C, Pointers, Arrays, Strings

Introduction to Computer Systems, Fall 2022

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Sofia Mouchtaris

How is/was your Halloween?

Logistics

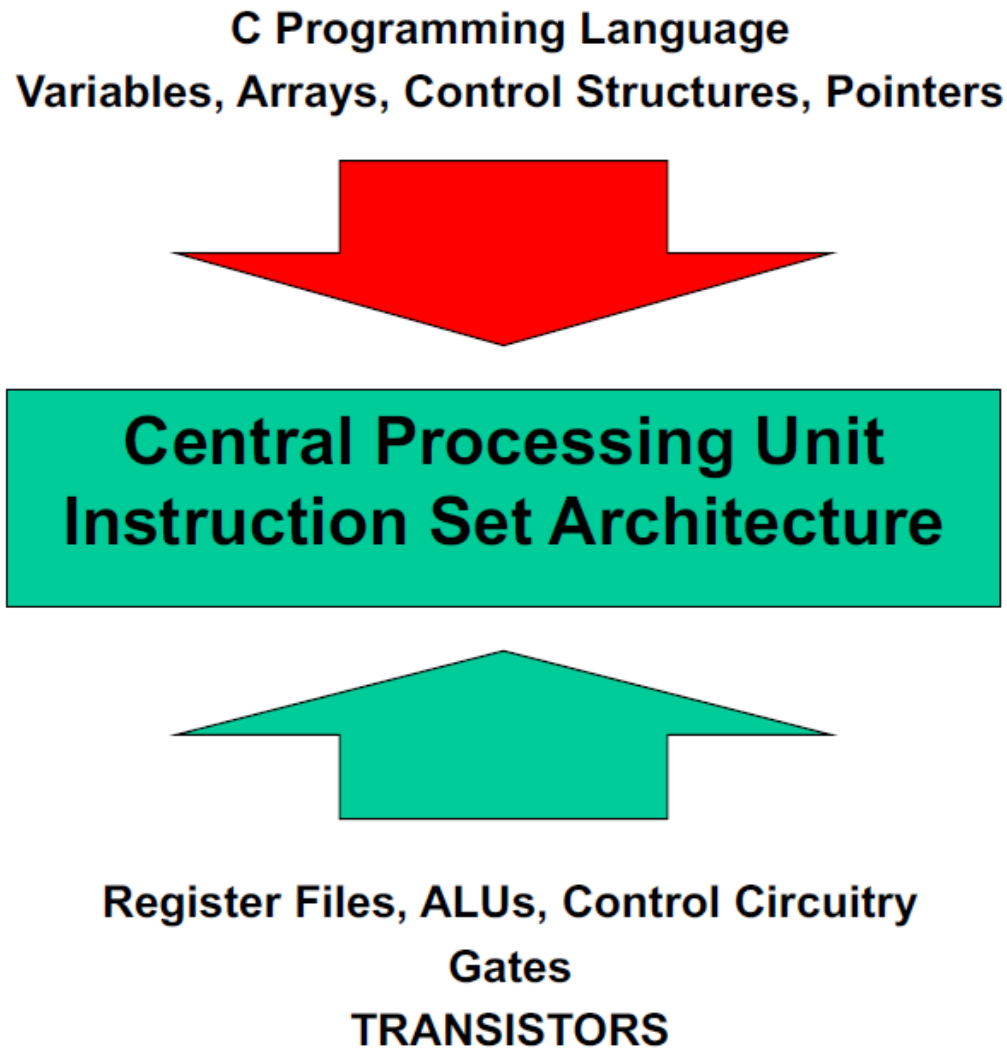
- Check-in06 Due Wednesday 11/2 @ 4:59 pm
- HW06 (Video Game) Due Friday 11/4 @ 11:59 pm
  - Should have everything you need after this lecture
- Midsemester Survey Due Wednesday 11/9 @ 11:59 pm
- HW03 Regrade Requests are open
  - Close at 11:59 pm Friday 11/4

Lecture Outline

- **Intro to C**
- Pointers
- Arrays
- Strings
- Formatted I/O
  - printf & scanf

CIS 2400

- First half of the course is more hardware focused
- Second Half is from a more software / programming perspective
- Later, we will connect these two halves



Brief C History

- The history of C is closely tied to UNIX
  - UNIX is an OS family/design, C is a programming language
  - C was developed alongside UNIX for writing various UNIX utilities and UNIX was eventually re-written in C. This made UNIX one of the first Operating Systems not written in just assembly
  - C allows users to have direct control over memory and expects most users to have knowledge of the underlying architecture
  - Unix and C are extremely influential.
    - Part of this is due to Bell Labs (where C and UNIX were made) not being allowed to copyright it. C and UNIX were "Open Source"
    - Most OS's are "Unix-like" (Android OS, Chrome OS, macOS, iOS, Linux)
    - Linux is sort of the "successor" of UNIX

C Language family

- Many languages adopted similar syntax to C due to it's success. (curly braces, function definitions, if/while/for syntax, variable declarations etc.)
- Examples
  - C (1969)
  - C++ (1979)
  - Objective-C (1986)
  - Perl (1988)
  - Java (1991)
  - Javascript (1995)
  - Rust (2010)
  - …

This means Java code can look very similar to C code. A lot of C code is readable if you are comfortable with Java

First C program: Hello World

Similar to import statements. Allows us to use the std I/O and std library modules of C

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

int main() {
  printf("Hello World!\n");
  return EXIT_SUCCESS;
}
```

Still have a main() function to indicate where the program starts execution.

Function is wrapped in curly braces

Return statements

Double quotes to indicate a string literal. parenthesis to call a function

Second C program: sum evens

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

int sum_evens(int n) {
  int sum = 0;
  for (int i = 0; i < n; i++) {
    if (i % 2 == 0) {
      sum += i;
    }
  }
  return sum;
}

int main() {
  int sum = sum_evens(5);
  printf("sum: %d\n", sum);
  return EXIT_SUCCESS;
}
```

Function declarations & parameters

Variables local to the function

For loops & if statements look similar

Print statements are different to format output. This replaces %d with the value of sum, more later in lecture

Another Similarity: Scope

- Variables declared inside of a function are local to that function and are not visible outside of that scope.

- Some older C compilers, **like lcc**, are picky about how you initialize variables. Lcc won't let you initialize variable in a for loop declaration (`for(int i = 0; …)`. Newer c compilers like clang and gcc do not require this.

- Variables can also be declared outside of a function – these variables typically have global scope but there are some subtleties

C vs Java Similarities Overview

- C and Java are very similar syntactically

- Similarities:
  - Control Structures (if/else/for/while/…)
  - Variables and data types (int/char/float/double/…)
  - Arrays and strings exist in both
    (but are also different implementation wise)
  - Statements & Expressions
    x = (y + z) / 2
  - Proper functions

C vs Java

- C and Java are Syntactically Similar, but …
  - **do not assume everything in C is like Java**
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- From my experience, a common source for making mistakes in C is forgetting that things are not like Java

C vs Java: Differences

- C is functionally very different than Java

- Some differences:
  - C doesn't default initialize anything
  - C doesn't have objects
  - C compiles down to machine code
  - C runs really fast
  - C doesn't check much in terms of safety, no nice error messages like Java has
  - C is "just above" assembly in terms of abstraction
  - C allows for direct memory access

C vs Java: Motivations

- Java aims to shield the programmer from the details of machine, including memory management
  - Garbage Collection
  - Default Initialization

- C expects you to be intimately familiar with how the machine works. Allows you to manipulate machine state directly.
  - Directly access memory locations
  - Store and manipulate addresses
  - Allocate and deallocate resources

Today's topic, extremely important in C

Wednesday's topic

Lecture Outline

- Intro to C
- **Pointers**
- Arrays
- Strings
- Formatted I/O
  - printf & scanf

Pointers

POINTERS ARE EXTREMELY IMPORTANT IN C

- Variables that store addresses
  - It stores the address to somewhere in memory
  - Must specify a type so the data at that address can be interpreted

- Generic definition: `type* name;` or `type *name;` (equivalent)
  - Example: `int *ptr;`
    - Declares a variable that can contain an address
    - Trying to access that data at that address will treat the data there as an int

Pointer Operators

- *Dereference* a pointer using the unary * operator
  - Access the memory referred to by a pointer
  - Can be used to read or write the memory at the address
  - Example:

```
int *ptr = ...; // Assume initialized
int a = *ptr; // read the value
*ptr = a + 2; // write the value
```

- Get the address of a variable with &
  - `&foo` gets the address of foo in memory
  - Example:

```
int a = 240;
int *ptr = &a;
*ptr = 2; // 'a' now holds 2
```

Pointer Example

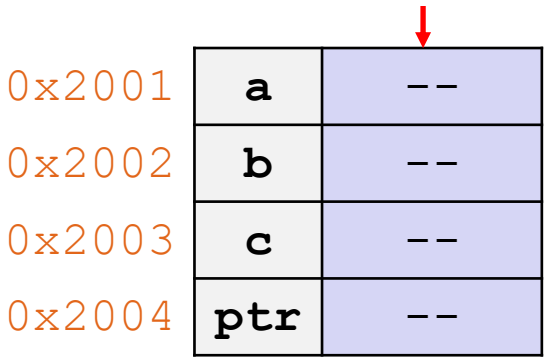
```
int main(int argc, char** argv) {
  int a, b, c;
  int* ptr;   // ptr is a pointer to an int

  a = 5;
  b = 3;
  ptr = &a;

  *ptr = 7;
  c = a + b;

  return 0;
}
```

Initial values are garbage



Assuming that integers and pointers each fit into a single memory location

Pointer Example

```
int main(int argc, char** argv) {
  int a, b, c;
  int* ptr;   // ptr is a pointer to an int

  a = 5;
  b = 3;
  ptr = &a;

  *ptr = 7;
  c = a + b;

  return 0;
}
```

0x2001	a	5
0x2002	b	3
0x2003	c	--
0x2004	ptr	--

Assuming that integers and pointers each fit into a single memory location

Pointer Example

```
int main(int argc, char** argv) {
  int a, b, c;
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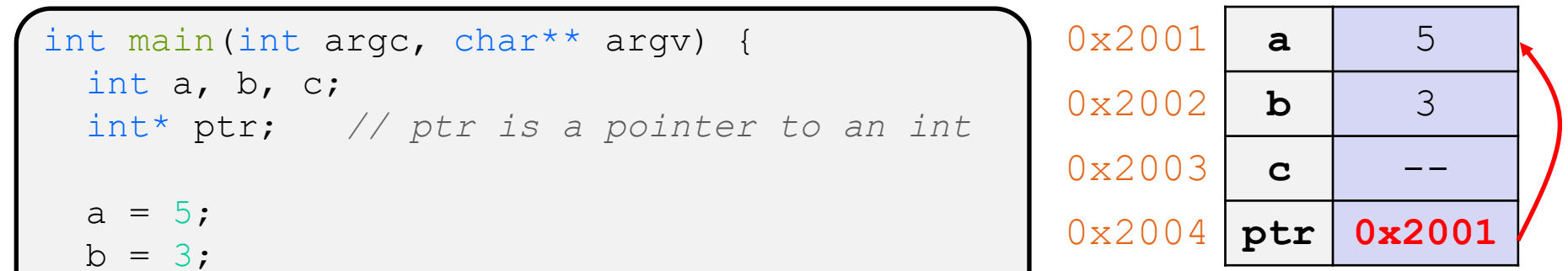

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Pointer Example

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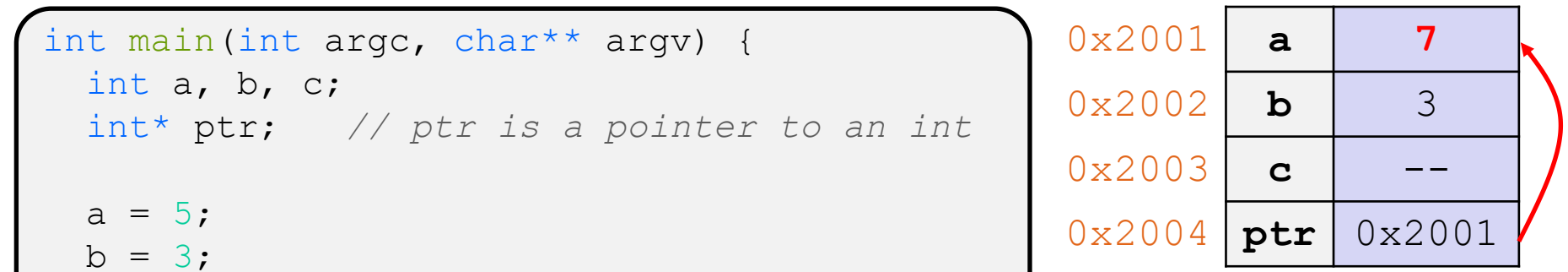
```



Assuming that integers and pointers each fit into a single memory location

Pointer Example

```
int main(int argc, char** argv) {
  int a, b, c;
  int* ptr;    // ptr is a pointer to an int

  a = 5;
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  ptr = &a;

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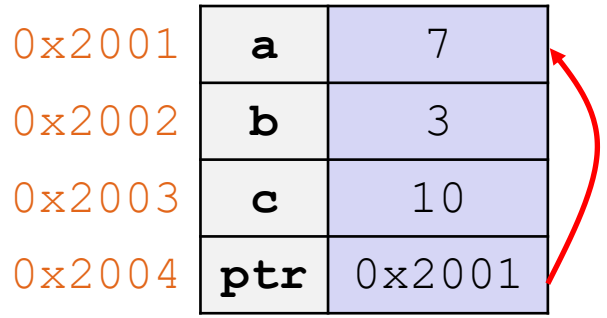
```



Assuming that integers and pointers each fit into a single memory location

Output Parameters

- Pointers can be used to "return" more than one value from a function

```
int solve_quadratic(double a, double b, double c,
                    double* soln1, double* soln2){
  double d = b*b - 4 * a * c;
  if (d >= 0) {
    *soln1 = (-b + sqrt(d)) / (2*a);
    *soln2 = (-b - sqrt(d)) / (2*a);
    return 1;
  } else {
    return 0;
  }
}

int main(int argc, char** argv) {
  double soln1, soln2; // populated by function call
  solve_quadratic(2.0, 4.0, 0.0, &soln1, &soln2);
  // ...
}
```

Red arrow indicates the NEXT line to execute

Output Parameters

- Pointers can be used to "return" more than one value from a function

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int solve_quadratic(double a, double b, double c,
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  // ...
}
```

main

soln1	?
soln2	?

Red arrow indicates the NEXT line to execute

Output Parameters

- Pointers can be used to "return" more than one value from a function

```
int solve_quadratic(double a, double b, double c,
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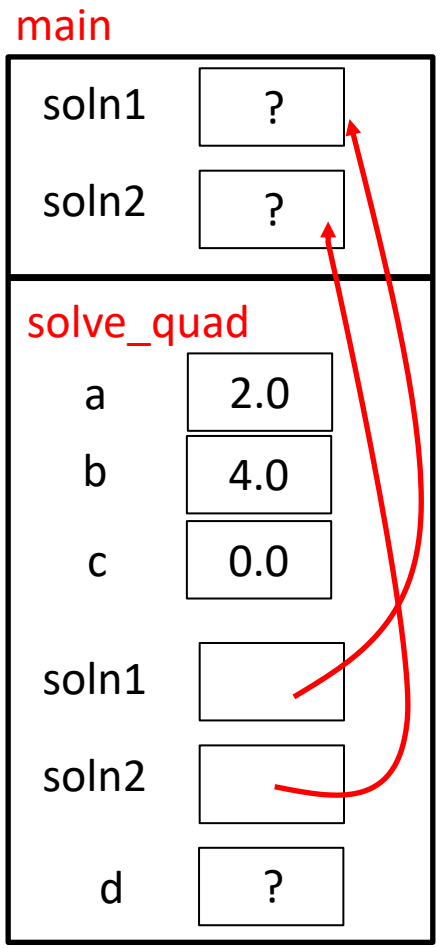

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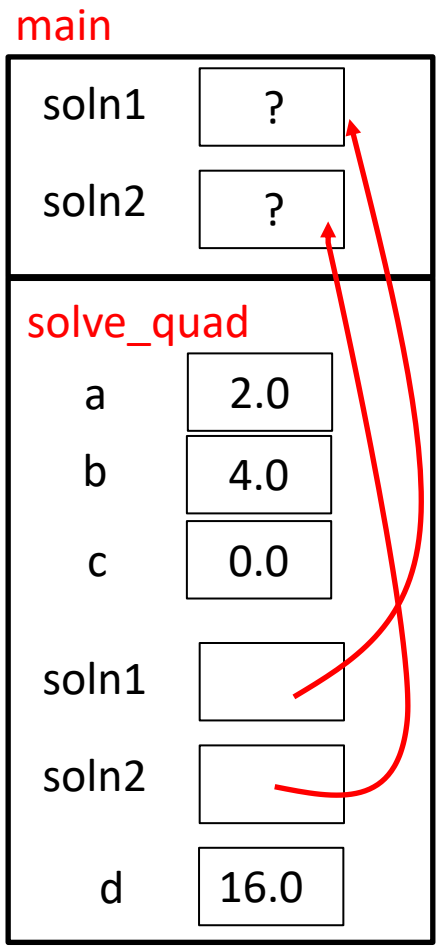
  // ...
}
```



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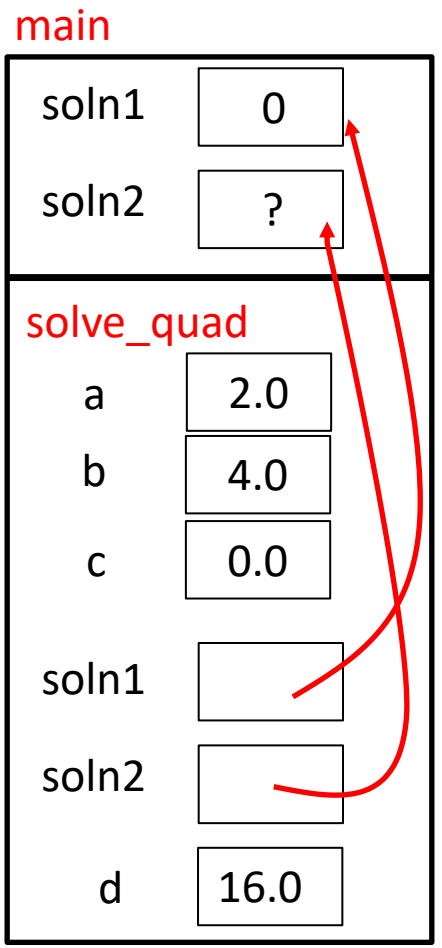

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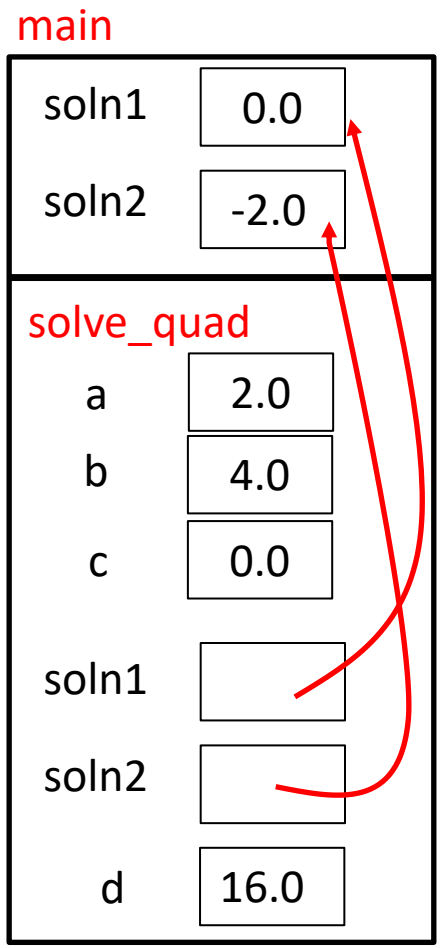

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int main(int argc, char** argv) {
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  solve_quadratic(2.0, 4.0, 0.0, &soln1, &soln2);
  // ...
}
```

main

soln1	0.0
soln2	-2.0

Poll Everywhere

pollev.com/tqm

- What is printed in this program?

```
void foo(int *x, int *y, int *z) {
  x = y;
  *x = *z;
  *z = 37;
}

int main() {
  int a = 5, b = 22, c = 42;
  foo(&a, &b, &c);
  printf("%d, %d, %d\n", a, b, c);
  return EXIT_SUCCESS;
}
```

A. 5, 22, 42

B. 42, 42, 37

C. 42, 22, 37

D. 5, 42, 37

E. I'm not sure

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pollev.com/tqm

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  foo(&a, &b, &c);
  printf("%d, %d, %d\n", a, b, c);
  return EXIT_SUCCESS;
}
```

Red arrow indicates the NEXT line to execute

main

a	5	b	22	c	42

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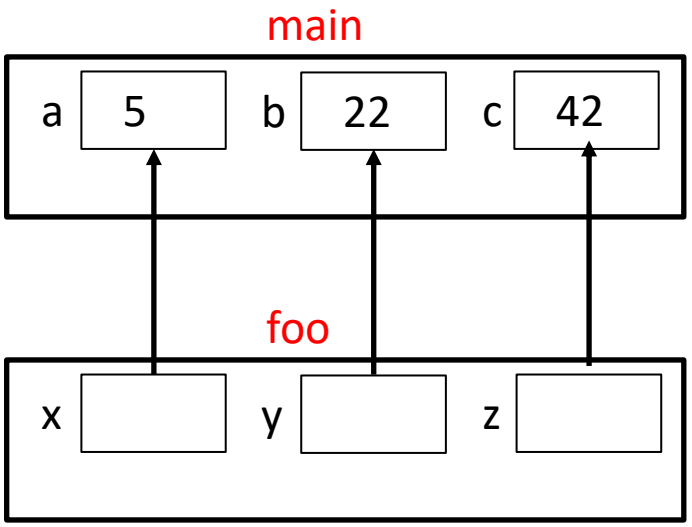

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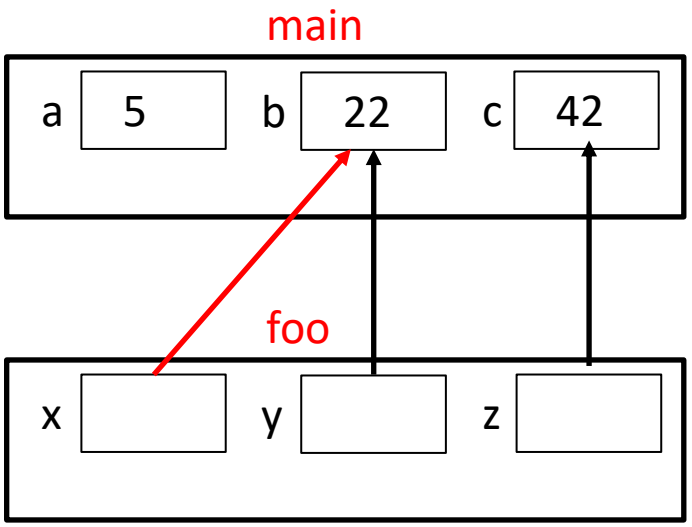

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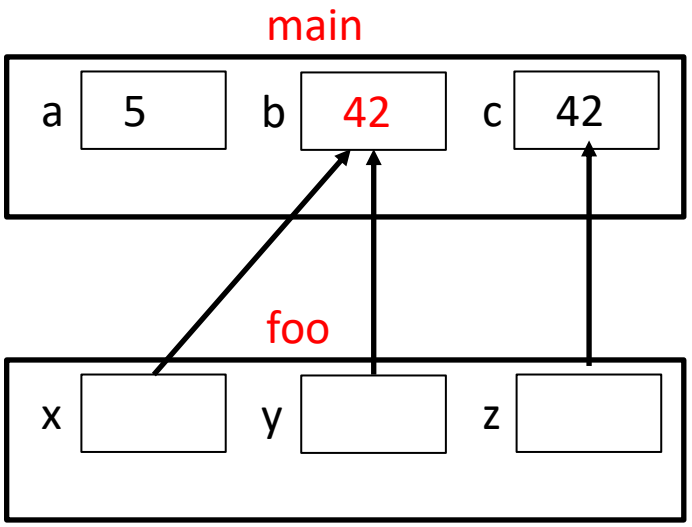

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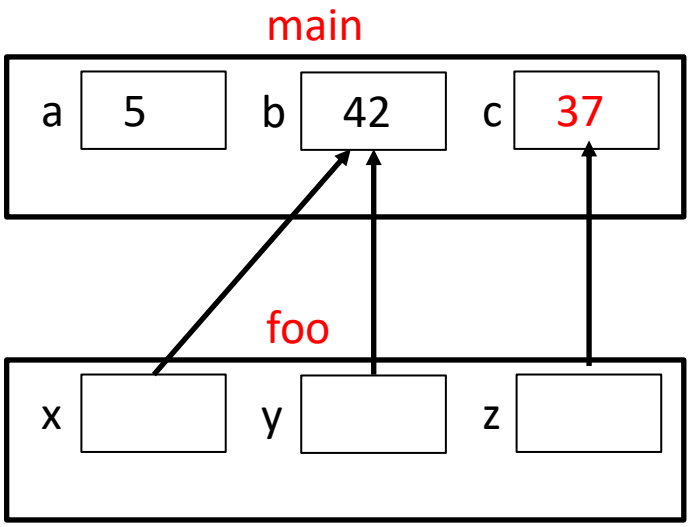

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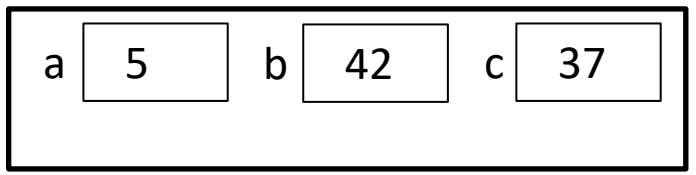

D. 5, 42, 37

Lecture Outline

- Intro to C
- Pointers
- **Arrays**
- Strings
- Formatted I/O
  - printf & scanf

Arrays

- Definition: `type name[size]`
  - Allocates `size*sizeof(type)` bytes of *contiguous* memory
  - Normal usage is a compile-time constant for `size` (*e.g.* `int scores[175];`)
  - Initially, array values are "garbage"

- Size of an array
  - **Not stored anywhere** – array does not know its own size!
  - The programmer will have to store the length in another variable or hard-code it in

Using Arrays

Optional when initializing

- Initialization: `type name[size] = {val0,…,valN};`
  - `{}` initialization can *only* be used at time of definition
  - If no size supplied, infers from length of array initializer

- Array name used as identifier for "collection of data"
  - `name[index]` specifies an element of the array and can be used as an assignment target or as a value in an expression
  - Array name (by itself) produces the address of the start of the array
    - Cannot be assigned to / changed

```
int primes[6] = {2, 3, 5, 6, 11, 13};
primes[3] = 7;
primes[100] = 0;  // memory smash!
```

No IndexOutOfBounds
Hope for segfault

Multi-dimensional Arrays

- Generic 2D format:

```
type name[rows][cols];
```

  - Still allocates a single, contiguous chunk of memory
  - C is *row-major*
  - Can access elements with multiple indices
    - `A[0][1] = 7;`
    - `my_int = A[1][2];`

  - The entries in this array are stored in memory in row major order as follows:
    - A[0][0], A[0][1], A[0][2], A[1][0], A[1][1], A[1][2]

  - 2-D arrays normally only useful if size known in advance. Otherwise use dynamically-allocated data and pointers (later)

Arrays as Parameters

- It's tricky to use arrays as parameters
  - What happens when you use an array name as an argument?
  - Arrays do not know their own size

Passes in address of start of array

```
int sumAll(int a[]) {
  int i, sum = 0;
  for (i = 0; i < ...???
}
```

Equivalent

```
int sumAll(int* a) {
  int i, sum = 0;
  for (i = 0; i < ...???
}
```

- Note: Array syntax works on pointers
  - E.g. `ptr[3] = ...;`

Solution: Pass Size as Parameter

```
int sumAll(int* a, int size) {
  int i, sum = 0;
  for (i = 0; i < size; i++) {
    sum += a[i];
  }
  return sum;
}
```

- Standard idiom in C programs

Pointer Arithmetic

- In LC4, we did arithmetic on addresses to iterate through arrays. We can do the same in C

```
double my_array[10]; // create an array of 10 doubles
double *ptr = my_array; // ptr has the address of the
                        // first element
ptr = ptr + 1; // increment ptr to point to
               // the next elemetnt
ptr[2] = 3.14; // equivalent to *(ptr + 2) = 3.14
```

- Pointers are *typed*
  - Tells the compiler the size of the data you are pointing to
- Pointer arithmetic is scaled by `sizeof(*ptr)`
  - Sometimes a single array element can span multiple addresses
  - Works nicely for arrays

Size (number of bytes) of thing being pointed at

Pointer Square Brackets

- We can use the "array syntax" on pointers

```
ptr[3] = ...;
```

- This syntax is the same as

```
*(ptr + 3) = ...;
```

- Fun Fact, these are all the same in C:

```
ptr[3] = ...;
```

```
*(ptr + 3) = ...;
```

```
*(3 + ptr) = ...;
```

```
3[ptr] = ...;
```

Poll Everywhere

pollev.com/tqm

- What are the final values of nums?

```
int nums[4] = {2, 3, 5, 6};
int *ptr = nums;

ptr[1] = 0;
ptr++;
ptr[0] = 38;
ptr++;
ptr[1] = nums[0];
```

A. 2, 3, 5, 6

B. 38, 38, 5, 6

C. 2, 38, 5, 2

D. 2, 38, 5, 5

E. I'm not sure

Poll Everywhere

pollev.com/tqm

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Red arrow indicates the NEXT line to execute

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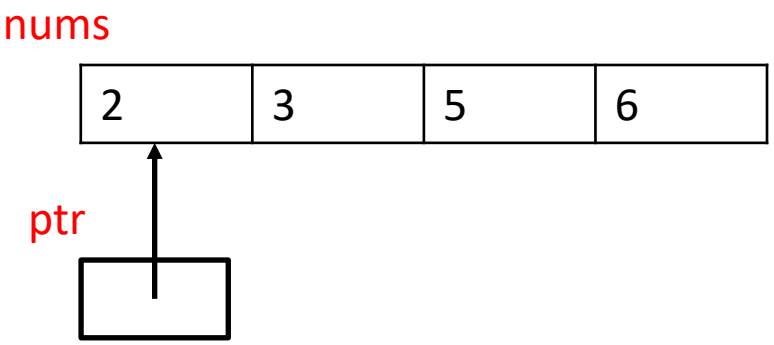

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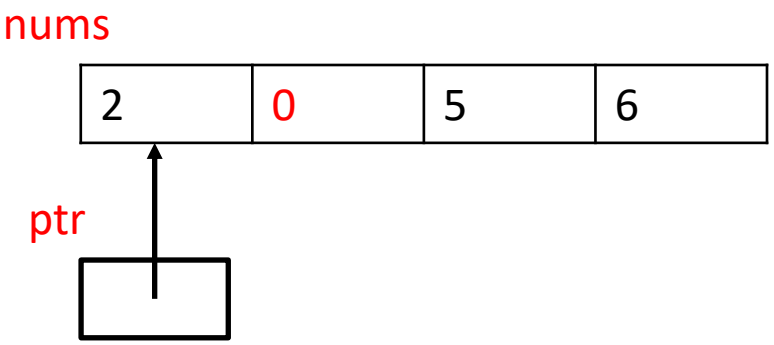

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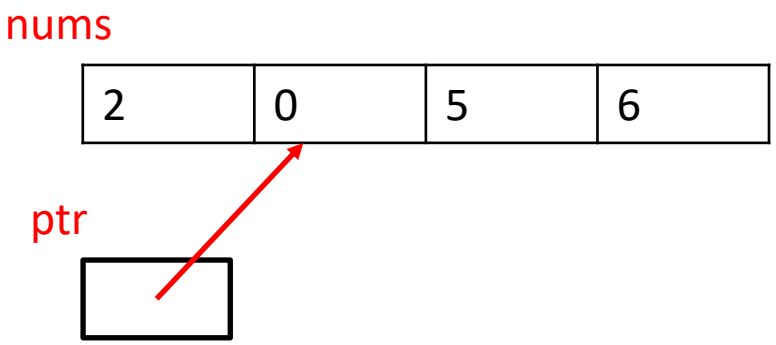

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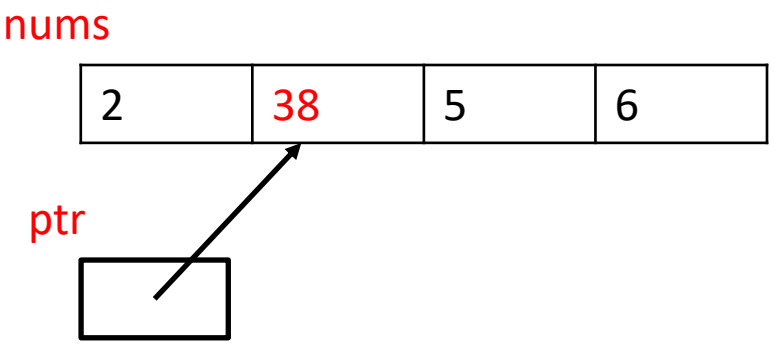

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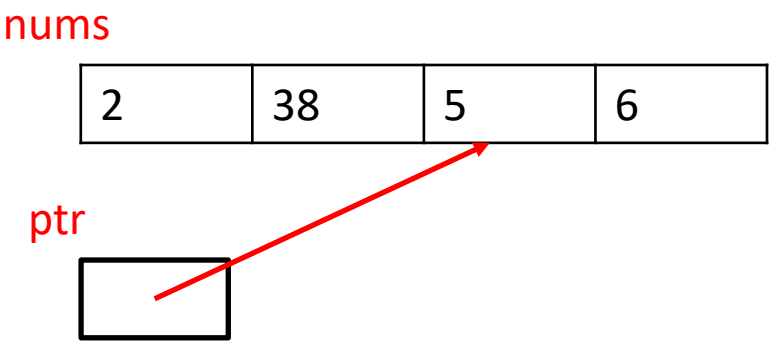

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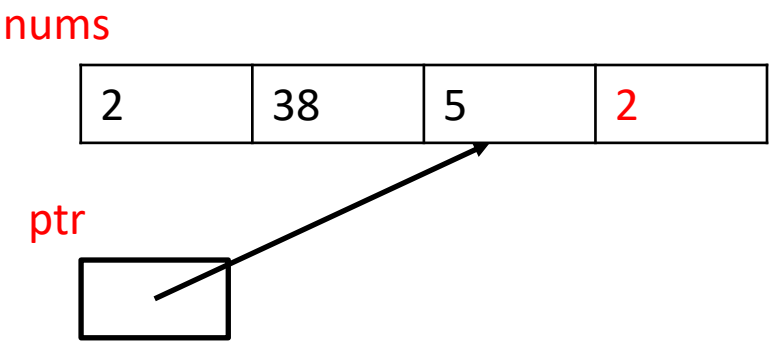

C. 2, 38, 5, 2

Lecture Outline

- Intro to C
- Pointers
- Arrays
- **Strings**
- Formatted I/O
  - printf & scanf

Strings without Objects

- Strings are central to C, very important for I/O
- In C, we don't have Objects but we need strings
- If a string is just a sequence of characters, we can have use array of characters as a string

- Example:

```
char str_arr[] = "Hello World!";
char *str_ptr = "Hello World!";
```

Null Termination

DO NOT FORGET THIS. THIS IS THE CAUSE OF MANY BUGS

- Arrays don't have a length, but we **mark the end of a string with the null terminator character.**
  - The null terminator has value **`0x00`** or **`'\0'`**
  - Well formed strings ***MUST*** be null terminated

- Example: `char str[] = "Hello";`
  - Takes up 6 characters, 5 for "Hello" and 1 for the null terminator

address	0x2000	0x2001	0x2002	0x2003	0x2004	0x2005
value	'H'	'e'	'l'	'l'	'o'	'\0'

String library Functions

- Many Library functions are provided for processing strings
- Most are found in the header file `<string.h>`
  - `strlen(char* str)` – returns the number of characters in the string **excluding** the null terminator.
  - `strcpy(char *s1, char *s2)` - copies the string in s2 into s1. Assumes that s1 has enough space to store the copy.
  - `strcmp(char *s1, char *s2)` – compares two strings and returns < 0 if s1 < s2, > 0 if s1 > s2 and 0 if they are the same string

More Library functions

- There are also other useful functions defined in <ctypes.h>
  - `isalnum(int c)` returns non-zero if c is an alphanumeric character
  - `isspace(int c)` returns non-zero if c is a space character
  - `tolower(int c)` if c is an uppercase letter, returns the lowercase counterpart. If c is not an uppercase letter, c is returned.
- There are more functions that exist that you may find useful.

C Standard Library

- Not as big as Java standard libraries but has many useful functions.
- Don't reinvent something that already exists

- Examples:
  - `stdio.h` useful for I/O, printing, reading input, etc.
  - `ctypes.h` functions for converting and testing char's
  - `math.h` mathematical functions (pow, sqrt, etc.)
  - `stdlib.h` general purpose functions
  - `string.h` functions for using strings

Lecture Outline

- Intro to C
- Pointers
- Arrays
- Strings
- **Formatted I/O**
  - **printf & scanf**

Formatted I/O

- Many programs need to convert between the bit values a computer manipulates and something a human can read
  - Example: converting between the binary encoding for an int into readable string

- Often done by the following functions or variants of them
  - `printf`
    - Prints a formatted string to the console
  - `scanf`
    - Reads a formatted string from the console

Formatted I/O

- Remember that **EVERYTHING** is stored as bits.
- Do not confuse what you read on the terminal with the actual representation of data in memory
- Converting bits to be human readable is a big part of formatted output

Formatting Example

- Do you recognize the following 32 bit single precision value?:
  - 01000000010010010000111111011011
- Let's run a number to string procedure to convert it into sequence of ASCII characters
  - 0x33, 0x2E, 0x31, 0x34, 0x31, 0x35, 0x39
- What about now?
  - 3.14159

Another Formatting Example

- Recognize the following 16 bit 2C integer value?
  - 1111001001110001

- Here are the ASCII characters in its decimal representation
  - 0x2D, 0x33, 0x34, 0x37, 0x30

- Here is what it would look like printed out.
  - -3470

Formatting Strings

- To specify how bits should be interpreted for printing and scanning. We must use a **format string**
- A format string is just a string with formatting specifiers:
  - `%d` – a decimal integer value
  - `%x` – a hexadecimal value
  - `%s` – a string
  - `%f` – a floating point value

- For `printf`- these formatting subsequences may be accompanied by field width and precision specifiers
  - `%12.3f` – prints a floating-point number using 12 characters with three digits after the decimal place

Special Characters

- There are also special characters that can show up in any string which have special meaning
  - `'\n'` : newline character
  - `'\t'` : tab character

Formatting Printing Example

```c
int main(int argc, char** argv) {
  int a = 27;
  double b = 3.14159;

  // simple string output with a newline at the end
  printf("Hello World\n");

  // formatted output that will perform
  // numerical conversions
  printf("a = %d, b = %7.3f\n", a, b);
}
```

Outputs:

```
Hello World
a = 27, b =   3.142
```

Formatted input

- Just as how we can format output, we can convert strings to binary representation when we read input with `scanf`
  - Example converts "134" to 16 bit integer 0000000010000110

- There are similar functions to `scanf` such as `sscanf`
  - `sscanf` takes a string as input for scanning rather than reading from the terminal

```
int x;
char* to_scan = "value: 240";
sscanf(to_scan, "value: %d", &x); // sets x to 240
```

Input Mismatch

- Input may not always match the expected string, function will parse as many as it can. Function returns the number of arguments successfully decoded

- Examples:

```
int x, y;
char* to_scan = "-108 97";
sscanf(to_scan, "%d %d", &x, &y); // returns 2
```

```
int x, y;
char* to_scan = "203 wtf";
sscanf(to_scan, "%d %d", &x, &y); // returns 1
```

Formatted I/O

Basic Data types – machine representations