Integers II
CSE 351 Autumn 2017

Instructor:
Justin Hsia

Teaching Assistants:

Lucas Wotton Michael Zhang Parker DeWilde Ryan Wong
Sam Gehman Sam Wolfson Savanna Yee Vinny Palaniappan

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
  - Vote at http://PollEv.com/justinh

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 *modulo* 2^w

- **4-bit Examples:**

4 0100 +3 +0011	-4 1100 +3 +0011	4 0100 -3 +1101
=7	=-1	=1

Why Does Two's Complement Work?

- For all representable positive integers x, we want:

$$\begin{array}{r} \textit{bit representation of } x \\ +\ \textit{bit representation of } -x \\ \hline 0 \end{array}$$ (ignoring the carry-out bit)

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

```
  00000001      00000010      11000011
+ ????????    + ????????    + ????????
  00000000      00000000      00000000
```

Why Does Two's Complement Work?

- For all representable positive integers x, we want:

  bit representation of x
  + bit representation of $-x$
  0 (ignoring the carry-out bit)

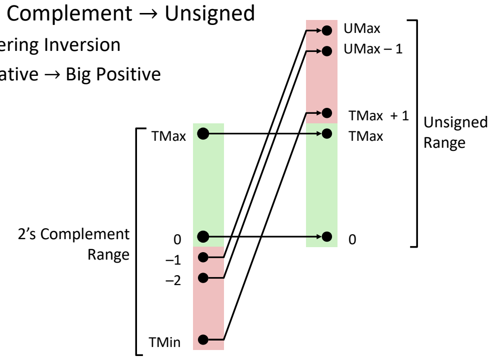
  - What are the 8-bit negative encodings for the following?

```
   00000001       00000010       11000011
+  11111111    +  11111110    +  00111101
  100000000      100000000      100000000
```

These are the bitwise complement plus 1!
`-x == ~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 $w = 64$

	Decimal	Hex
UMax	18,446,744,073,709,551,615	FF FF FF FF FF FF FF FF
TMax	9,223,372,036,854,775,807	7F FF FF FF FF FF FF FF
TMin	-9,223,372,036,854,775,808	80 00 00 00 00 00 00 00
-1	-1	FF FF FF FF FF FF FF FF
0	0	00 00 00 00 00 00 00 00

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

Left Constant	Order	Right Constant	Interpretation
0 0000 0000 0000 0000 0000 0000 0000 0000		**0U** 0000 0000 0000 0000 0000 0000 0000 0000	
-1 1111 1111 1111 1111 1111 1111 1111 1111		**0** 0000 0000 0000 0000 0000 0000 0000 0000	
-1 1111 1111 1111 1111 1111 1111 1111 1111		**0U** 0000 0000 0000 0000 0000 0000 0000 0000	
2147483647 0111 1111 1111 1111 1111 1111 1111 1111		**-2147483648** 1000 0000 0000 0000 0000 0000 0000 0000	
2147483647U 0111 1111 1111 1111 1111 1111 1111 1111		**-2147483648** 1000 0000 0000 0000 0000 0000 0000 0000	
-1 1111 1111 1111 1111 1111 1111 1111 1111		**-2** 1111 1111 1111 1111 1111 1111 1111 1110	
(unsigned) -1 1111 1111 1111 1111 1111 1111 1111 1111		**-2** 1111 1111 1111 1111 1111 1111 1111 1110	
2147483647 0111 1111 1111 1111 1111 1111 1111 1111		**2147483648U** 1000 0000 0000 0000 0000 0000 0000 0000	
2147483647 0111 1111 1111 1111 1111 1111 1111 1111		**(int) 2147483648U** 1000 0000 0000 0000 0000 0000 0000 0000	

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

Bits	Unsigned	Signed
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	-8
1001	9	-7
1010	10	-6
1011	11	-5
1100	12	-4
1101	13	-3
1110	14	-2
1111	15	-1

- 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!

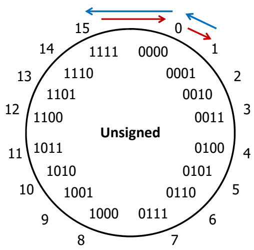
Overflow: Unsigned

- **Addition:** drop carry bit (-2^N)

```
  15       1111
+  2     + 0010
```
~~17~~ ~~1~~0001
1

- **Subtraction:** borrow ($+2^N$)

```
   1      10001
-  2     - 0010
```
~~-1~~ 1111
15



$\pm 2^N$ because of modular arithmetic

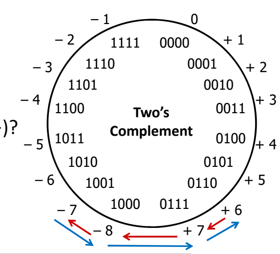
Overflow: Two's Complement

- **Addition:** (+) + (+) = (−) result?

```
   6       0110
+  3     + 0011
```
~~9~~ 1001
-7

- **Subtraction:** (−) + (−) = (+)?

```
  -7       1001
-  3     - 0011
```
~~-10~~ 0110
6



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

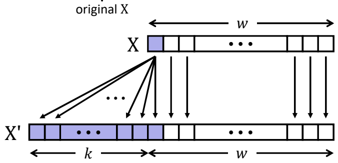
Peer Instruction Question

- Which of the following 8-bit numbers has the same *signed* value as the 4-bit number **0b1100**?
  - Underlined digit = MSB
  - Vote at http://PollEv.com/justinh

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 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
  - $\mathrm{X}' = \underbrace{x_{w-1}, \dots, x_{w-1}}_{k \text{ copies of MSB}}, \underbrace{x_{w-1}, x_{w-2}, \dots, x_1, x_0}_{\text{original X}}$



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;
```

Var	Decimal	Hex	Binary
x	12345	30 39	00110000 00111001
ix	12345	00 00 30 39	00000000 00000000 00110000 00111001
y	-12345	CF C7	11001111 11000111
iy	-12345	FF FF CF C7	11111111 11111111 11001111 11000111

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<<n)
  - Fill with 0s on right
- Right shift (x>>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≥w (bit width of x) are *undefined*
  - **In C:** behavior of >> is determined by compiler
    - In gcc / C lang, depends on data type of x (signed/unsigned)
  - **In Java:** logical shift is >>> and arithmetic shift is >>

	x	0010 0010
	x<<3	0001 0**000**
logical:	x>>2	**00**00 1000
arithmetic:	x>>2	**00**00 1000

	x	1010 0010
	x<<3	0001 0**000**
logical:	x>>2	**00**10 1000
arithmetic:	x>>2	**11**10 1000

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*2^n`?

```
                                Signed  Unsigned
x = 25;          00011001 =       25      25
L1=x<<2;       0001100100 =      100     100
L2=x<<3;      00011001000 =      -56     200
L3=x<<4;     000110010000 =     -112     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;   11110000        = 240
R1u=xu>>3;   00011110000     =  30
R2u=xu>>5;   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`?

```
xs = -16;    11110000        = -16
R1s=xu>>3;   11111110000     =  -2
R2s=xu>>5;   1111111110000   =  -1
```

rounding (down)

Peer Instruction Question

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

- Assume we are using 8-bit arithmetic:
  - `x == (unsigned char) x`
  - `x >= 128U`
  - `x != (x>>2)<<2`
  - `x == -x`
    - Hint: there are two solutions
  - `(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

BONUS SLIDES

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 2nd most significant *byte* of an `int`:
  - First shift, then mask: `(x>>16) & 0xFF`

x	00000001 00000010 00000011 00000100
x>>16	00000000 00000000 00000001 00000010
0xFF	00000000 00000000 00000000 11111111
(x>>16) & 0xFF	00000000 00000000 00000000 00000010

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

x	00000001 00000010 00000011 00000100
0xFF0000	00000000 11111111 00000000 00000000
x & 0xFF0000	00000000 00000010 00000000 00000000
(x&0xFF0000)>>16	00000000 00000000 00000000 00000010

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

x	00000001 00000010 00000011 00000100
x>>31	00000000 00000000 00000000 00000000
0x1	00000000 00000000 00000000 00000001
(x>>31) & 0x1	00000000 00000000 00000000 00000000

x	10000001 00000010 00000011 00000100
x>>31	11111111 11111111 11111111 11111111
0x1	00000000 00000000 00000000 00000001
(x>>31) & 0x1	00000000 00000000 00000000 00000001

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);`