Number Representation & I See The C…

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Signed Integers and Two's-Complement Representation

- Signed integers in C; want ½ numbers <0, want ½ numbers >0, and want one 0
- *Two's complement* treats 0 as positive, so 32-bit word represents 2^{32} integers from
  -2^{31} (–2,147,483,648) to $2^{31}-1$ (2,147,483,647)
  - Note: one negative number with no positive version
  - Book lists some other options, all of which are worse
  - Every computer uses two's complement today
- *Most-significant bit* (leftmost) is the *sign bit*, since 0 means positive (including 0), 1 means negative
  - Bit 31 is most significant, bit 0 is least significant

Two's-Complement Integers

Sign Bit

$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = 0_{ten}$
$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = 1_{ten}$
$0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = 2_{ten}$
...
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{two} = 2{,}147{,}483{,}645_{ten}$
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = 2{,}147{,}483{,}646_{ten}$
$0111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = 2{,}147{,}483{,}647_{ten}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000_{two} = -2{,}147{,}483{,}648_{ten}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0001_{two} = -2{,}147{,}483{,}647_{ten}$
$1000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0010_{two} = -2{,}147{,}483{,}646_{ten}$
...
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1101_{two} = -3_{ten}$
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1110_{two} = -2_{ten}$
$1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111_{two} = -1_{ten}$

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Ways to Make Two's Complement

- *In two's complement the sign-bit has negative weight:*
- So the value of an N-bit word $[b_{N-1}\ b_{N-2}\ \ldots\ b_1\ b_0]$ is:

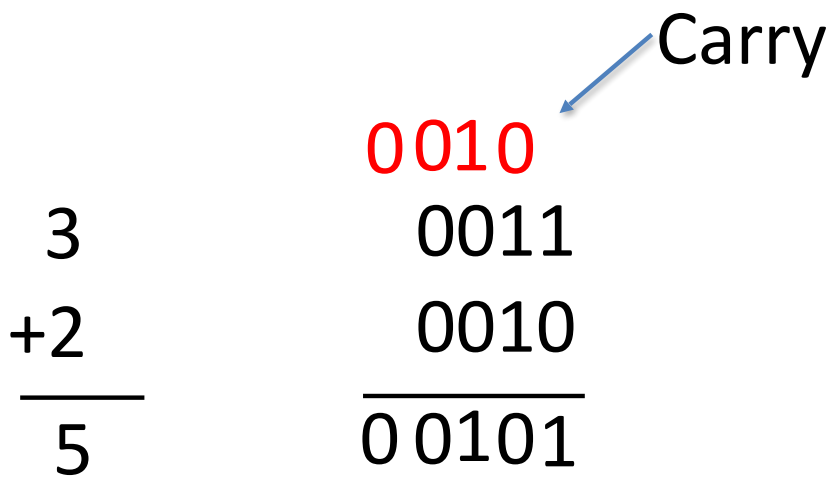
$$-2^{N-1} \times b^{N-1} + 2^{N-2} \times b^{N-2} + \ldots + 2^1 \times b^1 + 2^0 \times b^0$$

- For a 4-bit number, $3_{ten}=0011_{two}$, its two's complement $-3_{ten}=1101_{two}$ $(-1000_{two} + 0101_{two} = -8_{ten} + 5_{ten})$

- Here is an easier way:
  - Invert all bits and add 1
  - Computers circuits do it like this, too

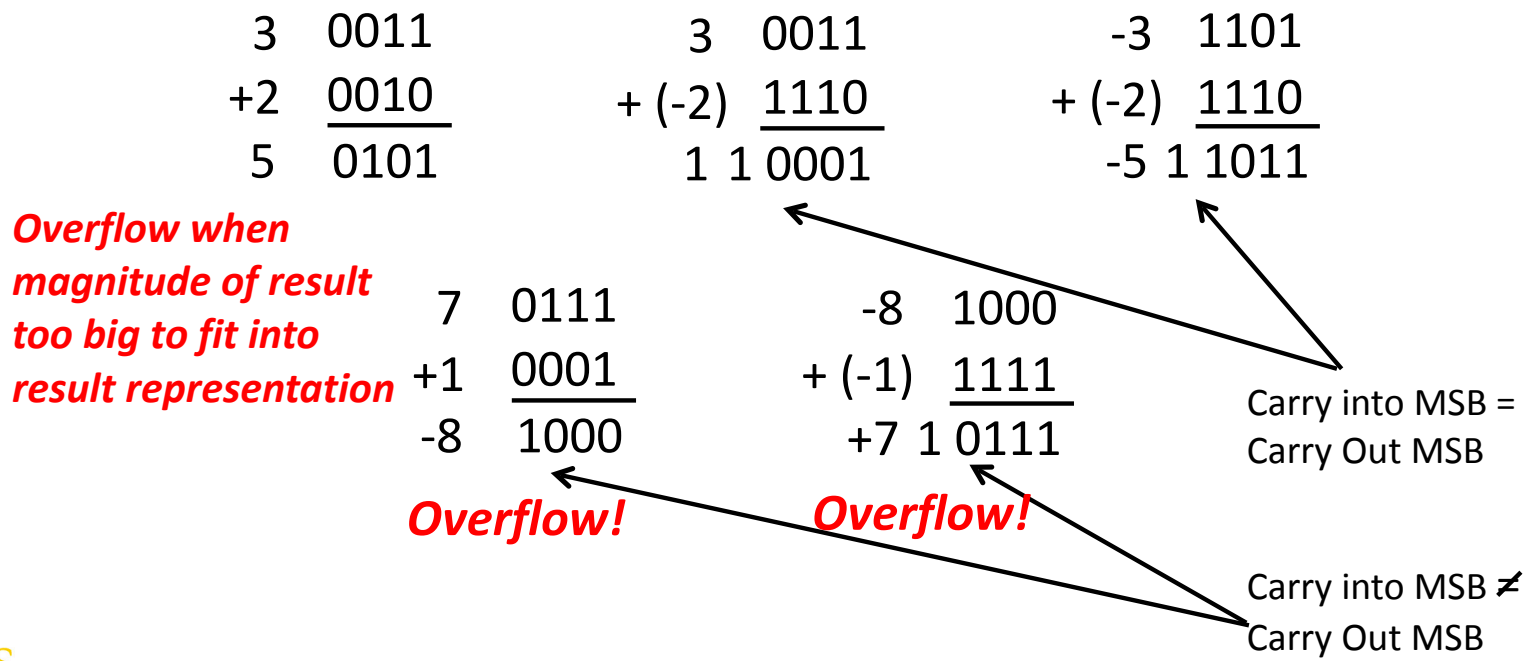
3_{ten}	0011_{two}
Bitwise Invert	1100_{two}
+	1_{two}
-3_{ten}	1101_{two}

Binary Addition Example



Two's-Complement Examples

- Assume for simplicity 4 bit width, -8 to +7 represented



Suppose we had a 5-bit word. What integers can be represented in two's complement?

- ☐ -32 to +31
- ☐ 0 to +31
- ☐ -16 to +15
- ☐ -15 to +16

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- ☐ -32 to +31
- ☐ 0 to +31
- ☐ -16 to +15
- ☐ -15 to +16

Summary: Number Representations

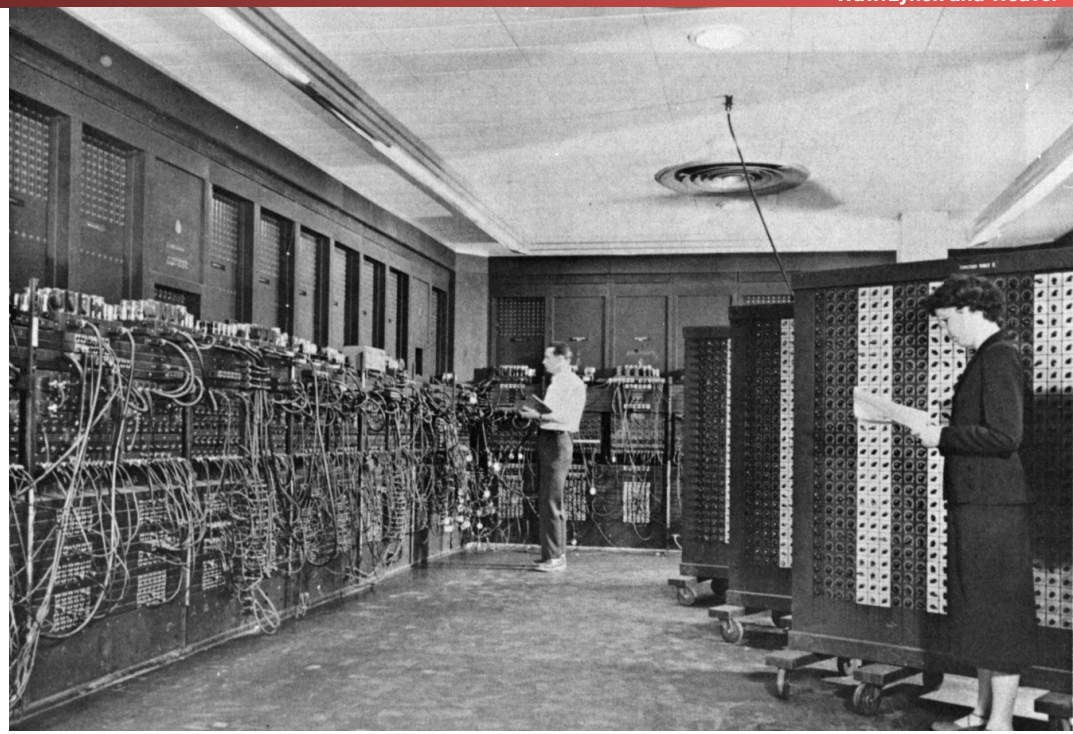
- Everything in a computer is a number, in fact only 0 and 1.
- Integers are interpreted by adhering to fixed length
- Negative numbers are represented with Two's complement
- Overflows can be detected utilizing the carry bit.

Agenda

- Computer Organization
- Compile vs. Interpret
- C vs Java
- Arrays and Pointers (perhaps)

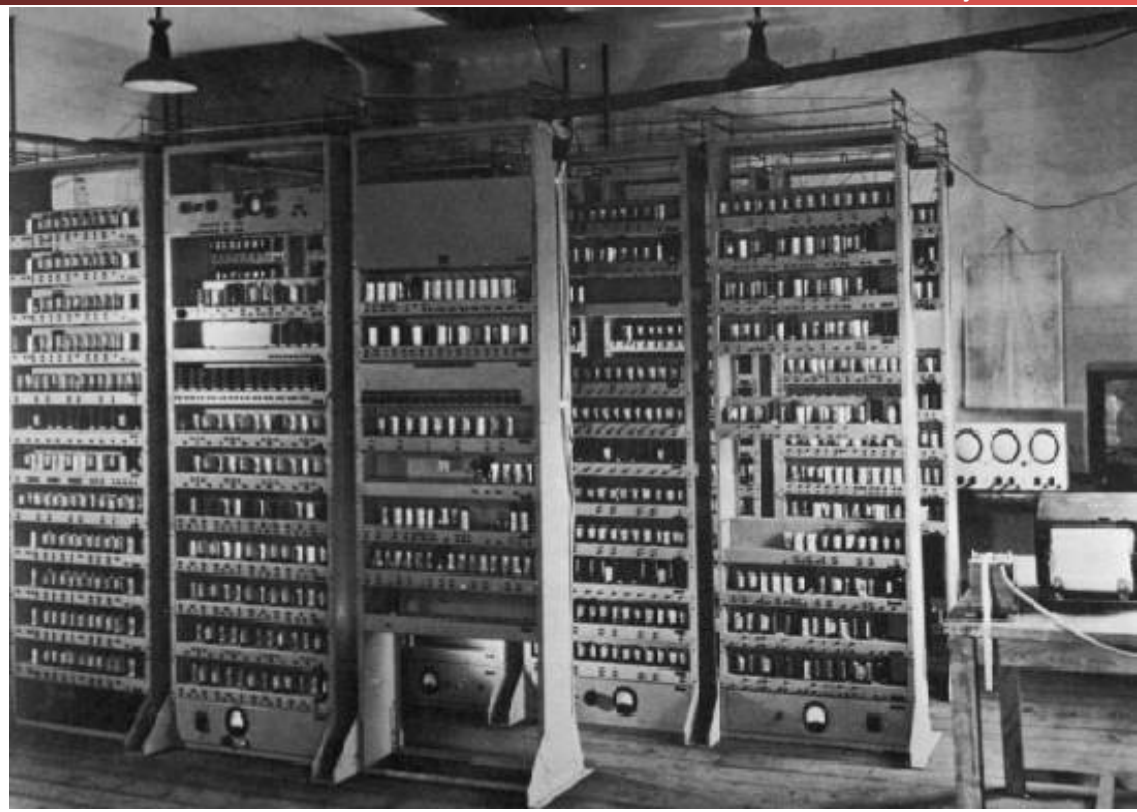
ENIAC (U.Penn., 1946)
First Electronic General-Purpose Computer

- Blazingly fast (multiply in 2.8ms!)
  - 10 decimal digits x 10 decimal digits
- But needed 2-3 days to setup new program, as programmed with patch cords and switches
  - At that time & before, "computer" mostly referred to ***people*** who did calculations

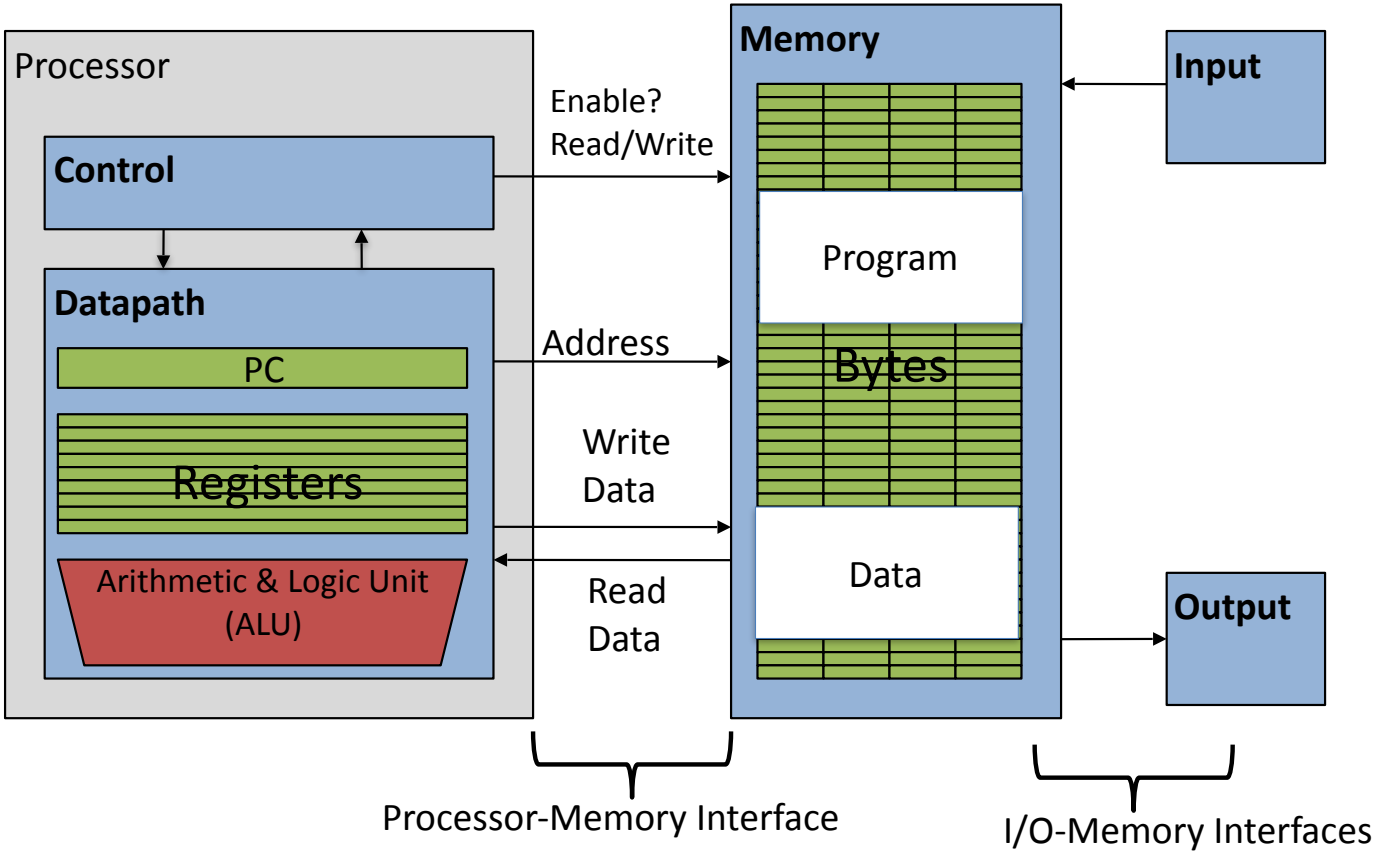


EDSAC (Cambridge, 1949)
First General ***Stored-Program*** Computer

- Programs held as numbers in memory
  - This is the revolution:
    It isn't just programmable, but the program is just the same type of data that the computer computes on
- 35-bit binary 2's complement words

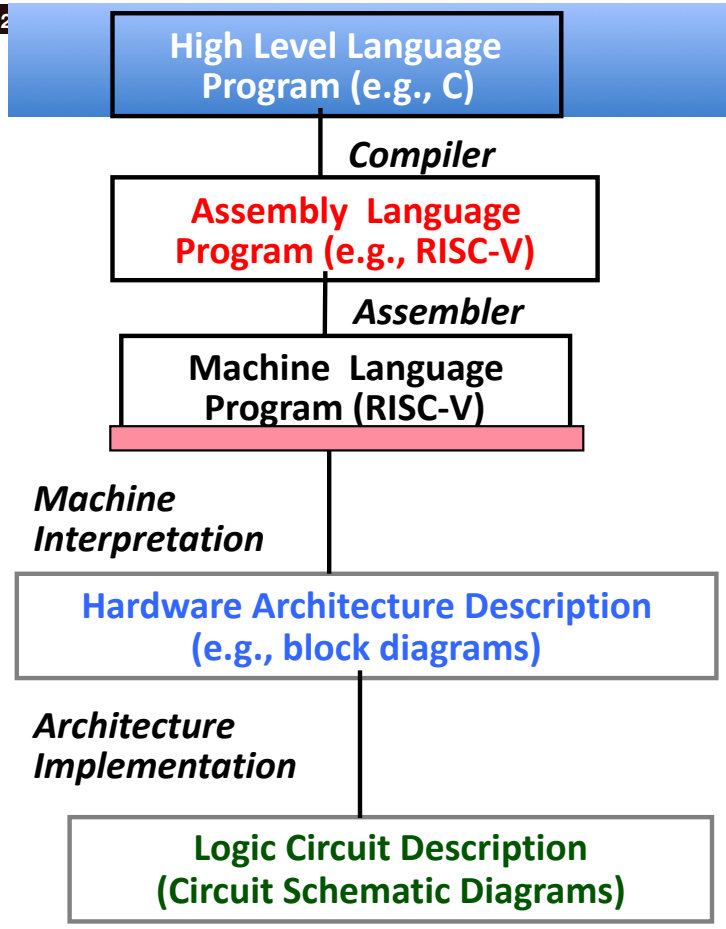


Components of a Computer



Great Idea: Levels of Representation/Interpretation


```
lw    t0, t2, 0
lw    t1, t2, 4
sw    t1, t2, 0
sw    t0, t2, 4
```

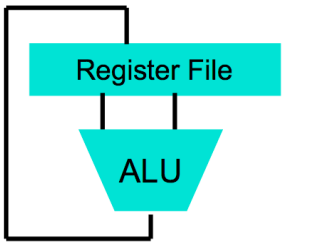


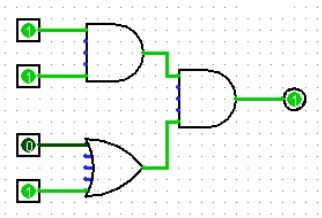

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

We are here!

Anything can be represented as a *number*, i.e., data or instructions

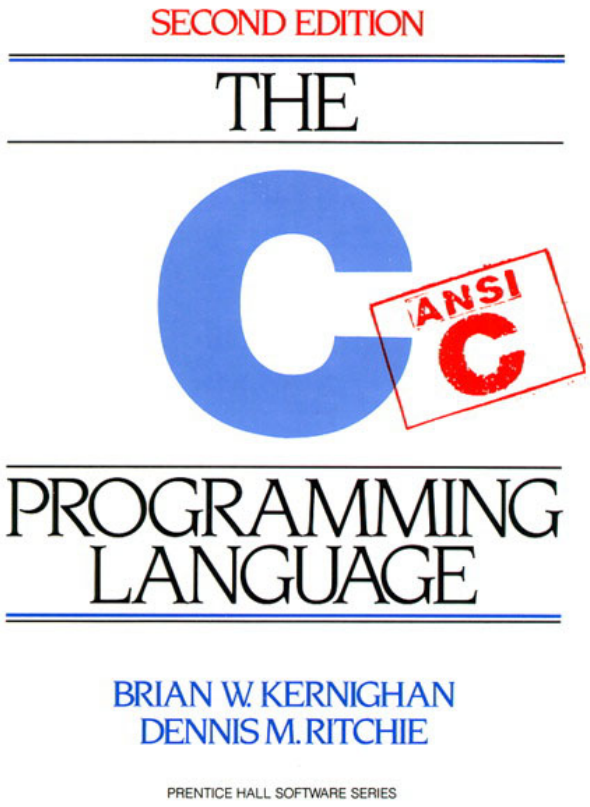
```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```





Introduction to C
"The Universal Assembly Language"

- Class pre-req included classes teaching Java
  - "Some" experience is required before CS61C
    - C++ or Java OK
- Python used in two labs
- C used for everything else "high" level
- Almost all low level assembly is RISC-V
  - But Project 4 may require touching some x86…



Language Poll

- Please raise your hand for the first one you can say yes to:
- I have programmed in C, C++, C#, or Objective-C
- I have programmed in Java
- I have programmed in Swift, Go, Rust, etc
- None of the above

Intro to C

- *C is not a "very high-level" language, nor a "big" one, and is not specialized to any particular area of application. But its absence of restrictions and its generality make it more convenient and effective for many tasks than supposedly more powerful languages.*
  - Kernighan and Ritchie
- Enabled first operating system not written in assembly language: *UNIX* - A portable OS!

Intro to C

- Why C?: *we can write programs that allow us to exploit underlying features of the architecture – memory management, special instructions, parallelism*
- C and derivatives (C++/Obj-C/C#) still one of the most popular application programming languages after >40 years!
  - Don't ask me why… If you are starting a new project where performance matters use either Go or Rust
    - Rust, "***C-but-safe***": By the time your C is (theoretically) correct with all the necessary checks it should be no faster than Rust
    - Go, "***Concurrency***": Actually able to do practical concurrent programming to take advantage of modern multi-core microprocessors

Disclaimer

- You will not learn how to fully code in C in these lectures! You'll still need your C reference for this course
  - K&R is a ***must-have***
  - Useful Reference: "JAVA in a Nutshell," O'Reilly
    - Chapter 2, "How Java Differs from C"
    - http://oreilly.com/catalog/javanut/excerpt/index.html
  - Brian Harvey's helpful transition notes
    - On CS61C class website: pages 3-19
    - http://inst.eecs.berkeley.edu/~cs61c/resources/HarveyNotesC1-3.pdf
- Key C concepts: Pointers, Arrays, Implications for Memory management
  - Key security concept: All of the above are ***unsafe***: If your program contains an error in these areas it might not crash immediately but instead leave the program in an inconsistent (and often exploitable) state

Administrivia Break…

- Exams:
  - Midterms in the evening (7pm-9pm) on Tuesday 2/13 and Tuesday 3/20
    - We will not have class those days
  - Final Friday 5/11 7-10pm
- DSP accommodations:
  - Get those in ASAP. You need to have your exam accommodation letters in by 2/1 to be considered for the 2/13 midterm
- For those with conflicts with other exams:
  - We will have make-up exams ***immediately after the scheduled exams***
    - Yes, this ***sucks***, but its necessary for exam security.
      Hopefully your other instructors aren't card-carrying paranoids…

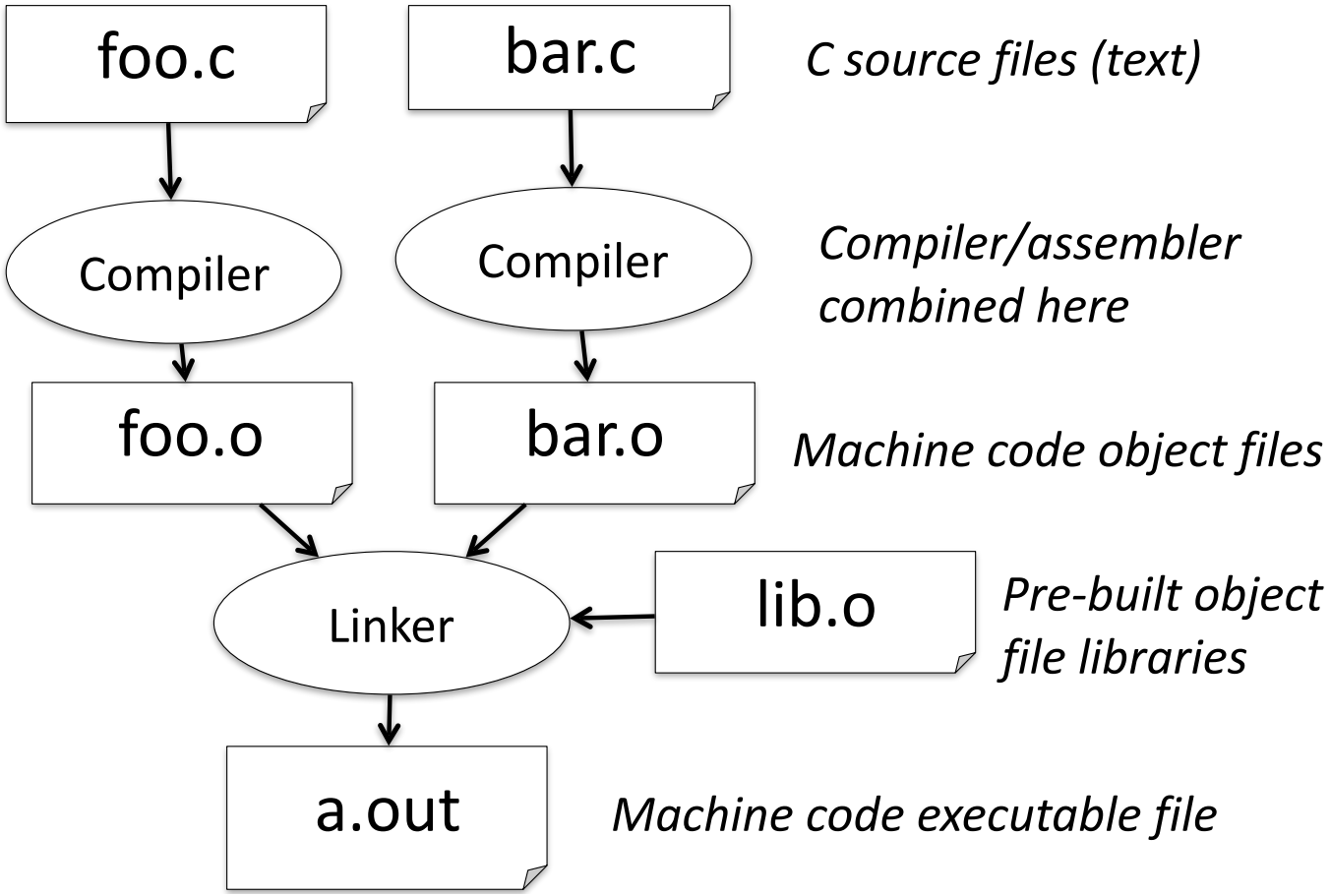
Agenda

- Computer Organization
- Compile vs. Interpret
- C vs Java

Compilation: Overview

- C compilers map C programs directly into architecture-specific *machine code* (string of 1s and 0s)
  - Unlike *Java*, which converts to architecture-independent bytecode that may then be compiled by a just-in-time compiler (JIT)
  - Unlike *Python* environments, which converts to a byte code at runtime
    - These differ mainly in exactly when your program is converted to low-level machine instructions ("levels of interpretation")
- For C, generally a two part process of compiling .c files to .o files, then linking the .o files into executables;
  - Assembling is also done (but is hidden, i.e., done automatically, by default); we'll talk about that later

C Compilation Simplified Overview (more later in course)



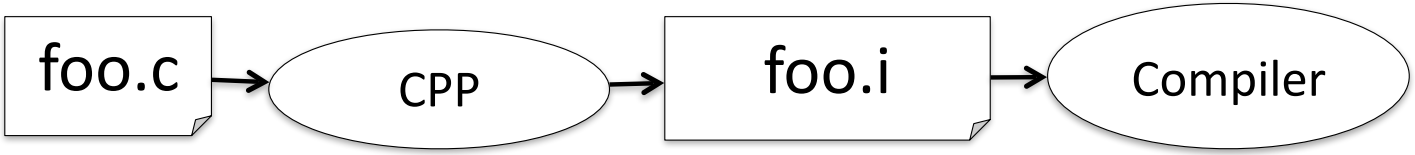
Compilation: Advantages

- Excellent run-time performance: generally much faster than Scheme or Java for comparable code (because it optimizes for a given architecture)
  - But these days, a lot of performance is in libraries:
    Plenty of people do scientific computation in ***python!?!***, because they have good libraries for accessing GPU-specific resources
- Reasonable compilation time: enhancements in compilation procedure (Makefiles) allow only modified files to be recompiled

Compilation: Disadvantages

- Compiled files, including the executable, are architecture-specific, depending on processor type (e.g., MIPS vs. RISC-V) and the operating system (e.g., Windows vs. Linux)
- Executable must be rebuilt on each new system
  - I.e., "porting your code" to a new architecture
- "Change → Compile → Run [repeat]" iteration cycle can be slow during development
  - but **`make`** only rebuilds changed pieces, and can do compiles in parallel (**`make -j X`**)
    - linker is sequential though → Amdahl's Law

C Pre-Processor (CPP)



- C source files first pass through macro processor, CPP, before compiler sees code
- CPP replaces comments with a single space
- CPP commands begin with "#"
- **`#include "file.h"`** /* Inserts file.h into output */
- **`#include <stdio.h>`** /* Looks for file in standard location, but no actual difference! */
- **`#define M_PI (3.14159)`** /* Define constant */
- **`#if/#endif /* Conditional inclusion of text */`**
- Use –save-temps option to gcc to see result of preprocessing
  - Full documentation at: http://gcc.gnu.org/onlinedocs/cpp/

CPP Macros: A Warning...

- You often see C preprocessor macros defined to create small "functions"
  - But they aren't actual functions, instead it just changes the text of the program
- This can produce, umm, interesting errors
  - `#define twox(x) (x + x)`
  - `twox(y++);`
  - `(y++ + y++);`

C vs. Java

	C	Java
Type of Language	Function Oriented	Object Oriented
Programming Unit	Function	Class = Abstract Data Type
Compilation	gcc hello.c creates machine language code	javac Hello.java creates Java virtual machine language bytecode
Execution	a.out loads and executes program	java Hello interprets bytecodes

hello, world	`#include<stdio.h>`
	`int main(void) {`
	`  printf("Hello\n");`
	`  return 0;`
	`}`
		`public class HelloWorld {`
		`  public static void main(String[] args) {`
		`  System.out.println("Hello");`
		`  }`
		`}`

Storage	Manual (malloc, free)	New allocates & initializes, Automatic (garbage collection) frees

From http://www.cs.princeton.edu/introcs/faq/c2java.html

C vs. Java

	C	Java
Comments	`/* … */`	`/* … */` or `//` … end of line
Constants	`#define`, `const`	`final`
Preprocessor	Yes	No
Variable declaration	At beginning of a block	Before you use it
Variable naming conventions	`sum_of_squares`	`sumOfSquares`
Accessing a library	`#include <stdio.h>`	`import java.io.File;`

From http://www.cs.princeton.edu/introcs/faq/c2java.html

Typed Variables in C


```
int   variable1   = 2;
float variable2   = 1.618;
char  variable3   = 'A';
```

- Must declare the type of data a variable will hold
  - Types can't change

Type	Description	Example
`int`	Integer Numbers (including negatives) At least 16 bits, can be larger	`0, 78, -217, 0x7337`
`unsigned int`	Unsigned Integers	`0, 6, 35102`
`float`	Floating point decimal	`0.0, 3.14159, 6.02e23`
`double`	Equal or higher precision floating point	`0.0, 3.14159, 6.02e23`
`char`	Single character	`'a', 'D', '\n'`
`long`	Longer int, Size >= sizeof(int), at least 32b	`0, 78, -217, 301720971`
`long long`	Even longer int, size >= sizeof(long), at least 64b	`317051927210925l2`

Integers: Python vs. Java vs. C

- C: **`int`** should be integer type that target processor works with most efficiently
- Only guarantee: sizeof(**`long long`**) ≥ sizeof(**`long`**) ≥ sizeof(**`int`**) ≥ sizeof(**`short`**)
  - Also, **`short`** >= 16 bits, **`long`** >= 32 bits
  - All could be 64 bits

Language	sizeof(int)
Python	>=32 bits (plain ints), infinite (long ints)
Java	32 bits
C	Depends on computer; 16 or 32 or 64

Consts and Enums in C

- Constant is assigned a typed value once in the declaration; value can't change during entire execution of program

```
const float golden_ratio = 1.618;
const int days_in_week = 7;
const double the_law = 2.997928e10;
```

- You can have a constant version of any of the standard C variable types
- Enums: a group of related integer constants. Ex:

```
enum cardsuit {CLUBS,DIAMONDS,HEARTS,SPADES};
enum color {RED, GREEN, BLUE};
```

Typed Functions in C


```
int number_of_people ()
{
  return 3;
}

float dollars_and_cents ()
{
  return 10.33;
}

int sum ( int x, int y)
{
   return x + y;
}
```

- You have to declare the type of data you plan to return from a function
- Return type can be any C variable type, and is placed to the left of the function name
- You can also specify the return type as **`void`**
  - Just think of this as saying that no value will be returned
- Also necessary to declare types for values passed into a function
- Variables and functions MUST be declared before they are used

Structs in C

- Structs are structured groups of variables, e.g.,

```
typedef struct {
  int length_in_seconds;
  int year_recorded;
} Song;

Song song1;
song1.length_in_seconds =  213;
song1.year_recorded      = 1994;

Song song2;
song2.length_in_seconds =  248;
song2.year_recorded      = 1988;
```

Dot notation: `x.y = value`

A First C Program: Hello World

Original C:

```
main()
{
  printf("\nHello World\n");
}
```

ANSI Standard C:

```
#include <stdio.h>

int main(void)
{
  printf("\nHello World\n");
  return 0;
}
```

C Syntax: `main`

- When C program starts
  - C executable **`a.out`** is loaded into memory by operating system (OS)
  - OS sets up stack, then calls into C runtime library,
  - Runtime 1st initializes memory and other libraries,
  - then calls your procedure named **`main()`**
- We'll see how to retrieve command-line arguments in **`main()`** later…

A Second C Program: Compute Table of Sines


```
#include <stdio.h>
#include <math.h>

int main(void)
{
    int    angle_degree;
    double angle_radian, pi, value;
    /* Print a header */
    printf("\nCompute a table of the
sine function\n\n");
    /* obtain pi once for all       */
    /* or just use pi = M_PI, where */
    /* M_PI is defined in math.h    */
    pi = 4.0*atan(1.0);
    printf("Value of PI = %f \n\n",
            pi);
    printf("angle     Sine \n");
    angle_degree = 0;
    /* initial angle value */
    /* scan over angle     */
    while (angle_degree <= 360)
    /* loop until angle_degree > 360 */
       {
          angle_radian = pi*
                angle_degree/180.0;
          value = sin(angle_radian);
          printf (" %3d      %f \n ",
                 angle_degree, value);
          angle_degree += 10;
          /* increment the loop index */
       }
    return 0;
}
```

Second C Program Sample Output


```
Compute a table of the sine function

Value of PI = 3.141593

angle      Sine
   0     0.000000
  10     0.173648
  20     0.342020
  30     0.500000
  40     0.642788
  50     0.766044
  60     0.866025
  70     0.939693
  80     0.984808
  90     1.000000
 100     0.984808
 110     0.939693
 120     0.866025
 130     0.766044
 140     0.642788
  .       .
  .       .
  .       .
```

C Syntax: Variable Declarations

- Similar to Java, but with a few minor but important differences
  - All variable declarations must appear before they are used
  - All must be at the beginning of a block.
  - A variable may be initialized in its declaration; ***if not, it holds garbage***! (the contents are undefined)
- Examples of declarations:
  - Correct: `{ int a = 0, b = 10; ...`
  - Incorrect: `for (int i = 0; i < 10; i++) { ...`

Newer C standards are more flexible about this

C Syntax : Control Flow (1/2)

- Within a function, remarkably close to Java constructs (shows Java's legacy) in terms of control flow
  - A statement can be a {} of code or just standalone
- if-else
  - `if (expression) statement`
    - `if (x == 0) y++;`
    - `if (x == 0) {y++;}`
    - `if (x == 0) {y++; j = j + y;}`
  - `if (expression) statement1 else statement2`
    - There is an ambiguity in a series of if/else if/else if you don't use `{}`s, so use `{}`s to block the code
- while
  - `while (expression) statement`
  - `do statement while (expression);`

C Syntax : Control Flow (2/2)

- for
  - `for (initialize; check; update) statement`
- switch
  - ```
    switch (expression){
      case const1:    statements
      case const2:    statements
      default:        statements
    }
    ```
  - `break;`
  - Note: until you do a break statement things keep executing in the switch statement
- C also has `goto`
  - But it can result in spectacularly bad code if you use it, so don't!

```
if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
    goto fail;
    goto fail;  /* MISTAKE! THIS LINE SHOULD NOT HAVE BEEN HERE */
```
```

C Syntax: True or False

- What evaluates to FALSE in C?
  - 0 (integer)
  - NULL (a special kind of pointer that is also 0: more on this later)
  - ***No explicit Boolean type***
    - Often you see `#define bool (int)`
- What evaluates to TRUE in C?
  - ***Anything*** that isn't false is true
  - Same idea as in Python: only 0s or empty sequences are false, anything else is true!

C and Java operators nearly identical

- arithmetic: `+, -, *, /, %`
- assignment: `=`
- augmented assignment: `+=, -=, *=, /=, %=, &=, |=, ^=, <<=, >>=`
- bitwise logic: `~, &, |, ^`
- bitwise shifts: `<<, >>`
- boolean logic: `!, &&, ||`
- equality testing: `==, !=`
- subexpression grouping: `()`
- order relations: `<, <=, >, >=`
- increment and decrement: `++` and `--`
- member selection: `., ->`
  - This is slightly different than Java because there are both structures and pointers to structures
- conditional evaluation: `? :`

Nick's Tip of the Day… Valgrind

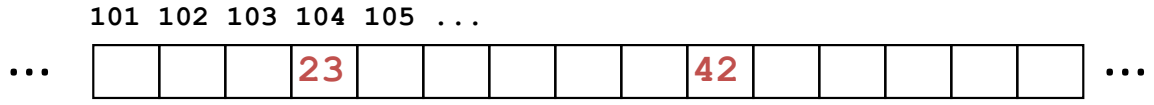
- Valgrind turns most unsafe "heisenbugs" into "bohrbugs"
  - It adds almost all the checks that Java does but C does not
  - The result is your program ***immediately*** crashes where you make a mistake
  - It is installed on the lab machines
- Nick's scars from 60C:
  - First C project, spent an entire day tracing down a fault...
  - That turned out to be a <= instead of a < in initializing an array!

Agenda

- Pointers
- Arrays in C

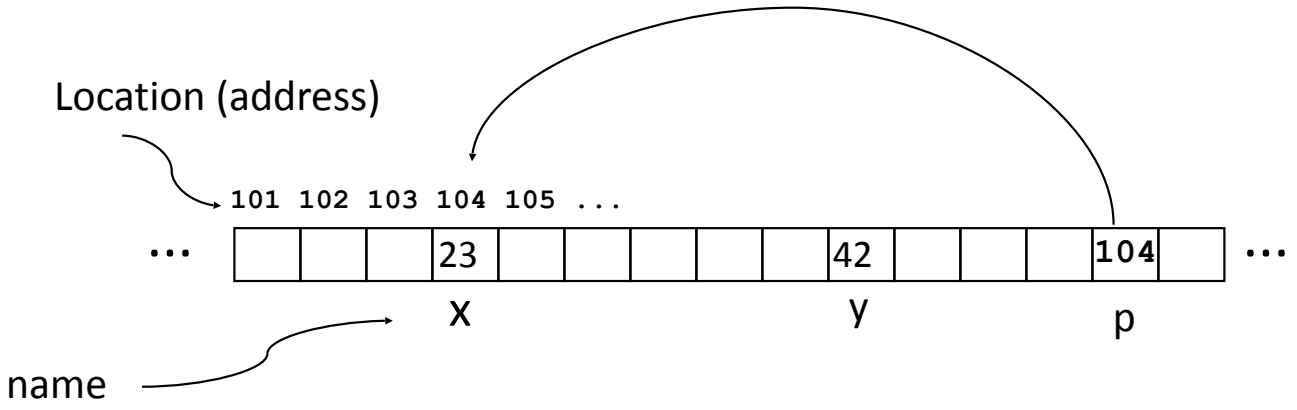
Address vs. Value

- Consider memory to be a ***single*** huge array
  - Each cell of the array has an address associated with it
  - Each cell also stores some value
  - For addresses do we use signed or unsigned numbers? Negative address?!
- Don't confuse the address referring to a memory location with the value stored there



Pointers

- An *address* refers to a particular memory location; e.g., it points to a memory location
- *Pointer*: A variable that contains the address of a variable



Pointer Syntax

- `int *p;`
  - Tells compiler that variable p is address of an `int`
- `p = &y;`
  - Tells compiler to assign address of `y` to `p`
  - `&` called the "address operator" in this context
- `z = *p;`
  - Tells compiler to assign value at address in `p` to `z`
  - `*` called the "dereference operator" in this context

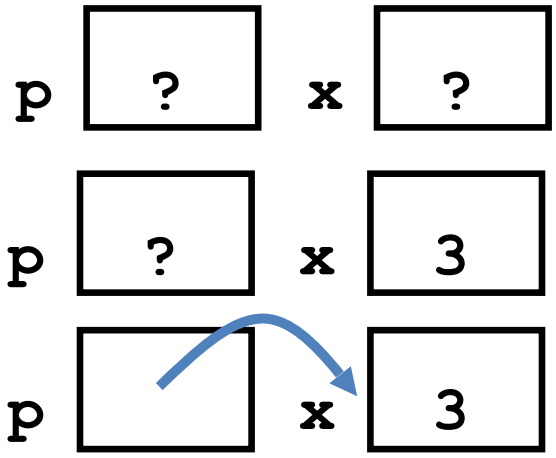
Creating and Using Pointers

- How to create a pointer:

  `&` operator: get address of a variable

```
int *p, x;      x = 3;

                p = &x;
```



Note the "`*`" gets used two different ways in this example. In the declaration to indicate that `p` is going to be a pointer, and in the `printf` to get the value pointed to by `p`.

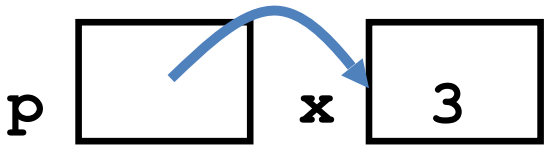
- How get a value pointed to?

  "`*`" (dereference operator): get the value that the pointer points to

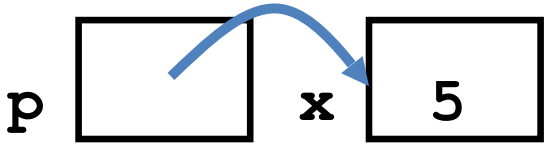
```
printf("p points to %d\n",*p);
```

Using Pointer for Writes

- How to change a variable pointed to?
  - Use the dereference operator * on left of assignment operator =




```
*p = 5;
```



Pointers and Parameter Passing

- Java and C pass parameters "by value": Procedure/function/method gets a copy of the parameter, *so changing the copy cannot change the original*

```
void add_one (int x)
{
     x = x + 1;
}
int y = 3;
add_one(y);
```

y remains equal to 3

Pointers and Parameter Passing

- How can we get a function to change the value held in a variable?

```
void add_one (int *p)
{
    *p = *p + 1;
}
int y = 3;

add_one(&y);
```

y is now equal to 4

Types of Pointers

- Pointers are used to point to any kind of data (**`int`**, **`char`**, a **`struct`**, etc.)
- Normally a pointer only points to one type (**`int`**, **`char`**, a **`struct`**, etc.).
  - **`void *`** is a type that can point to anything (generic pointer)
  - Use **`void *`** sparingly to help avoid program bugs, and security issues, and other bad things!
- You can even have pointers to functions…
  - **`int (*fn) (void *, void *) = &foo`**
    - **`fn`** is a function that accepts two **`void *`** pointers and returns an **`int`** and is initially pointing to the function **`foo`**.
    - **`(*fn)(x, y)`** will then call the function

More C Pointer Dangers

- *Declaring a pointer just allocates space to hold the pointer – it does not allocate the thing being pointed to!*
- Local variables in C are not initialized, they may contain anything (aka "garbage")
- What does the following code do?

```
void f()
{
    int *ptr;
    *ptr = 5;
}
```

Pointers and Structures


```
typedef struct {
    int x;
    int y;
} Point;

Point p1;
Point p2;
Point *paddr;
```

```
/* dot notation */
int h = p1.x;
p2.y = p1.y;

/* arrow notation */
int h = paddr->x;
int h = (*paddr).x;

/* This works too */
p1 = p2;
```

Pointers in C

- Why use pointers?
  - If we want to pass a large struct or array, it's easier / faster / etc. to pass a pointer than the whole thing
    - Otherwise we'd need to copy a huge amount of data
  - In general, pointers allow cleaner, more compact code
- So what are the drawbacks?
  - Pointers are probably the single largest source of bugs in C, so be careful anytime you deal with them
    - Most problematic with dynamic memory management—coming up next week
    - Dangling references and memory leaks

Why Pointers in C?

- At time C was invented (early 1970s), compilers often didn't produce efficient code
  - Computers 100,000x times faster today, compilers better
- C designed to let programmer say what they want code to do without compiler getting in way
  - Even give compilers hints which registers to use!
- Today's compilers produce much better code, so may not need to use pointers in application code
  - Low-level system code still needs low-level access via pointers