Integers II
CSE 351 Autumn 2017

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http://xkcd.com/557/
Administrivia

- Lab 1 due next Friday (10/13)
  - Prelim submission (3+ of `bits.c`) due on Monday (10/9)
  - Bonus slides at the end of today’s lecture have relevant examples
Integers

- Binary representation of integers
  - Unsigned and signed
  - Casting in C

- Consequences of finite width representations
  - Overflow, sign extension

- Shifting and arithmetic operations
Peer Instruction Question

- Take the 4-bit number encoding \( x = 0b1011 \)
- Which of the following numbers is NOT a valid interpretation of \( x \) using any of the number representation schemes discussed last lecture?
  - Unsigned, Sign and Magnitude, Two’s Complement

A. -4  
B. -5  
C. 11  
D. -3  
E. We’re lost...
Two’s Complement Arithmetic

- The same addition procedure works for both unsigned and two’s complement integers
  - **Simplifies hardware:** only one algorithm for addition
  - **Algorithm:** simple addition, discard the highest carry bit
    - Called modular addition: result is sum \( \mod 2^w \)

**4-bit Examples:**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0100</td>
<td>−4</td>
<td>1100</td>
</tr>
<tr>
<td>+3</td>
<td>+0011</td>
<td>+3</td>
<td>+0011</td>
</tr>
<tr>
<td>=7</td>
<td>=−1</td>
<td></td>
<td>=1</td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
<td>−3</td>
<td>+1101</td>
</tr>
</tbody>
</table>
Why Does Two’s Complement Work?

- For all representable positive integers $x$, we want:
  
  \[
  \text{bit representation of } x + \text{bit representation of } -x = 0 \quad \text{(ignoring the carry-out bit)}
  \]

- What are the 8-bit negative encodings for the following?

  \[
  \begin{array}{ccc}
  00000001 & + & ???????? \\
  + & 00000000 & 11000011 \\
  \hline
  00000000 & 00000000 & 00000000
  \end{array}
  \]
Why Does Two’s Complement Work?

- For all representable positive integers \( x \), we want:
  
  \[
  \begin{align*}
  \text{bit representation of } x & \\
  + \text{bit representation of } -x & \\
  0 & \quad \text{(ignoring the carry-out bit)}
  \end{align*}
  \]

- What are the 8-bit negative encodings for the following?

\[
\begin{align*}
00000001 & \quad + \quad 11111111 & \quad = \quad 100000000 \\
+ & \quad 11111111 & \quad + \quad 11111110 & \quad = \quad 100000000 \\
& \quad 100000000 & \quad + \quad 01111101 & \quad = \quad 100000000
\end{align*}
\]

These are the bitwise complement plus 1!

\(-x = \sim x + 1\)
Signed/Unsigned Conversion Visualized

- Two’s Complement → Unsigned
  - Ordering Inversion
  - Negative → Big Positive
Values To Remember

- **Unsigned Values**
  - UMin = 0b00...0 = 0
  - UMax = 0b11...1 = 2^w − 1

- **Two’s Complement Values**
  - Tmin = 0b10...0 = −2^{w−1}
  - Tmax = 0b01...1 = 2^{w−1} − 1
  - −1 = 0b11...1

- **Example:** Values for w = 64

<table>
<thead>
<tr>
<th></th>
<th>Decimal</th>
<th>Hex</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMax</td>
<td>18,446,744,073,709,551,615</td>
<td>FF FF FF FF FF FF FF FF FF</td>
</tr>
<tr>
<td>Tmax</td>
<td>9,223,372,036,854,775,807</td>
<td>7F FF FF FF FF FF FF FF FF</td>
</tr>
<tr>
<td>Tmin</td>
<td>-9,223,372,036,854,775,808</td>
<td>80 00 00 00 00 00 00 00 00</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>FF FF FF FF FF FF FF FF FF</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>00 00 00 00 00 00 00 00 00</td>
</tr>
</tbody>
</table>
In C: Signed vs. Unsigned

❖ Casting
  - Bits are unchanged, just interpreted differently!
    - `int` tx, ty;
    - `unsigned int` ux, uy;
  - Explicit casting
    - `tx = (int) ux;`
    - `uy = (unsigned int) ty;`
  - Implicit casting can occur during assignments or function calls
    - `tx = ux;`
    - `uy = ty;`
Casting Surprises

- **Integer literals (constants)**
  - By default, integer constants are considered *signed* integers
    - Hex constants already have an explicit binary representation
  - Use “U” (or “u”) suffix to explicitly force *unsigned*
    - Examples: 0U, 4294967259u

- **Expression Evaluation**
  - When you mixed unsigned and signed in a single expression, then *signed values are implicitly cast to unsigned*
  - Including comparison operators <, >, ==, <=, >=
Casting Surprises

- 32-bit examples:
  - TMin = -2,147,483,648, TMax = 2,147,483,647

<table>
<thead>
<tr>
<th>Left Constant</th>
<th>Order</th>
<th>Right Constant</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0U</td>
<td>0000 0000 0000 0000 0000 0000 0000 0000</td>
<td>0U 0000 0000 0000 0000 0000 0000 0000</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>0000 0000 0000 0000 0000 0000 0000 0000</td>
<td>0U 0000 0000 0000 0000 0000 0000 0000</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>0000 0000 0000 0000 0000 0000 0000 0000</td>
<td>0U 0000 0000 0000 0000 0000 0000 0000</td>
</tr>
<tr>
<td>2147483647</td>
<td>-2147483648</td>
<td>1000 0000 0000 0000 0000 0000 0000 0000</td>
<td>-2147483648</td>
</tr>
<tr>
<td>2147483647U</td>
<td>-2147483648</td>
<td>1000 0000 0000 0000 0000 0000 0000 0000</td>
<td>-2147483648</td>
</tr>
<tr>
<td>-1</td>
<td>-2</td>
<td>1111 1111 1111 1111 1111 1111 1111 1111</td>
<td>-2 1111 1111 1111 1111 1111 1111 1111 1110</td>
</tr>
<tr>
<td>(unsigned) -1</td>
<td>-2</td>
<td>1111 1111 1111 1111 1111 1111 1111 1111</td>
<td>-2 1111 1111 1111 1111 1111 1111 1111 1110</td>
</tr>
<tr>
<td>2147483647</td>
<td>2147483648U</td>
<td>1000 0000 0000 0000 0000 0000 0000 0000</td>
<td>2147483648U</td>
</tr>
<tr>
<td>2147483647</td>
<td>(int) 2147483648U</td>
<td>1000 0000 0000 0000 0000 0000 0000 0000</td>
<td>2147483648U</td>
</tr>
</tbody>
</table>
Integers

- Binary representation of integers
  - Unsigned and signed
  - Casting in C
- Consequences of finite width representations
  - Overflow, sign extension
- Shifting and arithmetic operations
Arithmetic Overflow

- When a calculation produces a result that can’t be represented in the current encoding scheme
  - Integer range limited by fixed width
  - Can occur in both the positive and negative directions
- C and Java ignore overflow exceptions
  - You end up with a bad value in your program and no warning/indication... oops!

<table>
<thead>
<tr>
<th>Bits</th>
<th>Unsigned</th>
<th>Signed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0011</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0100</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>0101</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>0110</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>0111</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>1000</td>
<td>8</td>
<td>-8</td>
</tr>
<tr>
<td>1001</td>
<td>9</td>
<td>-7</td>
</tr>
<tr>
<td>1010</td>
<td>10</td>
<td>-6</td>
</tr>
<tr>
<td>1011</td>
<td>11</td>
<td>-5</td>
</tr>
<tr>
<td>1100</td>
<td>12</td>
<td>-4</td>
</tr>
<tr>
<td>1101</td>
<td>13</td>
<td>-3</td>
</tr>
<tr>
<td>1110</td>
<td>14</td>
<td>-2</td>
</tr>
<tr>
<td>1111</td>
<td>15</td>
<td>-1</td>
</tr>
</tbody>
</table>
Overflow: Unsigned

- **Addition**: drop carry bit ($-2^N$)
  
  \[
  \begin{array}{c@{}c@{}c@{}c@{}c@{}c}
  1 & 5 & + & 2 & \hline
  1 & 7
  \end{array}
  \quad
  \begin{array}{c@{}c@{}c@{}c@{}c@{}c}
  1 & 1 & 1 & 1 & + & 0 & 0 & 1 & 0 \hline
  1 & 0 & 0 & 0 & 1
  \end{array}
  \]

- **Subtraction**: borrow ($+2^N$)
  
  \[
  \begin{array}{c@{}c@{}c@{}c@{}c@{}c}
  1 & - & 2 & \hline
  - & 1
  \end{array}
  \quad
  \begin{array}{c@{}c@{}c@{}c@{}c@{}c}
  1 & 0 & 0 & 0 & 1 & - & 0 & 0 & 1 & 0 \hline
  1 & 1 & 1 & 1
  \end{array}
  \]

$\pm 2^N$ because of modular arithmetic
Overflow: Two’s Complement

- **Addition**: 
  \[ (+) + (+) = (-) \text{ result?} \]
  
  
  \[
  \begin{array}{c}
  \text{6} \\
  + \text{3} \\
  \hline
  9
  \end{array}
  \quad
  \begin{array}{c}
  \text{0110} \\
  + \text{0011} \\
  \hline
  1001
  \end{array}
  \quad
  \text{9} \\
  \quad
  \text{ overflow if sign mismatch } \\
  \text{ (operands have same sign and result’s sign is different)}
  
- **Subtraction**: 
  \[ (-) + (-) = (+) \text{?} \]
  
  \[
  \begin{array}{c}
  \text{-7} \\
  - \text{3} \\
  \hline
  \text{-10}
  \end{array}
  \quad
  \begin{array}{c}
  \text{1001} \\
  - \text{0011} \\
  \hline
  \text{0110}
  \end{array}
  \quad
  \text{6}
  
\textbf{For signed:} overflow if operands have same sign and result’s sign is different
Sign Extension

- What happens if you convert a signed integral data type to a larger one?
  - e.g. `char` → `short` → `int` → `long`

- 4-bit → 8-bit Example:
  - Positive Case
    - Add 0’s?
      - 4-bit: 0010 = +2
      - 8-bit: 00000010 = +2
Peer Instruction Question

- Which of the following 8-bit numbers has the same signed value as the 4-bit number 0b1100?
  - Underlined digit = MSB

A. 0b 0000 1100
B. 0b 1000 1100
C. 0b 1111 1100
D. 0b 1100 1100
E. We’re lost...
**Sign Extension**

- **Task:** Given a \( w \)-bit signed integer \( X \), convert it to a \( w+k \)-bit signed integer \( X' \) *with the same value*

- **Rule:** Add \( k \) copies of sign bit
  - Let \( x_i \) be the \( i \)-th digit of \( X \) in binary
  - \( X' = x_{w-1}, \ldots, x_{w-1}, x_{w-1}, x_{w-2}, \ldots, x_1, x_0 \)
Sign Extension Example

- Convert from smaller to larger integral data types
- C automatically performs sign extension
  - Java too

```
short int x = 12345;
int ix = (int) x;
short int y = -12345;
int iy = (int) y;
```

<table>
<thead>
<tr>
<th>Var</th>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>12345</td>
<td>30 39</td>
<td>00110000 00111001</td>
</tr>
<tr>
<td>ix</td>
<td>12345</td>
<td>00 00 30 39</td>
<td>00000000 00000000 00110000 00111001</td>
</tr>
<tr>
<td>y</td>
<td>-12345</td>
<td>CF C7</td>
<td>11001111 11000111</td>
</tr>
<tr>
<td>iy</td>
<td>-12345</td>
<td>FF FF CF C7</td>
<td>11111111 11111111 11001111 11000111</td>
</tr>
</tbody>
</table>
Integers

- Binary representation of integers
  - Unsigned and signed
  - Casting in C
- Consequences of finite width representations
  - Overflow, sign extension
- **Shifting and arithmetic operations**
Shift Operations

- **Left shift** ($x << n$) bit vector $x$ by $n$ positions
  - Throw away (drop) extra bits on left
  - Fill with 0s on right

- **Right shift** ($x >> n$) bit-vector $x$ by $n$ positions
  - Throw away (drop) extra bits on right
  - Logical shift (for **unsigned** values)
    - Fill with 0s on left
  - Arithmetic shift (for **signed** values)
    - Replicate most significant bit on left
    - Maintains sign of $x$
Shift Operations

- **Left shift** \((x \ll n)\)
  - Fill with 0s on right

- **Right shift** \((x \gg n)\)
  - **Logical shift** (for *unsigned* values)
    - Fill with 0s on left
  - **Arithmetic shift** (for *signed* values)
    - Replicate most significant bit on left

- **Notes:**
  - Shifts by \(n < 0\) or \(n \geq w\) (bit width of \(x\)) are *undefined*
  - **In C:** behavior of \(\gg\) is determined by compiler
    - In gcc / C lang, depends on data type of \(x\) (signed/unsigned)
  - **In Java:** logical shift is \(\gg\gg\) and arithmetic shift is \(\gg\)
Shifting Arithmetic?

- What are the following computing?
  - `x>>n`
    - `0b 0100 >> 1 = 0b 0010`
    - `0b 0100 >> 2 = 0b 0001`
    - Divide by $2^n$
  - `x<<n`
    - `0b 0001 << 1 = 0b 0010`
    - `0b 0001 << 2 = 0b 0100`
    - Multiply by $2^n$

- Shifting is faster than general multiply and divide operations
Left Shifting Arithmetic 8-bit Example

- No difference in left shift operation for unsigned and signed numbers (just manipulates bits)
  - Difference comes during interpretation: $x \times 2^n$?

\[
x = 25; \quad 00011001 = 25 \quad 25
\]
\[
L1 = x << 2; \quad 0001100100 = 100 \quad 100
\]
\[
L2 = x << 3; \quad 00011001000 = -56 \quad 200
\]
\[
L3 = x << 4; \quad 000110010000 = -112 \quad 144
\]

Signed overflow

Unsigned overflow
Right Shifting Arithmetic 8-bit Examples

- **Reminder**: C operator `>>` does *logical* shift on unsigned values and *arithmetic* shift on signed values
  - **Logical Shift**: \( x / 2^n \)?

\[
xu = 240u; \quad 11110000 = 240
\]

\[
R1u=xu>>3; \quad 00011110000 = 30
\]

\[
R2u=xu>>5; \quad 0000011110000 = 7
\]

**rounding (down)**
Right Shifting Arithmetic 8-bit Examples

- **Reminder:** C operator `>>` does *logical* shift on unsigned values and *arithmetic* shift on signed values
  - **Arithmetic Shift:** \( x / 2^n \)?

\[
\begin{align*}
x_s &= -16; & 11110000 &= -16 \\
R1_s &= xu >> 3; & 111111110000 &= -2 \\
R2_s &= xu >> 5; & 1111111110000 &= -1
\end{align*}
\]
Peer Instruction Question

For the following expressions, find a value of \texttt{signed char} \texttt{x}, if there exists one, that makes the expression \texttt{TRUE}. Compare with your neighbor(s)!

- Assume we are using 8-bit arithmetic:
  - \texttt{x == (unsigned char) x}
  - \texttt{x >= 128U}
  - \texttt{x != (x>>2) << 2}
  - \texttt{x == -x}
    - Hint: there are two solutions
  - \texttt{(x < 128U) \&\& (x > 0x3F)}
Summary

- **Sign and unsigned variables in C**
  - Bit pattern remains the same, just *interpreted* differently
  - Strange things can happen with our arithmetic when we convert/cast between sign and unsigned numbers
    - Type of variables affects behavior of operators (shifting, comparison)

- We can only represent so many numbers in $w$ bits
  - When we exceed the limits, *arithmetic overflow* occurs
  - *Sign extension* tries to preserve value when expanding

- Shifting is a useful bitwise operator
  - Right shifting can be arithmetic (sign) or logical (0)
  - Can be used in multiplication with constant or bit masking
Some examples of using shift operators in combination with bitmasks, which you may find helpful for Lab 1. We will try to cover these in lecture or section if we have the time.

- Extract the 2nd most significant byte of an int
- Extract the sign bit of a signed int
- Conditionals as Boolean expressions
Using Shifts and Masks

- Extract the 2\textsuperscript{nd} most significant \textit{byte} of an \texttt{int}:
  - First shift, then mask: \((x>>16) \& 0xFF\)

<table>
<thead>
<tr>
<th>(x)</th>
<th>00000001 00000010 00000011 00000100</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x&gt;&gt;16)</td>
<td>00000000 00000000 00000001 00000010</td>
</tr>
<tr>
<td>0xFF</td>
<td>00000000 00000000 00000000 11111111</td>
</tr>
<tr>
<td>((x&gt;&gt;16) &amp; 0xFF)</td>
<td>00000000 00000000 00000000 00000010</td>
</tr>
</tbody>
</table>

- Or first mask, then shift: \((x \& 0xFF0000) >>16\)

<table>
<thead>
<tr>
<th>(x)</th>
<th>00000001 00000010 00000011 00000100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0xFF0000</td>
<td>00000000 11111111 00000000 00000000</td>
</tr>
<tr>
<td>(x &amp; 0xFF0000)</td>
<td>00000000 00000010 00000000 00000000</td>
</tr>
<tr>
<td>((x&amp;0xFF0000) &gt;&gt;16)</td>
<td>00000000 00000000 00000000 00000010</td>
</tr>
</tbody>
</table>
Using Shifts and Masks

- Extract the *sign bit* of a signed `int`:
  - First shift, then mask: `(x>>31) & 0x1`
    - Assuming arithmetic shift here, but this works in either case
    - Need mask to clear 1s possibly shifted in

<table>
<thead>
<tr>
<th>x</th>
<th>00000001 00000010 00000011 00000100</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>x&gt;&gt;31</code></td>
<td>00000000 00000000 00000000 00000000</td>
</tr>
<tr>
<td><code>0x1</code></td>
<td>00000000 00000000 00000000 00000001</td>
</tr>
<tr>
<td><code>(x&gt;&gt;31) &amp; 0x1</code></td>
<td>00000000 00000000 00000000 00000000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x</th>
<th>10000001 00000010 00000011 00000100</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>x&gt;&gt;31</code></td>
<td>11111111 11111111 11111111 11111111</td>
</tr>
<tr>
<td><code>0x1</code></td>
<td>00000000 00000000 00000000 00000001</td>
</tr>
<tr>
<td><code>(x&gt;&gt;31) &amp; 0x1</code></td>
<td>00000000 00000000 00000000 00000001</td>
</tr>
</tbody>
</table>
Using Shifts and Masks

- Conditionals as Boolean expressions
  - For int \( x \), what does \((x << 31) >> 31 \) do?

| \( x = !!123 \) | 00000000 00000000 00000000 00000001 |
| \( x << 31 \) | 10000000 00000000 00000000 00000000 |
| \((x << 31) >> 31 \) | 11111111 11111111 11111111 11111111 |
| \(! x \) | 00000000 00000000 00000000 00000000 |
| \(! x << 31 \) | 00000000 00000000 00000000 00000000 |
| \((! x << 31) >> 31 \) | 00000000 00000000 00000000 00000000 |

- Can use in place of conditional:
  - In C: if(x) \{a=y;\} else \{a=z;\} equivalent to \( a = x ? y : z \);
  - \( a = ( ((x << 31) >> 31) & y ) | ( ((!x << 31) >> 31) & z ) \);