CS107 Lecture 2
Bits and Bytes; Integer Representations

reading:
Bryant & O’Hallaron, Ch. 2.2-2.3
CS107 Topic 1: How can a computer represent integer numbers?
Demo: Unexpected Behavior

```sh
cp -r /afs(ir/class/cs107/lecture-code/lect2 .
```
Lecture Plan

• Bits and Bytes 5
• Hexadecimal 33
• Integer Representations 41
• Unsigned Integers 47
• Signed Integers 51
• Overflow 77
• Casting and Combining Types 90
• Live Session 119
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</table>

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<table>
<thead>
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<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Computers are built around the idea of two states: “on” and “off”. Transistors represent this in hardware, and bits represent this in software!
One Bit At A Time

• We can combine bits, like with base-10 numbers, to represent more data. 8 bits = 1 byte.

• Computer memory is just a large array of bytes! It is byte-addressable; you can’t address (store location of) a bit; only a byte.

• Computers still fundamentally operate on bits; we have just gotten more creative about how to represent different data as bits!
  • Images
  • Audio
  • Video
  • Text
  • And more…
Base 10

5 9 3 4

Digits 0-9 (0 to base-1)
Base 10

\[ 5 \times 1000 + 9 \times 100 + 3 \times 10 + 4 \times 1 \]
Base 10

5 9 3 4

$10^3$ $10^2$ $10^1$ $10^0$
Base 10

5 9 3 4

10^x:  3  2  1  0
Base 2

$2^x$: 3 2 1 0

1 0 1 1

Digits 0-1 (0 to base-1)
Base 2

1 0 1 1

$2^3$ $2^2$ $2^1$ $2^0$
Base 2

1 0 1 1

Most significant bit (MSB)       Least significant bit (LSB)
eights  fours  twos  ones

= 1*8 + 0*4 + 1*2 + 1*1 = 11_{10}
**Question:** What is 6 in base 2?

- **Strategy:**
  - What is the largest power of $2 \leq 6$?
Question: What is 6 in base 2?

• Strategy:
  • What is the largest power of 2 ≤ 6? \(2^2 = 4\)
**Question:** What is 6 in base 2?

- **Strategy:**
  - What is the largest power of 2 ≤ 6? \(2^2 = 4\)
  - Now, what is the largest power of 2 ≤ 6 – 2^2?
Question: What is 6 in base 2?

• Strategy:
  • What is the largest power of 2 ≤ 6? $2^2 = 4$
  • Now, what is the largest power of 2 ≤ 6 – $2^2$? $2^1 = 2$
Base 10 to Base 2

**Question:** What is 6 in base 2?

**Strategy:**
- What is the largest power of 2 ≤ 6? \(2^2 = 4\)
- Now, what is the largest power of 2 ≤ 6 – 2^2? \(2^1 = 2\)
- \(6 – 2^2 – 2^1 = 0!\)

\[
\begin{array}{cccc}
0 & 1 & 1 & 0 \\
\hline
2^3 & 2^2 & 2^1 & 2^0
\end{array}
\]
**Question:** What is 6 in base 2?

**Strategy:**
- What is the largest power of 2 ≤ 6? \(2^2 = 4\)
- Now, what is the largest power of 2 ≤ 6 − 2^2? \(2^1 = 2\)
- \(6 − 2^2 − 2^1 = 0!\)
**Question:** What is 6 in base 2?

**Strategy:**
- What is the largest power of 2 ≤ 6? $2^2 = 4$
- Now, what is the largest power of 2 ≤ 6 – $2^2$? $2^1 = 2$
- $6 – 2^2 – 2^1 = 0$

$$0 \times 8 + 1 \times 4 + 1 \times 2 + 0 \times 1 = 6$$
Practice: Base 2 to Base 10

What is the base-2 value 1010 in base-10?

a) 20
b) 101
c) 10
d) 5
e) Other
What is the base-10 value 14 in base 2?

a) 1111
b) 1110
c) 1010
d) Other
• What is the minimum and maximum base-10 value a single byte (8 bits) can store?
• What is the minimum and maximum base-10 value a single byte (8 bits) can store?  
  \[ \text{minimum} = 0 \quad \text{maximum} = ? \]
What is the minimum and maximum base-10 value a single byte (8 bits) can store?  

minimum = 0  maximum = ?

```
11111111
```

\[ 2^7: \quad 7 \quad 6 \quad 5 \quad 4 \quad 3 \quad 2 \quad 1 \quad 0 \]
Byte Values

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

  minimum = 0  
  maximum = ?

• Strategy 1:  

  \[1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 255\]
• What is the minimum and maximum base-10 value a single byte (8 bits) can store?  
  \[ \text{minimum} = 0 \quad \text{maximum} = 255 \]

• **Strategy 1:**  
  
  \[ 1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 255 \]

• **Strategy 2:**  
  
  \[ 2^8 - 1 = 255 \]
Multiplying by Base

1450 \times 10 = 14500

1100_2 \times 2 = 11000_2

*Key Idea*: inserting 0 at the end multiplies by the base!
Dividing by Base

\[1450 / 10 = 145\]
\[1100_2 / 2 = 110\]

*Key Idea*: removing 0 at the end divides by the base!
<table>
<thead>
<tr>
<th>Topic</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td><strong>Hexadecimal</strong></td>
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</tr>
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<td>90</td>
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</tr>
</tbody>
</table>
• When working with bits, oftentimes we have large numbers with 32 or 64 bits.
• Instead, we’ll represent bits in \textit{base-16 instead}; this is called \textbf{hexadecimal}.

\begin{center}
\begin{tabular}{c}
0110 & 1010 & 0011 \\
0-15 & 0-15 & 0-15 \\
\end{tabular}
\end{center}
Hexadecimal

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

Each is a base-16 digit!
Hexadecimal

• Hexadecimal is \textit{base-16}, so we need digits for 1-15. How do we do this?
## Hexadecimal

<table>
<thead>
<tr>
<th>Hex digit</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decimal value</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Binary value</td>
<td>0000</td>
<td>0001</td>
<td>0010</td>
<td>0011</td>
<td>0100</td>
<td>0101</td>
<td>0110</td>
<td>0111</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hex digit</th>
<th>8</th>
<th>9</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decimal value</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>Binary value</td>
<td>1000</td>
<td>1001</td>
<td>1010</td>
<td>1011</td>
<td>1100</td>
<td>1101</td>
<td>1110</td>
<td>1111</td>
</tr>
</tbody>
</table>
Hexadecimal

• We distinguish hexadecimal numbers by prefixing them with 0x, and binary numbers with 0b.
• E.g. 0xf5 is 0b11110101
### Practice: Hexadecimal to Binary

What is \(0x173A\) in binary?

<table>
<thead>
<tr>
<th>Hexadecimal</th>
<th>1</th>
<th>7</th>
<th>3</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary</td>
<td>0001</td>
<td>0111</td>
<td>0011</td>
<td>1010</td>
</tr>
</tbody>
</table>
## Practice: Hexadecimal to Binary

What is \texttt{0b111001010} in hexadecimal? \textit{(Hint: start from the right)}

<table>
<thead>
<tr>
<th>Binary</th>
<th>11</th>
<th>1100</th>
<th>1010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexadecimal</td>
<td>3</td>
<td>C</td>
<td>A</td>
</tr>
</tbody>
</table>
• Bits and Bytes 5
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• Overflow 77
• Casting and Combining Types 90
• Live Session 119
Number Representations

• **Unsigned Integers**: positive and 0 integers. (e.g. 0, 1, 2, ... 99999...)

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

• **Floating Point Numbers**: real numbers. (e.g. 0.1, -12.2, 1.5x10^{12})
Number Representations

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  Look up IEEE floating point if you're interested!
### Number Representations

<table>
<thead>
<tr>
<th>C Declaration</th>
<th>Size (Bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>int</td>
<td>4</td>
</tr>
<tr>
<td>double</td>
<td>8</td>
</tr>
<tr>
<td>float</td>
<td>4</td>
</tr>
<tr>
<td>char</td>
<td>1</td>
</tr>
<tr>
<td>char *</td>
<td>8</td>
</tr>
<tr>
<td>short</td>
<td>2</td>
</tr>
<tr>
<td>long</td>
<td>8</td>
</tr>
</tbody>
</table>
### In The Days Of Yore…

<table>
<thead>
<tr>
<th>C Declaration</th>
<th>Size (Bytes)</th>
</tr>
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<tbody>
<tr>
<td>int</td>
<td>4</td>
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<tr>
<td>short</td>
<td>2</td>
</tr>
<tr>
<td>long</td>
<td>4</td>
</tr>
</tbody>
</table>
Transitioning To Larger Datatypes

- **Early 2000s:** most computers were **32-bit**. This means that pointers were **4 bytes (32 bits)**.

- 32-bit pointers store a memory address from 0 to $2^{32}-1$, equaling $2^{32}$ **bytes of addressable memory**. This equals **4 Gigabytes**, meaning that 32-bit computers could have at most **4GB** of memory (RAM)!

- Because of this, computers transitioned to **64-bit**. This means that datatypes were enlarged; pointers in programs were now **64 bits**.

- 64-bit pointers store a memory address from 0 to $2^{64}-1$, equaling $2^{64}$ **bytes of addressable memory**. This equals **16 Exabytes**, meaning that 64-bit computers could have at most **$1024*1024*1024*16$ GB** of memory (RAM)!
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Unsigned Integers

• An **unsigned** integer is 0 or a positive integer (no negatives).
• We have already discussed converting between decimal and binary, which is a nice 1:1 relationship. Examples:
  
  \[
  \begin{align*}
  0b0001 & = 1 \\
  0b0101 & = 5 \\
  0b1011 & = 11 \\
  0b1111 & = 15 \\
  \end{align*}
  \]
  
  • The range of an unsigned number is \(0 \rightarrow 2^w - 1\), where \(w\) is the number of bits. E.g. a 32-bit integer can represent 0 to \(2^{32} - 1\) (4,294,967,295).
Unsigned Integers

4-bit unsigned integer representation

0000 0001 0010 0011 0100 0101 0110 0111
0100 0101 0110 0111 1000 1001 1010 1011
1100 1101 1110 1111 15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Let’s Take A Break

To ponder during the break:

A signed integer is a negative, 0, or positive integer. How can we represent both negative and positive numbers in binary?
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Signed Integers

• A **signed** integer is a negative integer, 0, or a positive integer.

• *Problem:* How can we represent negative *and* positive numbers in binary?
Signed Integers

• A **signed** integer is a negative integer, 0, or a positive integer.
• *Problem*: How can we represent negative *and* positive numbers in binary?

**Idea**: let’s reserve the *most significant bit* to store the sign.
Sign Magnitude Representation

0110
positive 6

1011
negative 3
Sign Magnitude Representation

0000

positive  0

1000

negative  0
## Sign Magnitude Representation

| 1000 = -0 | 0000 = 0 |
| 1001 = -1 | 0001 = 1 |
| 1010 = -2 | 0010 = 2 |
| 1011 = -3 | 0011 = 3 |
| 1100 = -4 | 0100 = 4 |
| 1101 = -5 | 0101 = 5 |
| 1110 = -6 | 0110 = 6 |
| 1111 = -7 | 0111 = 7 |

- We’ve only represented 15 of our 16 available numbers!
Sign Magnitude Representation

• **Pro:** easy to represent, and easy to convert to/from decimal.
• **Con:** +0 is not intuitive
• **Con:** we lose a bit that could be used to store more numbers
• **Con:** arithmetic is tricky: we need to find the sign, then maybe subtract (borrow and carry, etc.), then maybe change the sign. This complicates the hardware support for something as fundamental as addition.

Can we do better?
A Better Idea

• Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

\[
\begin{array}{c}
0101 \\
+????
\end{array}
\]

\[
00000
\]
A Better Idea

- Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

\[
\begin{array}{c}
0101 \\
+1011 \\
\hline
0000
\end{array}
\]
• Ideally, binary addition would *just work regardless* of whether the number is positive or negative.
A Better Idea

• Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

```
  0011
+1101
```

```
  00000
```
A Better Idea

• Ideally, binary addition would *just work regardless* of whether the number is positive or negative.
A Better Idea

• Ideally, binary addition would *just work regardless* of whether the number is positive or negative.

```
  00000
+ 00000
  _____
  00000
```
# A Better Idea

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

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>9</td>
<td>1001 (same as -7!)</td>
<td>NA</td>
</tr>
<tr>
<td>10</td>
<td>1010 (same as -6!)</td>
<td>NA</td>
</tr>
<tr>
<td>11</td>
<td>1011 (same as -5!)</td>
<td>NA</td>
</tr>
<tr>
<td>12</td>
<td>1100 (same as -4!)</td>
<td>NA</td>
</tr>
<tr>
<td>13</td>
<td>1101 (same as -3!)</td>
<td>NA</td>
</tr>
<tr>
<td>14</td>
<td>1110 (same as -2!)</td>
<td>NA</td>
</tr>
<tr>
<td>15</td>
<td>1111 (same as -1!)</td>
<td>NA</td>
</tr>
</tbody>
</table>
• The negative number is the positive number \textit{inverted, plus one!}
A binary number plus its inverse is all 1s.

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

• To find the negative equivalent of a number, work right-to-left and write down all digits through when you reach a 1. Then, invert the rest of the digits.

100100
+???????
0000000
Another Trick

• To find the negative equivalent of a number, work right-to-left and write down all digits *through* when you reach a 1. Then, invert the rest of the digits.

$\begin{array}{c}
100100 \\
+ \text{???100} \\
\hline
0000000
\end{array}$
Another Trick

- To find the negative equivalent of a number, work right-to-left and write down all digits *through* when you reach a 1. Then, invert the rest of the digits.

\[ \begin{align*}
100100 & \quad 011100 \\
+ & \quad 011100 \\
\hline
0000000 & 
\end{align*} \]
Two’s Complement

4-bit two's complement signed integer representation
Two’s Complement

• In two’s complement, we represent a positive number as itself, and its negative equivalent as the two’s complement of itself.

• The two’s complement of a number is the binary digits inverted, plus 1.

• This works to convert from positive to negative, and back from negative to positive!
Two’s Complement

- **Con:** more difficult to represent, and difficult to convert to/from decimal and between positive and negative.
- **Pro:** only 1 representation for 0!
- **Pro:** all bits are used to represent as many numbers as possible
- **Pro:** the most significant bit still indicates the sign of a number.
- **Pro:** addition works for any combination of positive and negative!
• Adding two numbers is just...adding! There is no special case needed for negatives. E.g. what is $2 + (-5)$?

\[ \begin{array}{c}
0010 \\
+ 1011 \\
\hline
1101 \\
\end{array} \]

$2 + (-5) = -3$
Two’s Complement

• Subtracting two numbers is just performing the two’s complement on one of them and then adding. E.g. $4 - 5 = -1$. 

$\begin{align*}
\text{(4)} & \quad 0100 \\
\text{(5)} & \quad 0101 \\
\hline
\text{+} & \quad 1011 \\
\hline
\text{1111} & \quad -1
\end{align*}$
What are the negative or positive equivalents of the numbers below?

a) -4 (1100)
b) 7 (0111)
c) 3 (0011)
d) -8 (1000)
Practice: Two’s Complement

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

a) -4 (1100)
b) 7 (0111)
c) 3 (0011)
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Overflow

• If you exceed the maximum value of your bit representation, you wrap around or overflow back to the smallest bit representation.

\[0b1111 + 0b1 = 0b0000\]

• If you go below the minimum value of your bit representation, you wrap around or overflow back to the largest bit representation.

\[0b0000 - 0b1 = 0b1111\]
## Min and Max Integer Values

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (Bytes)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>1</td>
<td>-128</td>
<td>127</td>
</tr>
<tr>
<td>unsigned char</td>
<td>1</td>
<td>0</td>
<td>255</td>
</tr>
<tr>
<td>short</td>
<td>2</td>
<td>-32768</td>
<td>32767</td>
</tr>
<tr>
<td>unsigned short</td>
<td>2</td>
<td>0</td>
<td>65535</td>
</tr>
<tr>
<td>int</td>
<td>4</td>
<td>-2147483648</td>
<td>2147483647</td>
</tr>
<tr>
<td>unsigned int</td>
<td>4</td>
<td>0</td>
<td>4294967295</td>
</tr>
<tr>
<td>long</td>
<td>8</td>
<td>-9223372036854775808</td>
<td>9223372036854775807</td>
</tr>
<tr>
<td>unsigned long</td>
<td>8</td>
<td>0</td>
<td>18446744073709551615</td>
</tr>
</tbody>
</table>
Min and Max Integer Values

INT_MIN, INT_MAX, UINT_MAX, LONG_MIN, LONG_MAX, ULONG_MAX, ...
Overflow
At which points can overflow occur for signed and unsigned int? (assume binary values shown are all 32 bits)

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

$\approx +4\text{billion}$

Discontinuity means overflow possible here

Increasing positive numbers

More increasing positive numbers

$0$

111...110
111...101
111...100

100...010
100...001
100...000

000...000
000...001
000...010
000...011

011...101
011...110
011...111

...
Signed Numbers

Discontinuity means overflow possible here

Increasing positive numbers

Increasing negative numbers (i.e. increasing)

\( \approx +2 \text{billion} \)

\( \approx -2 \text{billion} \)
Overflow In Practice: PSY

YouTube: “We never thought a video would be watched in numbers greater than a 32-bit integer (=2,147,483,647 views), but that was before we met PSY. "Gangnam Style" has been viewed so many times we had to upgrade to a 64-bit integer (9,223,372,036,854,775,808)!"
Overflow In Practice: Timestamps

- Many systems store timestamps as the number of seconds since Jan. 1, 1970 in a signed 32-bit integer.
- **Problem:** the latest timestamp that can be represented this way is 3:14:07 UTC on Jan. 13 2038!
Overflow In Practice: Gandhi

• In the game “Civilization”, each civilization leader had an “aggression” rating. Gandhi was meant to be peaceful, and had a score of 1.

• If you adopted “democracy”, all players’ aggression reduced by 2. Gandhi’s went from 1 to 255!

• Gandhi then became a big fan of nuclear weapons.

https://kotaku.com/why-gandhi-is-such-an-asshole-in-civilization-1653818245
Overflow in Practice:

- **Pacman Level 256**
- Make sure to reboot Boeing Dreamliners *every 248 days*
- Comair/Delta airline had to *cancel thousands of flights* days before Christmas
- **Reported vulnerability CVE-2019-3857** in libssh2 may allow a hacker to remotely execute code
- **Donkey Kong Kill Screen**
Demo Revisited: Unexpected Behavior

airline.c
Lecture Plan

• Bits and Bytes 5
• Hexadecimal 33
• Integer Representations 41
• Unsigned Integers 47
• Signed Integers 51
• Overflow 77
• Casting and Combining Types 90
• Live Session 119
There are 3 placeholders for 32-bit integers that we can use:

- `%d`: signed 32-bit int
- `%u`: unsigned 32-bit int
- `%x`: hex 32-bit int

The placeholder—not the expression filling in the placeholder—dictates what gets printed!
Casting

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

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

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

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

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

The bit representation for -12345 is `0b11111111111111110011111100111`. If we treat this binary representation as a positive number, it’s huge!
Casting

4-bit two's complement signed integer representation

4-bit unsigned integer representation
Comparisons Between Different Types

- **Be careful** when comparing signed and unsigned integers. **C will implicitly cast** the signed argument to unsigned, and then performs the operation assuming both numbers are non-negative.

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

s₃ > u₃
u₂ > u₄
s₂ > s₄
s₁ > s₂
u₁ > u₂
s₁ > u₃
Which many of the following statements are true? (assume that variables are set to values that place them in the spots shown)

- $s_3 > u_3$ - true
- $u_2 > u_4$
- $s_2 > s_4$
- $s_1 > s_2$
- $u_1 > u_2$
- $s_1 > u_3$
Comparisons Between Different Types

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

- $s_3 > u_3$ - true
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Which many of the following statements are true? *(assume that variables are set to values that place them in the spots shown)*

- $s_3 > u_3$ - true
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- $s_3 > u_3$ - true
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- $s_1 > s_2$ - true
- $u_1 > u_2$
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Which many of the following statements are true? (assume that variables are set to values that place them in the spots shown)

- \( s_3 > u_3 \) - true
- \( u_2 > u_4 \) - true
- \( s_2 > s_4 \) - false
- \( s_1 > s_2 \) - true
- \( u_1 > u_2 \) - true
- \( s_1 > u_3 \)
Comparisons Between Different Types

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

s3 > u3 - true
u2 > u4 - true
s2 > s4 - false
s1 > s2 - true
u1 > u2 - true
s1 > u3 - true
Expanding Bit Representations

• Sometimes, we want to convert between two integers of different sizes (e.g. short to int, or int to long).

• We might not be able to convert from a bigger data type to a smaller data type, but we do want to always be able to convert from a smaller data type to a bigger data type.

• For unsigned values, we can add leading zeros to the representation ("zero extension")

• For signed values, we can repeat the sign of the value for new digits ("sign extension")

• Note: when doing <, >, <=, >= comparison between different size types, it will promote to the larger type.
unsigned short s = 4;
// short is a 16-bit format, so s = 0000 0000 0000 0100b

unsigned int i = s;
// conversion to 32-bit int, so i = 0000 0000 0000 0000 0000 0000 0000 0100b
short s = 4;
// short is a 16-bit format, so
s = 0000 0000 0000 0100b

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

— or —

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

int i = s;
// conversion to 32-bit int, so
i = 1111 1111 1111 1111 1111 1111 1111 1100b
If we want to **reduce** the bit size of a number, C **truncates** the representation and discards the **more significant bits**.

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

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

```
0000 0000 0000 0000 1100 1111 1100 0111
```

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

```
1100 1111 1100 0111
```

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

```
1111 1111 1111 1111 1100 1111 1100 0111  // still -12345
```
Truncating Bit Representation

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

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

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

```
1111 1111 1111 1111 1111 1111 1111 1101
```

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

```
1111 1111 1111 1101
```

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

```
1111 1111 1111 1111 1111 1111 1111 1101 // still -3
```
If we want to **reduce** the bit size of a number, C **truncates** the representation and discards the *more significant bits*.

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

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

```
0000 0000 0000 0001 1111 0100 0000 0000
```

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

```
1111 0100 0000 0000
```

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

```
0000 0000 0000 0000 1111 0100 0000 0000  // still 62464
```
long sizeof(type);

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

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

• Bits and Bytes
• Hexadecimal
• Integer Representations
• Unsigned Integers
• Signed Integers
• Overflow
• Casting and Combining Types

Next time: How can we manipulate individual bits and bytes?
Additional Live Session Slides
Live Session

• Optional, led by what is most helpful for us to review!
• Video and slides posted
• Post any lecture questions while watching videos in our Ed thread for lecture
Plan For Today

• 5 minutes: post questions or comments on Ed for what we should discuss
• 25 minutes: extra practice
• 15 minutes: open Q&A

Lecture 2 takeaway: computers represent everything in binary. We must determine how to represent our data (e.g., base-10 numbers) in a binary format so a computer can manipulate it. There may be limitations to these representations! (overflow)
Practice: Two’s Complement

While you wait, fill in the below table:

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<th>char x = ____;</th>
<th>char y = -x;</th>
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<td>decimal</td>
<td>binary</td>
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<tr>
<td>0b1111 1100</td>
<td></td>
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<td>0b0001 1000</td>
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It’s easier to compute base-10 for positive numbers, so use two’s complement first if negative.
Practice: Two’s Complement

While you wait, fill in the below table:

<table>
<thead>
<tr>
<th>char x = ____;</th>
<th>char y = -x;</th>
</tr>
</thead>
<tbody>
<tr>
<td>decimal</td>
<td>binary</td>
</tr>
<tr>
<td>1.</td>
<td>-4</td>
</tr>
<tr>
<td>2.</td>
<td>24</td>
</tr>
<tr>
<td>3.</td>
<td>36</td>
</tr>
<tr>
<td>4.</td>
<td>-33</td>
</tr>
</tbody>
</table>

It’s easier to compute base-10 for positive numbers, so use two’s complement first if negative.
History: Two’s complement

- The binary representation was first proposed by John von Neumann in *First Draft of a Report on the EDVAC* (1945)
  - That same year, he also invented the merge sort algorithm

- Many early computers used sign-magnitude or one’s complement

- The System/360, developed by IBM in 1964, was widely popular (had 1024KB memory) and established two’s complement as the dominant binary representation of integers

\[
\begin{align*}
+7 & \quad 0b0000\ 0111 \\
-7 & \quad 0b1111\ 1000
\end{align*}
\]

8-bit one’s complement
Hexadecimal: It’s funky but concise

- Let’s take a byte (8 bits):

  165

  Base-10: Human-readable, but cannot easily interpret on/off bits

  0b10100101

  Base-2: Yes, computers use this, but not human-readable

  0xa5

  Base-16: Easy to convert to Base-2, More “portable” as a human-readable format
  (fun fact: a half-byte is called a nibble or nybble)
For each initialization of \( x \), what will be printed?

i. \( x = 130; \quad // \ 0x82 \)

ii. \( x = -132; \quad // \ 0xff7c \)

iii. \( x = 25;\quad // \ 0x19 \)

i. \( 0xface \)

ii. \( 0x0a \)

iii. \( 0xdec1de \)

iv. \( 0xc0ffeecaca\)

```c
short x = _____;
char cx = x;
printf("%d", cx);
```
Hexadecimal and Truncation

For each initialization of $x$, what will be printed?

- 126
  i. $x = 130$; // 0x82

  124
  ii. $x = -132$; // 0xff7c

  25
  iii. $x = 25$; // 0x19

```c
short x = ______;
char cx = x;
printf("%d", cx);
```
Signed vs. Unsigned Integers
What is the following base-2 number in base-10?

0b1101
What is the following base-2 number in base-10?

0b1101

If 4-bit signed:  -3
If 4-bit unsigned:  13
If >4-bit signed or unsigned:  13

You need to know the type to determine the number! (Note by default, numeric constants in C are signed ints)
Overflow

• What is happening here? Assume 4-bit numbers.

\[ \text{Overflow} \]

\[ \begin{align*}
\quad & \text{0b1101} \\
+ & \text{0b0100} \\
\end{align*} \]

🤔
• What is happening here? Assume 4-bit numbers.

\[
\begin{align*}
0b1101 + 0b0100 &= 0b10011 \\
\text{Signed} &\quad \text{Unsigned} \\
-3 + 4 &= 1 & 13 + 4 &= 1 \\
\text{No overflow} &\quad \text{Overflow}
\end{align*}
\]
Limits and Comparisons

1. What is the... | Largest unsigned? | Largest signed? | Smallest signed?
---|---|---|---
char | | | |
int | | | |

2. Will the following char comparisons evaluate to true or false?
   i. \(-7 < 4\)
   iii. \((\text{char}) \, 130 \, > \, 4\)
   
   ii. \(-7 < 4\U\)
   iv. \((\text{char}) \, -132 \, > \, 2\)
# Limits and Comparisons

1. What is the...  

<table>
<thead>
<tr>
<th></th>
<th>Largest unsigned?</th>
<th>Largest signed?</th>
<th>Smallest signed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>$2^8 - 1 = 255$</td>
<td>$2^7 - 1 = 127$</td>
<td>$-2^7 = -128$</td>
</tr>
<tr>
<td>int</td>
<td>$2^{32} - 1 = 4294967296$</td>
<td>$2^{31} - 1 = 2147483647$</td>
<td>$-2^{31} = -2147483648$</td>
</tr>
</tbody>
</table>

These are available as UCHAR_MAX, INT_MIN, INT_MAX, etc. in the `<limits.h>` header.
Limits and Comparisons

2. Will the following char comparisons evaluate to true or false?

i. \(-7 < 4\) \hspace{1cm} \text{true} \hspace{1cm} \text{iii. (char) 130 > 4} \hspace{1cm} \text{false}

ii. \(-7 < 4u\) \hspace{1cm} \text{false} \hspace{1cm} \text{iv. (char) -132 > 2} \hspace{1cm} \text{true}

By default, numeric constants in C are signed ints, unless they are suffixed with u (unsigned) or L (long).
Tools: A binary/hex calculator

• Yes. Next week, we will learn more about **gdb**, our debugger.

• gdb can print out variables/constants in any format: hex, decimal, unsigned...

• To look ahead, check out our GDB guide and read about print format codes. Or watch Lecture 3!

Is there a program to quickly convert between hex, binary, and decimal?