157 | ¥ | 173 | ½ | 189 | 205 | 221 | 237 | ϕ | 253 |
| 141 | í | 158 | _ | 174 | « | 190 | 206 | 222 | 238 | ε | 254 |
| 142 | Ä | 159 | ß | 175 | » | 191 | 207 | 223 | 239 | Ω | 255 |
| 143 | Å | 160 | á | 176 | å | 192 | 208 | 224 | α | 240 | = |

Source: www.LookupTables.com
(This allowed totally sweet ASCII art in the 1990s)

Sources:
About those control codes…

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<th>Char</th>
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<td>4</td>
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<td>011</td>
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<td>013</td>
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<td>NAK (negative acknowledge)</td>
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<td>22</td>
<td>16</td>
<td>026</td>
<td>SYN (synchronous idle)</td>
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<td>17</td>
<td>027</td>
<td>ETB (end of trans. block)</td>
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<td>1D</td>
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<td>RS (record separator)</td>
</tr>
<tr>
<td>31</td>
<td>1F</td>
<td>037</td>
<td>US (unit separator)</td>
</tr>
</tbody>
</table>

We need to talk about CR and LF…

(Greyed out ones almost never used)
About CR and LF

- History: first computer “displays” were modified typewriters
- CR = “Carriage return” = \r = 0x0D
  - Move typey part to the left → move cursor to left of screen
- LF = “Line feed” = \n = 0x0A
  - Move paper one line down → Move cursor one down
- Windows: “Pretend to be a typewriter”
  - Every time you press enter you get CR+LF (bytes 0D,0A)
- Linux/Mac: “You are not a typewriter”
  - Every time you press enter you get LF (byte 0A)
- This effects ALL TEXT DOCUMENTS!!!
  - Not all apps cope automatically! It will bite you one day for sure!
Outline

• Previously:
  • Computer is machine that does what we tell it to do

• Next:
  • How do we tell computers what to do?
  • How do we represent data objects in binary?
  • How do we represent data locations in binary?
Computer Memory

• Where do we put these numbers?
  • Registers  [more on these later]
    • In the processor core
    • Compute directly on them
    • Few of them (~16 or 32 registers, each 32-bit or 64-bit)

• Memory  [Our focus now]
  • External to processor core
  • Load/store values to/from registers
  • Very large (multiple GB)
Memory Organization

- Memory: billions of locations...how to get the right one?
  - Each memory location has an address
  - Processor asks to read or write specific address
    - Memory, please load address 0x123400
    - Memory, please write 0xFE into address 0x8765000
  - Kind of like a giant array
    - Array of what?
      - Bytes?
      - 32-bit ints?
      - 64-bit ints?
Memory Organization

- Most systems: byte (8-bit) addressed
  - Memory is “array of bytes”
    - Each address specifies 1 byte
  - Support to load/store 8, 16, 32, 64 bit quantities
    - Byte ordering varies from system to system

- Some systems “word addressed”
  - Memory is “array of words”
    - Smaller operations “faked” in processor
  - Not very common
**Word of the Day: Endianess**

**Byte Order**

- **Big Endian:** byte 0 is eight **most** significant bits
  
  MIPS, IBM 360/370, Motorola 68k, Sparc, HP PA

- **Little Endian:** byte 0 is eight **least** significant bits
  
  Intel 80x86, DEC Vax, DEC Alpha

---

### Program

```c
X = 0x12345678; // X lives at address 0x1000
```

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
<th>Memory Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>12</td>
<td>big endian byte 0</td>
</tr>
<tr>
<td>0x1001</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>0x1002</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>0x1003</td>
<td>78</td>
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**Memory layout on a big endian system:**

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**Memory layout on a little endian system:**
What is an array?

- The shocking truth: You’ve been using pointers all along!
- Every array *is* a pointer to a block of memory
- **Pointer arithmetic:** If you add an integer N to a pointer P, you get the address of N *things* later from pointer P
  - “Thing” depends on the datatype of the P
- Can *dereference* such pointers to get what’s there
  - Interpreted according to the datatype of P
  - E.g. *(nums-1) is a number related to how we represent the letter ‘o’.*

```
int x = 9;
char msg[] = “hello”;
short nums[] = {6,7,8};
```
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```

![Diagram showing memory layout and pointer arithmetic]
Memory Layout

- Memory is array of bytes, but there are conventions as to what goes where in this array
  - **Text**: instructions (the program to execute)
  - **Data**: global variables
  - **Stack**: local variables and other per-function state; starts at top & grows down
  - **Heap**: dynamically allocated variables; grows up
- What if stack and heap overlap????
int anumber = 3;

int factorial (int x) {
    if (x == 0) {
        return 1;
    }
    else {
        return x * factorial (x - 1);
    }
}

int main (void) {
    int z = factorial (anumber);
    int* p = malloc(sizeof(int)*64);
    printf("%d\n", z);
    return 0;
} // p is a local on stack, *p is in heap
Everything must be represented in binary!

Pointer is memory location that contains address of another memory location

Computer memory is linear array of bytes
  - **Integers:**
    - *unsigned* \{0..2\(^n\)-1\} vs *signed* \{-2\(^{n-1}\) .. 2\(^{n-1}\)-1\} (“2’s complement”)
    - *char* (8-bit), *short* (16-bit), *int*/*long* (32-bit), *long long* (64-bit)
  - **Floats:** IEEE representation,
    - *float* (32-bit: 1 sign, 8 exponent, 23 mantissa)
    - *double* (64-bit: 1 sign, 11 exponent, 52 mantissa)
  - **Strings:** char array, ASCII representation

Memory layout
  - *Stack* for local, *static* for globals, *heap* for malloc’d stuff (must free!)
The following slides re-state a lot of what we’ve covered but in a different way. We’ll likely skip it for time, but you can use the slides as an additional reference.
Let’s do a little Java…

```java
public class Example {
    public static void swap (int x, int y) {
        int temp = x;
        x = y;
        y = temp;
    }
    public static void main (String[] args) {
        int a = 42;
        int b = 100;
        swap (a, b);
        System.out.println("a = " + a + " b = " + b);
    }
}
```

- What does this print? Why?
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    }
}

• What does this print? Why?
public class Ex2 {
    int data;
    public Ex2 (int d) { data = d; }
    public static void swap (Ex2 x, Ex2 y) {
        int temp = x.data;
        x.data = y.data;
        y.data = temp;
    }
    public static void main (String[] args) {
        Example a = new Example (42);
        Example b = new Example (100);
        swap (a, b);
        System.out.println("a =" + a.data +
                           " b = " + b.data);
    }
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}
```

• What does this print? Why?
References and Pointers (review)

- Java has **references**:
  - Any variable of object type is a reference
  - Point at objects (which are all in the heap)
    - Under the hood: is the memory address of the object
  - Cannot explicitly manipulate them (*e.g.*, add 4)

- Some languages (C, C++, assembly) have explicit **pointers**:
  - Hold the memory address of something
  - Can explicitly compute on them
  - Can de-reference the pointer (*ptr) to get thing-pointed-to
  - Can take the **address-of** (&x) to get something’s address
  - Can do very **unsafe** things, shoot yourself in the foot
Pointers

- “address of” operator &
  - don’t confuse with bitwise AND operator (&&)

Given

```c
int x; int* p;  // p points to an int
p = &x;
```

Then

```c
*p = 2;  and x = 2; produce the same result
```

Note: p is a pointer, *p is an int

- What happens for p = 2?;

On 32-bit machine, p is 32-bits

```
x 0x26cf0

...```

```
p 0x26d00 0x26cbf0
```

```c
```
• Java:
  ```java
  int [] x = new int [nElems];
  ```

• C:
  ```c
  int data[42]; //if size is known constant
  int* data = (int*)malloc (nElem * sizeof(int));
  ```

  • `malloc` takes number of bytes
  • `sizeof` tells how many bytes something takes
• x is a pointer, what is x+33?
• A pointer, but where?
  • what does calculation depend on?
• Result of adding an int to a pointer depends on size of object pointed to
  • One reason why we tell compiler what type of pointer we have, even though all pointers are really the same thing (and same size)

\[
\text{int* } a = \text{malloc(100*\text{sizeof(int))}}; \\
0 \quad 1 \quad 32 \quad 33 \quad 98 \quad 99 \\
a[33] \text{ is the same as } * (a + 33) \\
\text{if } a \text{ is 0x00a0, then } a + 1 \text{ is 0x00a4, } a + 2 \text{ is 0x00a8} \\
(\text{decimal 160, 164, 168})
\]

\[
\text{double* } d = \text{malloc(200*\text{sizeof(double))}}; \\
0 \quad 1 \quad 3 \quad 199 \\
* (d + 33) \text{ is the same as } d[33] \\
\text{if } d \text{ is 0x00b0, then } d + 1 \text{ is 0x00b8, } d + 2 \text{ is 0x00c0} \\
(\text{decimal 176, 184, 192})
\]
More Pointer Arithmetic

- address one past the end of an array is ok for pointer comparison only

- what’s at *(begin+44)?

- what does begin++ mean?

- how are pointers compared using < and using ==?

- what is value of end - begin?

```cpp
char* a = new char[44];
char* begin = a;
char* end = a + 44;

while (begin < end)
{
    *begin = 'z';
    begin++;
}
```
More Pointers & Arrays

```cpp
int* a = new int[100];

0 1 32 33 98 99

a is a pointer
*a is an int
a[0] is an int (same as *a)
a[1] is an int
a+1 is a pointer
a+32 is a pointer
*(a+1) is an int (same as a[1])
*(a+99) is an int
*(a+100) is trouble
```
Array Example

#include <stdio.h>

main()
{
    int* a = (int*)malloc (100 * sizeof(int));
    int* p = a;
    int k;

    for (k = 0; k < 100; k++)
    {
        *p = k;
        p++;
    }
    printf("entry 3 = %d\n", a[3])
}
Memory Manager (Heap Manager)

- `malloc()` and `free()`
- Library routines that handle memory management for heap (allocation / deallocation)
- Java has garbage collection (reclaim memory of unreferenced objects)
- C must use `free`, else memory leak
Strings as Arrays (review)

- A string is an array of characters with ‘\0’ at the end
- Each element is one byte, ASCII code
- ‘\0’ is null (ASCII code 0)
**strlen() again**

- `strlen()` returns the number of characters in a string
  - same as number elements in char array?

```c
int strlen(char * s)
// pre: '\0' terminated
// post: returns # chars
{
    int count=0;
    while (*s++)
        count++;
    return count;
}
```
Vector Class vs. Arrays

- **Vector Class**
  - insulates programmers
  - array bounds checking
  - automagically growing/shrinking when more items are added/deleted

- **How are Vectors implemented?**
  - Arrays, re-allocated as needed

- **Arrays can be more efficient**