CS 61C: Great Ideas in Computer Architecture

*Introduction to C, Part I*

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http://inst.eecs.Berkeley.edu/~cs61c/sp15
Review & Correction:
Two’s-Complement Examples

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

<table>
<thead>
<tr>
<th></th>
<th>0011</th>
<th>0011</th>
<th>1101</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0010</td>
<td>+2</td>
<td>0101</td>
</tr>
<tr>
<td>+2</td>
<td>0101</td>
<td>+ (+2)1110</td>
<td>0101</td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
<td>11001</td>
<td>1101</td>
</tr>
</tbody>
</table>

Overflow when magnitude of result too big to fit into result representation

-8 1000
+7 10111

Carry into MSB = Carry Out MSB

Overflow!

Carry in = carry from less significant bits
Carry out = carry to more significant bits
Agenda

• Compile vs. Interpret
• C vs. Java vs. Python
• Administrivia
• Quick Start Introduction to C
• News/Technology Break
• Pointers
• And in Conclusion, ...
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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
EDSAC (Cambridge, 1949)
First General Stored-Program Computer

- Programs held as numbers in memory
- 35-bit binary 2’s complement words
Components of a Computer

Processor

Control

Datapath

Registers

Arithmetic & Logic Unit (ALU)

Memory

Program

Bytes

Data

Input

Output

Processor-Memory Interface

Enable?
Read/Write

Address

Write Data

Read Data

I/O-Memory Interfaces
Great Idea: Levels of Representation/Interpretation

High Level Language Program (e.g., C) → Compiler
Assembly Language Program (e.g., MIPS) → Assembler
Machine Language Program (MIPS) → Machine Interpretation

Compiler

Assembly Language Program (e.g., MIPS)

Assembler

Machine Language Program (MIPS)

Machine Interpretation

Hardware Architecture Description (e.g., block diagrams)

Architecture Implementation

Logic Circuit Description (Circuit Schematic Diagrams)

We are here!

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

lw $t0, 0($2)
lw $t1, 4($2)
sw $t1, 0($2)
sw $t0, 4($2)

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”

• “Some” experience is required before CS61C
  C++ or Java OK

• Class pre-req included classes teaching Java

• Python used in two labs and one project

• C used for everything else
Language Poll!

Please raise hand for *first* one of following you can say yes to

- I have programmed in C, C++, C#, or Objective-C
- I have programmed in Java
- I have programmed in FORTRAN, Cobol, Algol-68, Ada, Pascal, or Basic
- 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!

- C and derivatives (C++/Obj-C/C#) still one of the most popular application programming languages after >40 years!
# TIOBE Index of Language Popularity

<table>
<thead>
<tr>
<th>Jan 2015</th>
<th>Jan 2014</th>
<th>Change</th>
<th>Programming Language</th>
<th>Ratings</th>
<th>Change</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td>C</td>
<td>16.703%</td>
<td>-1.24%</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td></td>
<td>Java</td>
<td>15.528%</td>
<td>-1.00%</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td></td>
<td>Objective-C</td>
<td>6.953%</td>
<td>-4.14%</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td></td>
<td>C++</td>
<td>6.705%</td>
<td>-0.86%</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td></td>
<td>C#</td>
<td>5.045%</td>
<td>-0.80%</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td></td>
<td>PHP</td>
<td>3.784%</td>
<td>-0.82%</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>↑</td>
<td>JavaScript</td>
<td>3.274%</td>
<td>+1.70%</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td></td>
<td>Python</td>
<td>2.613%</td>
<td>+0.24%</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>↑</td>
<td>Perl</td>
<td>2.256%</td>
<td>+1.33%</td>
</tr>
<tr>
<td>10</td>
<td>17</td>
<td>↑</td>
<td>PL/SQL</td>
<td>2.014%</td>
<td>+1.38%</td>
</tr>
</tbody>
</table>

[http://www.tiobe.com]
TIOBE Programming Community Index
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
    • Check online for more sources
  – “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
Compilation: Overview

• C *compilers* map C programs into architecture-specific machine code (string of 1s and 0s)
  – Unlike *Java*, which converts to architecture-independent *bytecode*
  – Unlike *Python* environments, which *interpret* the code
  – 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)

foo.c

bar.c

Compiler

foo.o

bar.o

Machine code object files

Linker

lib.o

Pre-built object file libraries

Combined here

Compiler/assembler

Machine code executable file

C source files (text)
Compilation: Advantages

- Excellent run-time performance: generally much faster than Scheme or Java for comparable code (because it optimizes for a given architecture)
- Fair compilation time: enhancements in compilation procedure (Makefiles) allow only modified files to be recompiled
- Why C?: *we can write programs that allow us to exploit underlying features of the architecture – memory management, special instructions, parallelism*
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 tool only rebuilds changed pieces, and can do compiles in parallel (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 */
- `#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/
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## C vs. Java

<table>
<thead>
<tr>
<th>Feature</th>
<th>C</th>
<th>Java</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Language</strong></td>
<td>Function Oriented</td>
<td>Object Oriented</td>
</tr>
<tr>
<td><strong>Programming Unit</strong></td>
<td>Function</td>
<td>Class = Abstract Data Type</td>
</tr>
<tr>
<td><strong>Compilation</strong></td>
<td>gcc hello.c creates machine language code</td>
<td>javac Hello.java creates Java virtual machine language byte code</td>
</tr>
<tr>
<td><strong>Execution</strong></td>
<td>a.out loads and executes program</td>
<td>java Hello interprets bytecodes</td>
</tr>
<tr>
<td><strong>Hello, world</strong></td>
<td>#include&lt;stdio.h&gt; int main(void) { printf(&quot;Hello\n&quot;); return 0; }</td>
<td>public class HelloWorld { public static void main(String[] args) { System.out.println(&quot;Hello&quot;); } }</td>
</tr>
<tr>
<td><strong>Storage</strong></td>
<td>Manual (malloc, free)</td>
<td>Automatic (garbage collection)</td>
</tr>
</tbody>
</table>

## C vs. Java

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

Typed Variables in C

```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

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>int</td>
<td>integer numbers, including negatives</td>
<td>0, 78, -1400</td>
</tr>
<tr>
<td>unsigned int</td>
<td>integer numbers (no negatives)</td>
<td>0, 46, 900</td>
</tr>
<tr>
<td>float</td>
<td>floating point decimal numbers</td>
<td>0.0, 1.618, -1.4</td>
</tr>
<tr>
<td>char</td>
<td>single text character or symbol</td>
<td>'a', 'D', '?'</td>
</tr>
<tr>
<td>double</td>
<td>greater precision/big FP number</td>
<td>10E100</td>
</tr>
<tr>
<td>long</td>
<td>larger signed integer</td>
<td>6,000,000,000,000</td>
</tr>
</tbody>
</table>
### Integers: Python vs. Java vs. C

<table>
<thead>
<tr>
<th>Language</th>
<th>sizeof(int)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Python</td>
<td>&gt;=32 bits (plain ints), infinite (long ints)</td>
</tr>
<tr>
<td>Java</td>
<td>32 bits</td>
</tr>
<tr>
<td>C</td>
<td>Depends on computer; 16 or 32 or 64</td>
</tr>
</tbody>
</table>

- **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
Consts and Enums in C

• Constant is assigned a typed value once in the declaration; value can't change during entire execution of program
  
  ```c
  const float golden_ratio = 1.618;
  const int days_in_week = 7;
  ```

• You can have a constant version of any of the standard C variable types

• Enums: a group of related integer constants used to parameterize libraries:
  
  ```c
  enum cardsuit {CLUBS,DIAMONDS,HEARTS,SPADES};
  ```
Clicker Test

- Clicker participation starting on Tuesday
- No web-based clickers or phone apps
- Participation only is recorded, not correctness of answers
- Register at: https://www1.iclicker.com/register-clicker/
Compare “#define PI 3.14” and “const float pi=3.14” – which is true?

A: Constants “PI” and “pi” have same type

B: Can assign to “PI” but not “pi”

C: Code runs at same speed using “PI” or “pi”

D: “pi” takes more memory space than “PI”

E: Both behave the same in all situations
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Administrivia

• HW0 out
  – Mini-bio due in lab 1/30, 2/2, or 2/3
  – Rest due Sunday 2/1 @ 23:59:59

• Labs start tomorrow
  – 330 Soda should be open by then
  – watch for announcements if 330 not open!

• Tentative office hour schedule posted on website:
  – http://inst.eecs.Berkeley.edu/~cs61c/sp15

• Clickers!
Agenda

• Compile vs. Interpret
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• Administrivia

• **Quick Start Introduction to C**
• News/Technology Break
• Pointers
• And in Conclusion, ...
int number_of_people ()
{
    return 3;
}

float dollars_and_cents ()
{
    return 10.33;
}

char first_letter ()
{
    return 'A';
}

• 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.,

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

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

int main(void)
{
    int angle_degree;
    double angle_radian, pi, value;
    /* Print a header */
    printf("Compute a table of the sine function\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 = angle_degree + 10;
        /* increment the loop index */
    }
    return 0;
}
Compute a table of the sine function

Value of PI = 3.141593

<table>
<thead>
<tr>
<th>angle</th>
<th>Sine</th>
<th>angle</th>
<th>Sine</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000000</td>
<td>190</td>
<td>-0.173648</td>
</tr>
<tr>
<td>10</td>
<td>0.173648</td>
<td>200</td>
<td>-0.342020</td>
</tr>
<tr>
<td>20</td>
<td>0.342020</td>
<td>210</td>
<td>-0.500000</td>
</tr>
<tr>
<td>30</td>
<td>0.500000</td>
<td>220</td>
<td>-0.642788</td>
</tr>
<tr>
<td>40</td>
<td>0.642788</td>
<td>230</td>
<td>-0.766044</td>
</tr>
<tr>
<td>50</td>
<td>0.766044</td>
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<td>-0.866025</td>
</tr>
<tr>
<td>60</td>
<td>0.866025</td>
<td>250</td>
<td>-0.939693</td>
</tr>
<tr>
<td>70</td>
<td>0.939693</td>
<td>260</td>
<td>-0.984808</td>
</tr>
<tr>
<td>80</td>
<td>0.984808</td>
<td>270</td>
<td>-1.000000</td>
</tr>
<tr>
<td>90</td>
<td>1.000000</td>
<td>280</td>
<td>-0.984808</td>
</tr>
<tr>
<td>100</td>
<td>0.984808</td>
<td>290</td>
<td>-0.939693</td>
</tr>
<tr>
<td>110</td>
<td>0.939693</td>
<td>300</td>
<td>-0.866025</td>
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<tr>
<td>120</td>
<td>0.866025</td>
<td>310</td>
<td>-0.766044</td>
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<td>-0.642788</td>
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<tr>
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<td>0.642788</td>
<td>330</td>
<td>-0.500000</td>
</tr>
<tr>
<td>150</td>
<td>0.500000</td>
<td>340</td>
<td>-0.342020</td>
</tr>
<tr>
<td>160</td>
<td>0.342020</td>
<td>350</td>
<td>-0.173648</td>
</tr>
<tr>
<td>170</td>
<td>0.173648</td>
<td>360</td>
<td>-0.000000</td>
</tr>
</tbody>
</table>
C Syntax: Variable Declarations

• Similar to Java, but with a few minor but important differences
• *All* variable declarations must appear before they are used (e.g., at the beginning of the block)
• A variable may be initialized in its declaration; if not, it holds garbage!
• 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, more later*
• Within a function, remarkably close to Java constructs (shows Java’s legacy) in terms of control flow
  – if-else
    • if (expression) statement
    • if (expression) statement1 else statement2
  – 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
C Syntax: True or False

• What evaluates to FALSE in C?
  – 0 (integer)
  – NULL (a special kind of pointer: more on this later)
  – *No explicit Boolean type*

• 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: ., ->
- conditional evaluation: ? :
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• News/Technology Break
• Pointers
• And in Conclusion, …
In the News

• Microsoft HoloLens
• Announced with Windows 10
• Virtual Reality headset
• Contains CPU and GPU, plus a holographic processing unit, or HPU!
Break
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• 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
  – Do you think they 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 *x;`
  – Tells compiler that variable x is address of an int

• `x = &y;`
  – Tells compiler to assign address of y to x
  – & called the “address operator” in this context

• `z = *x;`
  – Tells compiler to assign value at address in x to z
  – * called the “dereference operator” in this context
Creating and Using Pointers

• How to create a pointer:
  & operator: get address of a variable

```c
int *p, x;
p ? ? x ?

x = 3;
p ? ? x 3

p = &x;
p ? x 3
```

Note the “*” gets used 2 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

```c
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 =

\[ \text{p} \quad \text{x} \quad 3 \]

\[ \text{*p} = 5 \; ; \quad \text{p} \quad \text{x} \quad 5 \]
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

```java
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?

```c
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!
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?

```c
void f()
{
    int *ptr;
    *ptr = 5;
}
```
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
  – 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 25,000 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
Agenda

• Compile vs. Interpret
• C vs. Java vs. Python
• Administrivia
• Quick Start Introduction to C
• News/Technology Break
• Pointers

• And in Conclusion, ...
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- All data is in memory
  - Each memory location has an address to use to refer to it and a value stored in it
- Pointer is a C version (abstraction) of a data address
  - * “follows” a pointer to its value
  - & gets the address of a value
  - Arrays and strings are implemented as variations on pointers
- C is an efficient language, but leaves safety to the programmer
  - Variables not automatically initialized
  - Use pointers with care: they are a common source of bugs in programs