ECE/CS 250
Computer Architecture
Summer 2022

From C to Binary

Tyler Bletsch
Duke University

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:**

```cpp
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!
• Key Idea: 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
- Original Nintendo: 8 bit
- Super Nintendo: 16 bit
- Intel x86 (classic): 32 bit
- Nintendo 64: 64 bit
- Intel x86_64 (modern): 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?
  • $\log_2 4G = \ldots \ldots$?
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:**
  
  $$2^{XY} \text{ bytes} = 2^Y \cdot 2^{X0} \text{ bytes} = 2^Y \text{ <X_prefix> B}$$

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

This matters a lot later on.
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

• 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 ÷ 2 =</td>
<td>228</td>
<td>1</td>
</tr>
<tr>
<td>228 ÷ 2 =</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>114 ÷ 2 =</td>
<td>57</td>
<td>0</td>
</tr>
<tr>
<td>57 ÷ 2 =</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>28 ÷ 2 =</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>14 ÷ 2 =</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>7 ÷ 2 =</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3 ÷ 2 =</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1 ÷ 2 =</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

111001001
Decimal to binary using comparison

<table>
<thead>
<tr>
<th>Num</th>
<th>Compare $2^n$</th>
<th>≥ ?</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>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
## 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

- 010110110010011\_2 \rightarrow
- 0101 1011 0010 0011\_2 \rightarrow
- 5 B 2 3\_16

1 F 4 B\_16 \rightarrow

0001 1111 0100 1011\_2 \rightarrow
0001111101001011\_2
BitOps: Unary

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

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

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

```c
char i, j1, j2, j3;
i = 0x0d; \quad // binary \quad 00001101
j1 = \sim i; \quad // binary \quad 11110010
j2 = -i; \quad // binary \quad 11110011
j3 = !i; \quad // binary \quad 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):**
- \( X \& 1 = X \) \( ANDing \) with 1 does nothing
- \( X \& 0 = 0 \) \( ANDing \) with 0 gives zero
- \( X | 0 = X \) \( ORing \) with 0 does nothing
- \( X | 1 = 1 \) \( ORing \) with 1 gives one
- \( X ^ 0 = X \) \( XORing \) with 0 does nothing
- \( X ^ 1 = \sim X \) \( XORing \) with 1 flips the bit
Two Operands... (cont’d)

- **Examples**

<table>
<thead>
<tr>
<th>0011 1000</th>
<th>0011 1000</th>
<th>0011 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp; 1101 1110</td>
<td>1101 1110</td>
<td>^ 1101 1110</td>
</tr>
<tr>
<td>0001 1000</td>
<td>1111 1110</td>
<td>1110 0110</td>
</tr>
</tbody>
</table>
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

```
01111001 \ll 3
---------------------
11001000
```

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

\[
\begin{array}{c}
01111001 \\ \hline
00001111
\end{array}
\]

these 3 bits are discarded

these 3 bits are zero filled
Bitwise Recipes

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

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

- 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:
    
    \[ v = 0x67; \quad \text{// 01100111}_2 \]
    \[ v >>= 2; \quad \text{// 00011001}_2 \]
    \[ v \&\!|= 0x0F; \quad \text{// 00001001}_2 \]
Binary Math : Addition

• Suppose we want to add two numbers:

```
  00011101
+  00101011
```

=  00101011

• How do we do this?
Binary Math : Addition

• Suppose we want to add two numbers:

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

• 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:

  \[
  \begin{array}{c}
  00011101 \\
  + 00101011 \\
  \hline
  00100100
  \end{array}
  \]

  \[
  \begin{array}{c}
  695 \\
  + 232 \\
  \hline
  727
  \end{array}
  \]

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

• Suppose we want to add two numbers:

\[
\begin{array}{c}
00011101 \\
+ 00101011
\end{array}
\quad
\begin{array}{c}
1 \\
695 + 232 \\
\hline
27
\end{array}
\]

• 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:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
695 + 232 \\
927
\end{array}
\]

• 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:

\[
\begin{array}{c}
00011101 \\
+ 00101011 \\
\hline
00100100
\end{array}
\]

• Back to the binary:

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

• Suppose we want to add two numbers:

\[
\begin{array}{c}
1 \\
0001110 \ \\
+ \ 0010101 \ \\
\hline
0010111
\end{array}
\]

• 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:

\[
\begin{array}{c}
11 \\
00111101 \\
+ 00101011 \
\end{array}
\]

\[
00
\]

• 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:

\[
\begin{array}{c}
111111 \\
00011101 &= 29 \\
+ 00101011 &= 43 \\
\hline
01001000 &= 72
\end{array}
\]

• 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 → 1
  1 → 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>
</tr>
<tr>
<td>1011</td>
<td>-4</td>
</tr>
<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>
2’s Complement Integers

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

6-bit examples:

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>000000</td>
</tr>
<tr>
<td>1</td>
<td>000001</td>
</tr>
<tr>
<td>2</td>
<td>000010</td>
</tr>
<tr>
<td>3</td>
<td>000011</td>
</tr>
<tr>
<td>4</td>
<td>000100</td>
</tr>
<tr>
<td>5</td>
<td>000101</td>
</tr>
<tr>
<td>6</td>
<td>001000</td>
</tr>
<tr>
<td>7</td>
<td>001001</td>
</tr>
<tr>
<td>-1</td>
<td>111111</td>
</tr>
<tr>
<td>-2</td>
<td>111110</td>
</tr>
<tr>
<td>-3</td>
<td>111101</td>
</tr>
<tr>
<td>-4</td>
<td>111100</td>
</tr>
<tr>
<td>-5</td>
<td>111101</td>
</tr>
<tr>
<td>-6</td>
<td>111100</td>
</tr>
<tr>
<td>-7</td>
<td>111111</td>
</tr>
<tr>
<td>-8</td>
<td>100001</td>
</tr>
</tbody>
</table>

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:
1101
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
• 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>0 .. 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>

Hey, remember that “if I have N bits I can represent 2^N things? Remember how I said that was important? Well here ya go.
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:

\[
\begin{align*}
1111111 \\
01011101 &= 93 \\
+ 01101011 &= 107 \\
\hline
11001000 &= -56
\end{align*}
\]

• 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
Subtraction

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

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

- There are infinitely many real numbers between two integers
- Many important numbers are real
  - Speed of light $\sim= 3 \times 10^8$
  - $\pi = 3.1415...$
- Fixed number of bits limits range of integers
  - Can’t represent some important numbers
- Humans use Scientific Notation
  - $1.3 \times 10^4$
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:
    \[ 6.02 \times 10^{23} \]
  • 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: 
  \[ \pm 1.YYYYY \times 2^{(N-127)} \]
- “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 \textit{binary point}
- 23-bit \textit{mantissa} (YYYYY)
Binary fractions

1. YYYYY 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
- ...

[Diagram representing fractions]
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
Floating Point Representation

Example:
What floating-point number is: 0xC1580000?
Answer

What floating-point number is 0xC1580000?

\[ \begin{array}{cccccc}
1100 & 0001 & 0101 & 1000 & 0000 & 0000 \\
\end{array} \]

\[\begin{array}{cccccc}
31 & 30 & 23 & 22 & 0 \\
\end{array}\]

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

Sign = 1 which is negative

Exponent = (128+2)-127 = 3

Mantissa = 1.1011

\[-1.1011 \times 2^3 = -1101.1 = -13.5\]
• How do you represent 0.0?
  • Why is this a trick question?
  • 0.0 = 0.00000
  • But need 1.XXXX 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: +/- ∞
    - 1/0 = +∞
    - -1/0 = -∞
  - Non zero mantissa: Not a Number (NaN)
    - \( \text{sqrt}(-42) = \text{NaN} \)
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++, ...

<table>
<thead>
<tr>
<th>S</th>
<th>Exp</th>
<th>Mantissa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11-bit</td>
<td>52 - bit</td>
</tr>
</tbody>
</table>
What About Strings?

- Many important things stored as strings...
  - E.g., your name
- How should we store strings?
## Standardized ASCII (0-127)

<table>
<thead>
<tr>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>000</td>
<td>NUL</td>
<td>(null)</td>
<td>32</td>
<td>20</td>
<td>040</td>
<td>&lt;#32;</td>
<td>Space</td>
<td>64</td>
<td>40</td>
<td>100</td>
<td>&lt;#64;</td>
<td>@</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>001</td>
<td>SOH</td>
<td>(start of heading)</td>
<td>33</td>
<td>21</td>
<td>041</td>
<td>&lt;#33;</td>
<td>!</td>
<td>65</td>
<td>41</td>
<td>101</td>
<td>&lt;#65;</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>002</td>
<td>STX</td>
<td>(start of text)</td>
<td>34</td>
<td>22</td>
<td>042</td>
<td>&lt;#34;</td>
<td>&quot;</td>
<td>66</td>
<td>42</td>
<td>102</td>
<td>&lt;#66;</td>
<td>B</td>
</tr>
<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>&lt;#35;</td>
<td>#</td>
<td>67</td>
<td>43</td>
<td>103</td>
<td>&lt;#67;</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>004</td>
<td>EOT</td>
<td>(end of transmission)</td>
<td>36</td>
<td>24</td>
<td>044</td>
<td>&lt;#36;</td>
<td>$</td>
<td>68</td>
<td>44</td>
<td>104</td>
<td>&lt;#68;</td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>005</td>
<td>ENQ</td>
<td>(enquiry)</td>
<td>37</td>
<td>25</td>
<td>045</td>
<td>&lt;#37;</td>
<td>%</td>
<td>69</td>
<td>45</td>
<td>105</td>
<td>&lt;#69;</td>
<td>E</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>006</td>
<td>ACK</td>
<td>(acknowledge)</td>
<td>38</td>
<td>26</td>
<td>046</td>
<td>&lt;#38;</td>
<td>&amp;</td>
<td>70</td>
<td>46</td>
<td>106</td>
<td>&lt;#70;</td>
<td>F</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>007</td>
<td>BEL</td>
<td>(bell)</td>
<td>39</td>
<td>27</td>
<td>047</td>
<td>&lt;#39;</td>
<td>'</td>
<td>71</td>
<td>47</td>
<td>107</td>
<td>&lt;#71;</td>
<td>G</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>010</td>
<td>BS</td>
<td>(backspace)</td>
<td>40</td>
<td>28</td>
<td>050</td>
<td>&lt;#40;</td>
<td>(</td>
<td>72</td>
<td>48</td>
<td>110</td>
<td>&lt;#72;</td>
<td>H</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>011</td>
<td>TAB</td>
<td>(horizontal tab)</td>
<td>41</td>
<td>29</td>
<td>051</td>
<td>&lt;#41;</td>
<td>)</td>
<td>73</td>
<td>49</td>
<td>111</td>
<td>&lt;#73;</td>
<td>I</td>
</tr>
<tr>
<td>10</td>
<td>A</td>
<td>012</td>
<td>LF</td>
<td>(NL line feed, new line)</td>
<td>42</td>
<td>2A</td>
<td>052</td>
<td>&lt;#42;</td>
<td>*</td>
<td>74</td>
<td>4A</td>
<td>112</td>
<td>&lt;#74;</td>
<td>J</td>
</tr>
<tr>
<td>11</td>
<td>B</td>
<td>013</td>
<td>VT</td>
<td>(vertical tab)</td>
<td>43</td>
<td>2B</td>
<td>053</td>
<td>&lt;#43;</td>
<td>+</td>
<td>75</td>
<td>4B</td>
<td>113</td>
<td>&lt;#75;</td>
<td>K</td>
</tr>
<tr>
<td>12</td>
<td>C</td>
<td>014</td>
<td>FF</td>
<td>(NP form feed, new page)</td>
<td>44</td>
<td>2C</td>
<td>054</td>
<td>&lt;#44;</td>
<td>,</td>
<td>76</td>
<td>4C</td>
<td>114</td>
<td>&lt;#76;</td>
<td>L</td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>015</td>
<td>CR</td>
<td>(carriage return)</td>
<td>45</td>
<td>2D</td>
<td>055</td>
<td>&lt;#45;</td>
<td>-</td>
<td>77</td>
<td>4D</td>
<td>115</td>
<td>&lt;#77;</td>
<td>M</td>
</tr>
<tr>
<td>14</td>
<td>E</td>
<td>016</td>
<td>SO</td>
<td>(shift out)</td>
<td>46</td>
<td>2E</td>
<td>056</td>
<td>&lt;#46;</td>
<td>.</td>
<td>78</td>
<td>4E</td>
<td>116</td>
<td>&lt;#78;</td>
<td>N</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>017</td>
<td>SI</td>
<td>(shift in)</td>
<td>47</td>
<td>2F</td>
<td>057</td>
<td>&lt;#47;</td>
<td>/</td>
<td>79</td>
<td>4F</td>
<td>117</td>
<td>&lt;#79;</td>
<td>O</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>020</td>
<td>DLE</td>
<td>(data link escape)</td>
<td>48</td>
<td>30</td>
<td>060</td>
<td>&lt;#48;</td>
<td>0</td>
<td>80</td>
<td>50</td>
<td>120</td>
<td>&lt;#80;</td>
<td>P</td>
</tr>
<tr>
<td>17</td>
<td>11</td>
<td>021</td>
<td>DC1</td>
<td>(device control 1)</td>
<td>49</td>
<td>31</td>
<td>061</td>
<td>&lt;#49;</td>
<td>1</td>
<td>81</td>
<td>51</td>
<td>121</td>
<td>&lt;#81;</td>
<td>Q</td>
</tr>
<tr>
<td>18</td>
<td>12</td>
<td>022</td>
<td>DC2</td>
<td>(device control 2)</td>
<td>50</td>
<td>32</td>
<td>062</td>
<td>&lt;#50;</td>
<td>2</td>
<td>82</td>
<td>52</td>
<td>122</td>
<td>&lt;#82;</td>
<td>R</td>
</tr>
<tr>
<td>19</td>
<td>13</td>
<td>023</td>
<td>DC3</td>
<td>(device control 3)</td>
<td>51</td>
<td>33</td>
<td>063</td>
<td>&lt;#51;</td>
<td>3</td>
<td>83</td>
<td>53</td>
<td>123</td>
<td>&lt;#83;</td>
<td>S</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>024</td>
<td>DC4</td>
<td>(device control 4)</td>
<td>52</td>
<td>34</td>
<td>064</td>
<td>&lt;#52;</td>
<td>4</td>
<td>84</td>
<td>54</td>
<td>124</td>
<td>&lt;#84;</td>
<td>T</td>
</tr>
<tr>
<td>21</td>
<td>15</td>
<td>025</td>
<td>NAK</td>
<td>(negative acknowledge)</td>
<td>53</td>
<td>35</td>
<td>065</td>
<td>&lt;#53;</td>
<td>5</td>
<td>85</td>
<td>55</td>
<td>125</td>
<td>&lt;#85;</td>
<td>U</td>
</tr>
<tr>
<td>22</td>
<td>16</td>
<td>026</td>
<td>SYN</td>
<td>(synchronous idle)</td>
<td>54</td>
<td>36</td>
<td>066</td>
<td>&lt;#54;</td>
<td>6</td>
<td>86</td>
<td>56</td>
<td>126</td>
<td>&lt;#86;</td>
<td>V</td>
</tr>
<tr>
<td>23</td>
<td>17</td>
<td>027</td>
<td>ETB</td>
<td>(end of trans. block)</td>
<td>55</td>
<td>37</td>
<td>067</td>
<td>&lt;#55;</td>
<td>7</td>
<td>87</td>
<td>57</td>
<td>127</td>
<td>&lt;#87;</td>
<td>W</td>
</tr>
<tr>
<td>24</td>
<td>18</td>
<td>030</td>
<td>CAN</td>
<td>(cancel)</td>
<td>56</td>
<td>38</td>
<td>070</td>
<td>&lt;#56;</td>
<td>8</td>
<td>88</td>
<td>58</td>
<td>130</td>
<td>&lt;#88;</td>
<td>X</td>
</tr>
<tr>
<td>25</td>
<td>19</td>
<td>031</td>
<td>EM</td>
<td>(end of medium)</td>
<td>57</td>
<td>39</td>
<td>071</td>
<td>&lt;#57;</td>
<td>9</td>
<td>89</td>
<td>59</td>
<td>131</td>
<td>&lt;#89;</td>
<td>Y</td>
</tr>
<tr>
<td>26</td>
<td>1A</td>
<td>032</td>
<td>SUB</td>
<td>(substitute)</td>
<td>58</td>
<td>3A</td>
<td>072</td>
<td>&lt;#58;</td>
<td>:</td>
<td>90</td>
<td>5A</td>
<td>132</td>
<td>&lt;#90;</td>
<td>Z</td>
</tr>
<tr>
<td>27</td>
<td>1B</td>
<td>033</td>
<td>ESC</td>
<td>(escape)</td>
<td>59</td>
<td>3B</td>
<td>073</td>
<td>&lt;#59;</td>
<td>;</td>
<td>91</td>
<td>5B</td>
<td>133</td>
<td>&lt;#91;</td>
<td>[</td>
</tr>
<tr>
<td>28</td>
<td>1C</td>
<td>034</td>
<td>FS</td>
<td>(file separator)</td>
<td>60</td>
<td>3C</td>
<td>074</td>
<td>&lt;#60;</td>
<td>&lt;</td>
<td>92</td>
<td>5C</td>
<td>134</td>
<td>&lt;#92;</td>
<td>\</td>
</tr>
<tr>
<td>29</td>
<td>1D</td>
<td>035</td>
<td>GS</td>
<td>(group separator)</td>
<td>61</td>
<td>3D</td>
<td>075</td>
<td>&lt;#61;</td>
<td>=</td>
<td>93</td>
<td>5D</td>
<td>135</td>
<td>&lt;#93;</td>
<td>{</td>
</tr>
<tr>
<td>30</td>
<td>1E</td>
<td>036</td>
<td>RS</td>
<td>(record separator)</td>
<td>62</td>
<td>3E</td>
<td>076</td>
<td>&lt;#62;</td>
<td>&gt;</td>
<td>94</td>
<td>5E</td>
<td>136</td>
<td>&lt;#94;</td>
<td>^</td>
</tr>
<tr>
<td>31</td>
<td>1F</td>
<td>037</td>
<td>US</td>
<td>(unit separator)</td>
<td>63</td>
<td>3F</td>
<td>077</td>
<td>&lt;#63;</td>
<td>?</td>
<td>95</td>
<td>5F</td>
<td>137</td>
<td>&lt;#95;</td>
<td>_</td>
</tr>
</tbody>
</table>
# One Interpretation of 128-255

| 128 | Ç |  #144 | É | 161 | î | 177 | 193 | 209 | 225 | ² | 241 | ± |
| 129 | ü |  #145 | æ | 162 | õ | 178 | 194 | 210 | 226 | ² | 242 | ± |
| 130 | é |  #146 | Æ | 163 | û | 179 | 195 | 211 | 227 | ² | 243 | ± |
| 131 | å |  #147 | ô | 164 | ŋ | 180 | 196 | 212 | 228 | ² | 244 | ± |
| 132 | ä |  #148 | ö | 165 | Ń | 181 | 197 | 213 | 229 | ² | 245 | ± |
| 133 | ä |  #149 | ô | 166 | ¨ | 182 | 198 | 214 | 230 | ² | 246 | ± |
| 134 | å |  #150 | ū | 167 | ¨ | 183 | 199 | 215 | 231 | ² | 247 | ± |
| 135 | ç |  #151 | û | 168 | ¨ | 184 | 200 | 216 | 232 | ² | 248 | ± |
| 136 | è |  #152 | ¯ | 169 | ¨ | 185 | 201 | 217 | 233 | ² | 249 | ± |
| 137 | é |  #153 | Ö | 170 | ¯ | 186 | 202 | 218 | 234 | ² | 250 | ± |
| 138 | è |  #154 | Ü | 171 | ² | 187 | 203 | 219 | 235 | ² | 251 | ± |
| 139 | i |  #156 | £ | 172 | ² | 188 | 204 | 220 | 236 | ² | 252 | ± |
| 140 | î |  #157 | ¥ | 173 | î | 189 | 205 | 221 | 237 | ² | 253 | ± |
| 141 | i |  #158 | ¯ | 174 | « | 190 | 206 | 222 | 238 | ² | 254 | ± |
| 142 | Ä |  #159 | f | 175 | » | 191 | 207 | 223 | 239 | ² | 255 | ± |
| 143 | Å |  #160 | á | 176 | ² | 192 | 208 | 224 | ² | 240 | ± | ± |

Source: www.LookupTables.com
(This allowed totally sweet ASCII art in the 90s)

Sources:
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
X = 0x12345678;  // X lives at address 0x1000
```

Memory layout on a big endian system:

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>12</td>
</tr>
<tr>
<td>0x1001</td>
<td>34</td>
</tr>
<tr>
<td>0x1002</td>
<td>56</td>
</tr>
<tr>
<td>0x1003</td>
<td>78</td>
</tr>
</tbody>
</table>

Memory layout on a little endian system:

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x1000</td>
<td>78</td>
</tr>
<tr>
<td>0x1001</td>
<td>56</td>
</tr>
<tr>
<td>0x1002</td>
<td>34</td>
</tr>
<tr>
<td>0x1003</td>
<td>12</td>
</tr>
</tbody>
</table>
• 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
”, z);
    return 0;
}

    // p is a local on stack, *p is in heap
Summary: From C to Binary

- 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.
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?
public class Example {
    public static void swap (int x, int y) {
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        x = y;
        y = temp;
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        swap (a, b);
        System.out.println("a =" + a + " b = " + b);
    }
}

What does this print? Why?
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);
    }
}
```

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        int a = 42;
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}

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        int a = 42;
        int b = 100;
        swap (a, b);
        System.out.println("a = " + a + " b = " + b);
    }
}

• 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);
    }
}

• 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);
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        swap (a, b);
        System.out.println("a = " + a.data + " b = " + b.data);
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}

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        Example a = new Example (42);
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        swap (a, b);
        System.out.println("a = " + a.data + " b = " + b.data);
    }
}

• What does this print? Why?
Let’s do some different Java…

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);
    }
}

• 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);
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        swap (a, b);
        System.out.println("a = " + a.data + " b = " + b.data);
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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);
    }
}

• What does this print? Why?
Let’s do some different Java...

```java
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);
    }
}
```

- 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);
    }
}

• 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

```c
    x  0x26cf0
        ...
    p  0x26d00 0x26cbf0
```
Back to Arrays

- **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
Arrays, Pointers, and Address Calculation

- **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)

```c
int* a = malloc(100*sizeof(int));
```
```
0 1 32 33 98 99
```

*a[33]* is the same as *(a+33)
if a is 0x00a0, then a+1 is 0x00a4, a+2 is 0x00a8
(decimal 160, 164, 168)

```c
double* d = malloc(200*sizeof(double));
```
```
0 1 3 199
```

*(d+33) is the same as d[33]
if d is 0x00b0, then d+1 is 0x00b8, d+2 is 0x00c0
(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?

char* a = new char[44];
char* begin = a;
char* end = a + 44;
while (begin < end)
{
    *begin = ‘z’;
    begin++;
}

```c
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];

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
```
#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)
\textbf{strlen() again}

- \texttt{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