Introductions, C refresher

Computer Operating Systems, Spring 2024

Instructor: Travis McGaha

Head TAs: Nate Hoaglund & Seungmin Han

TAs:

Adam Gorka	Haoyun Qin	Kyrie Dowling	Ryoma Harris
Andy Jiang	Jeff Yang	Oliver Hendrych	Shyam Mehta
Charis Gao	Jerry Wang	Maxi Liu	Tom Holland
Daniel Da	Jinghao Zhang	Rohan Verma	Tina Kokoshvili
Emily Shen	Julius Snipes	Ryan Boyle	Zhiyan Lu

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- How are you?

Lecture Outline

- **Introduction & Logistics**
  - **Course Overview**
  - **Assignments & Exams**
  - **Policies**
- C Refresher
  - Memory Layout
  - Demo (make, man pages)
  - Malloc, free, pointers
  - stdin, stdout

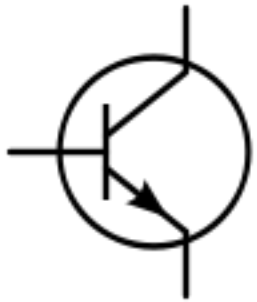
Instructor: Travis McGaha

- UPenn CIS faculty member since August 2021
  - Second Semester with CIS 3800 (and we are trying new stuff)
  - CIS 2400 in 21fa & 22fa
  - CIT 5950 in 22sp & 23sp

- More on my personal website: https://www.cis.upenn.edu/~tqmcgaha/

- Schedule meeting w/ me
- Unofficial office hours right after class
- Official office hours TBD

Course Overview



Course Overview

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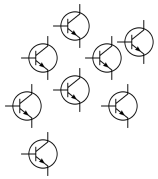

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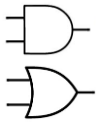

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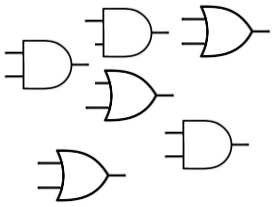

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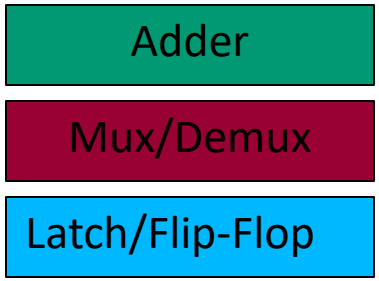

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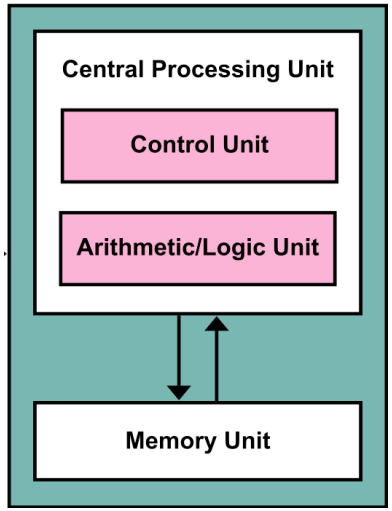

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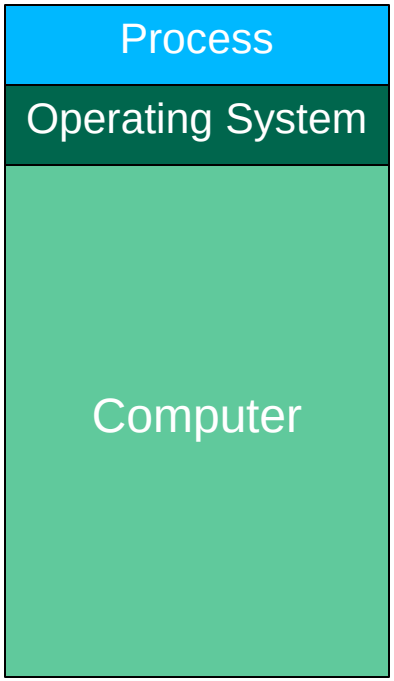

Course Overview

Wittgenstein's Ladder

- "My propositions serve as elucidations in the following way: anyone who understands me eventually recognizes them as nonsensical, when he has used them—as steps—to climb beyond them. (He must, so to speak, throw away the ladder after he has climbed up it.)

  He must transcend these propositions, and then he will see the world aright."
  - Ludwig Wittgenstein (Tractatus Logico-Philosophicus)

“Lies-to-children”

- "The necessarily simplified stories we tell children and students as a foundation for understanding so that eventually they can discover that they are not, in fact, true."
  - Andrew Sawyer (Narrativium and Lies-to-Children: 'Palatable Instruction in 'The Science of Discworld' ‘)

“Lies-to-children”

- "A lie-to-children is a statement that is false, but which nevertheless leads the child's mind towards a more accurate explanation, one that the child will only be able to appreciate if it has been primed with the lie"

  - Terry Pratchett, Ian Stewart & Jack Cohen (The Science of Discworld)

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- What color is the sky?

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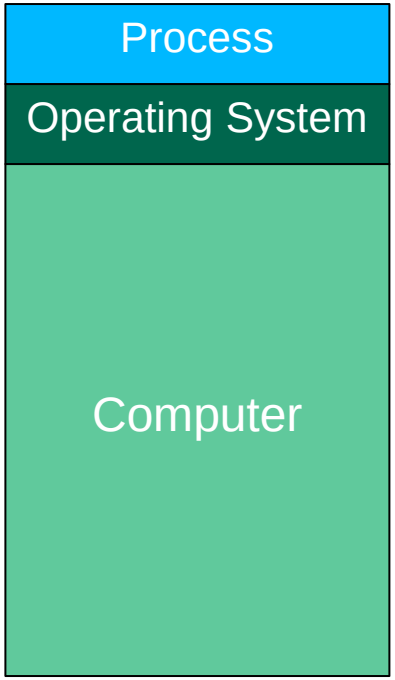
- What color is grass?

We lied to you (but in a good way)

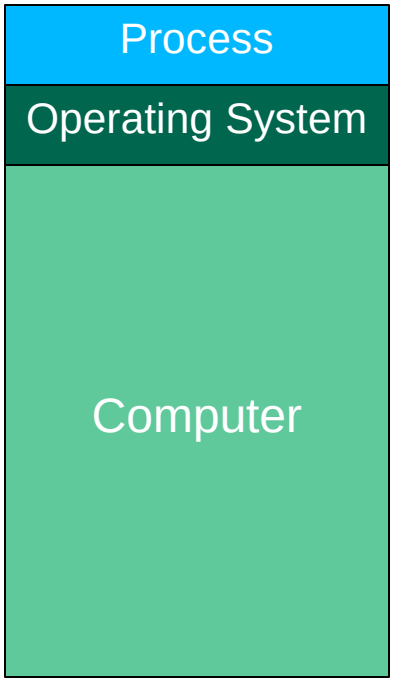
- Is the LC4 model for a computer true? **Eh……. no**
- Is it a useful model? **Yes**



We lied to you (but in a good way)

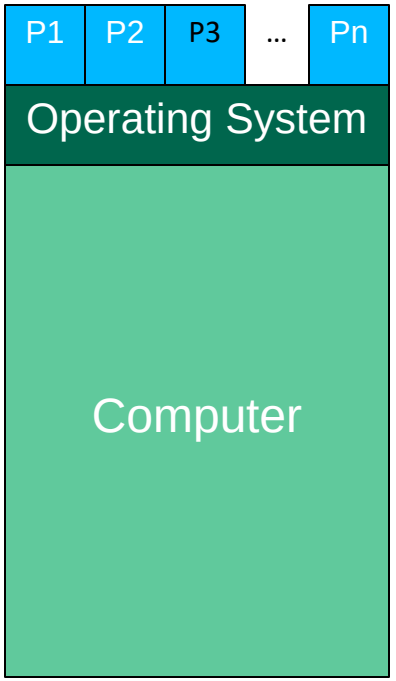
- Is memory one giant array of bytes? **Eh……. no**
- Is this a useful model? **Yes**

Course Overview



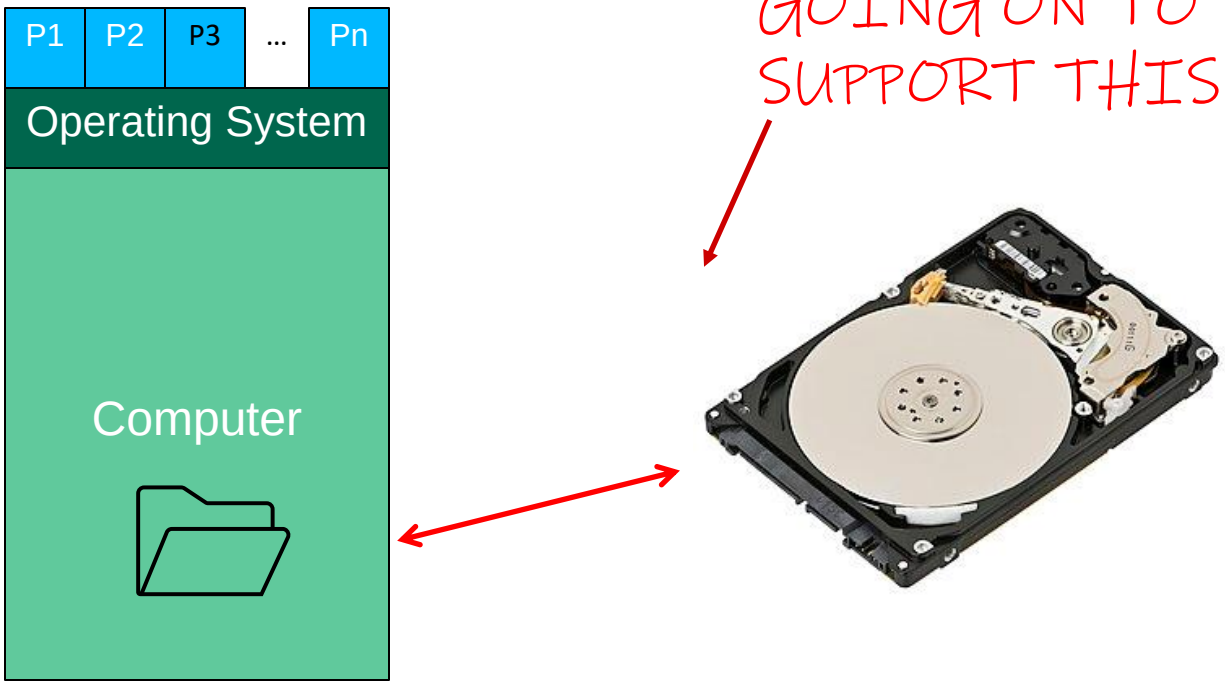
OS does A LOT more than just printing, reading input, video display, and timer

Course Overview



THERE IS A LOT GOING ON TO SUPPORT THIS

Course Overview



I'm going to lie to you (but in a good way)

- "All models are wrong, but some are useful."
  - Same source as below.

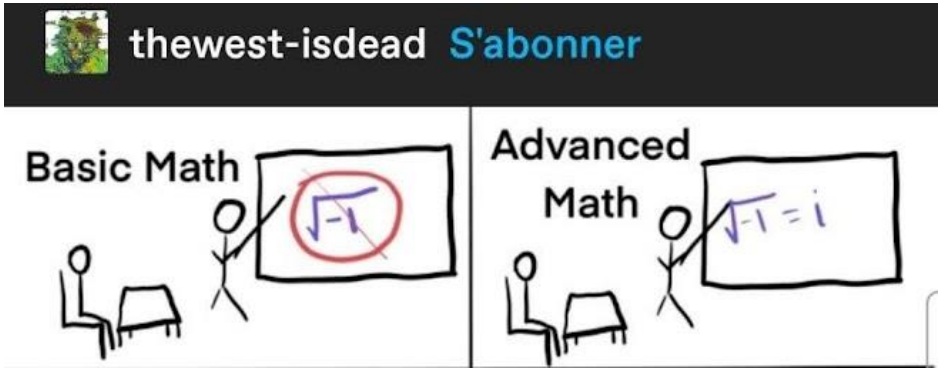
- "If it were necessary for us to understand how every component of our daily lives works in order to function - we simply would not."
  - AnRel (UNHINGED: A Guide to Revolution for Nerds & Skeptics)

- This course will reveal more details, but there is still a ton I am leaving out. Even what I say that is accurate, will likely change in the future.

I'M ALREADY LYING TO YOU

- This idea of a "ladder" and how one just goes up it is a lie. Education is often not linear and often is a tangled web of ideas.
- But it is a good metaphor :)
- I think there is also a good discussion of whether these count as "lies". Is using the word "lie" a lie?

This goes beyond this course



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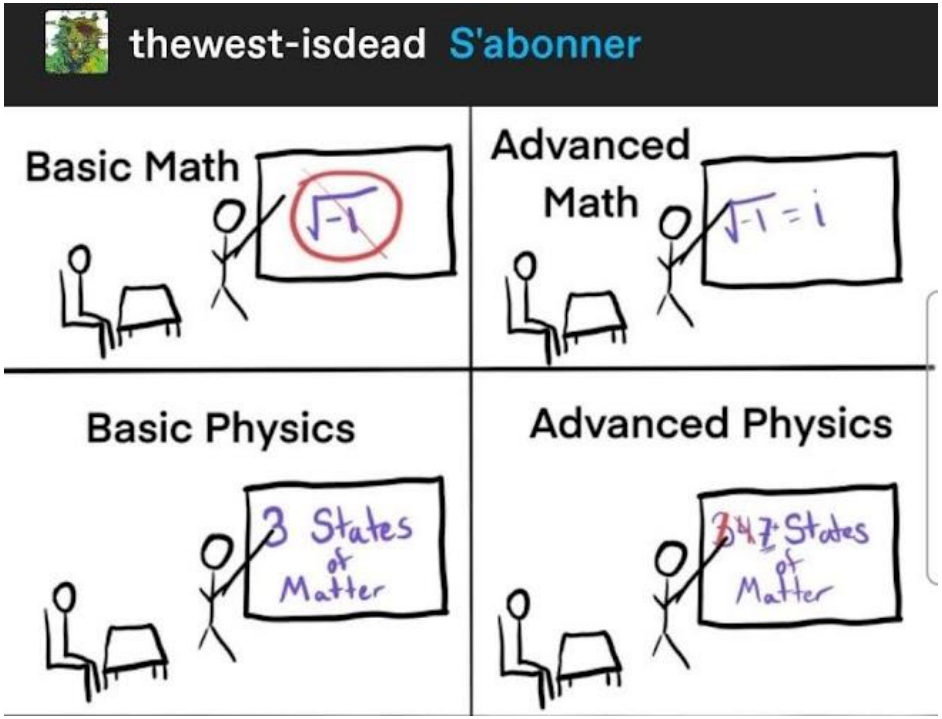

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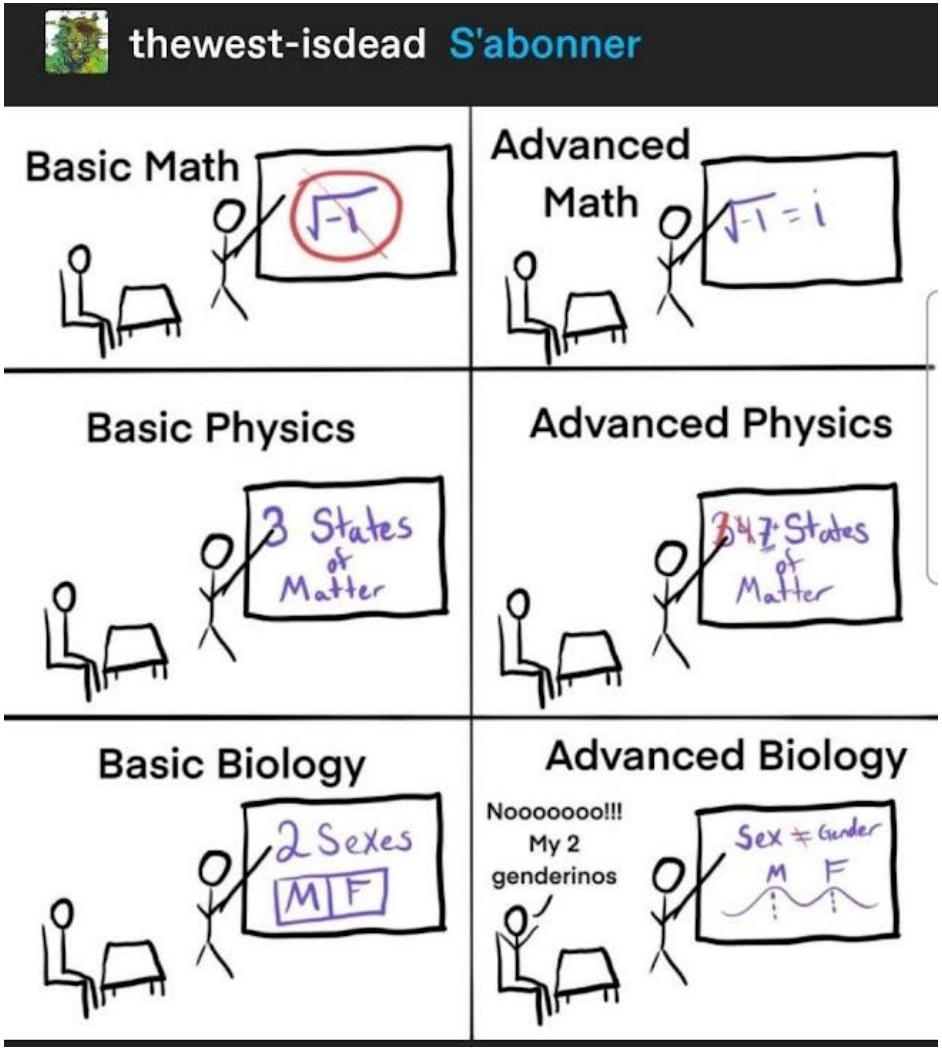

This goes beyond this course

Prerequisites

- Course Prerequisites:
  - CIS 2400
  - Teamwork & Willingness/happy to spend substantial time coding
- What you should be familiar with already:
  - C programming
  - C Memory Model
  - Computer Architecture Model
  - Basic UNIX command line skills
- HW0 is tuned so that it will help refresh you on these.
  - But it still covers new content!
  - Even if you think you know C, get started sooner rather than later.

CIS 3800 Learning Objectives

- To leave the course with a better understanding of:
  - How a computer runs/manages multiple programs
  - How the previous point may affect the code we write
  - How to read documentation
  - Experience writing a massive programming project FROM SCRATCH with others.
  - More comfortable writing C code

- Topics list/schedule can be found on course website
  - Note: These topics may be tweaked

Disclaimer

- This is a digest, **READ THE SYLLABUS**
  - https://www.seas.upenn.edu/~cis3800/current/documents/syllabus

Course Components: Textbook

- Textbook (0)
  - Textbooks recommended in pasts
    - A.S. Tanenbaum. Modern Operating Systems (4th Edition onwards). Prentice-Hall.
    - W. Richard Stevens and Stephen A. Rago. Advanced Programming in the UNIX Environment (2/e or 3/e). Addison-Wesley Professional.
  - Systems for all: https://diveintosystems.org/book/
    - Free online textbook, pretty well written
  - Linux Man pages:
    - https://linux.die.net/man/
    - https://www.man7.org/linux/man-pages/
    - The **`man`** command in the terminal
    - DEMO:
      - name a C function
      - tcsetpgrp

Course Components: Part 1

- Lectures (~26)
  - Introduces concepts, slides & recordings available on canvas
  - In lecture polling. Polls are not counted towards credit
- Pre-recorded videos (many)
  - Entirely optional
  - Goes over lecture material or demonstrates something for projects
- Check-ins "Quizzes" (~10)
  - Unlimited attempt low-stake quizzes on canvas to make sure you are caught up with material
  - Lowest two are dropped
- Exams (2)
  - Two in-person exams, two pages of notes allowed
  - Details TBD

Programming Facilities

- Docker
  - Same environment as the autograder
  - Instructions for setup to be posted soon
- Speclab cluster, as a fallback incase Docker does not work
  - Instructions on course website
  - To see status: https://www.seas.upenn.edu/checklab/?lab=speclab
- **DO NOT use Eniac machines to develop projects for this class!**

Project 0

- Project 0
  - Parsing a C string for into a “command” so that it is easier for us to use that data in future projects.
  - Idea is to help you get comfortable with coding in C
    - C strings
    - Structs
    - Pointers
    - Allocation
  - New project! We tried to calibrate the difficulty correctly
  - Done Individually
  - **Will be posted soon!!**

Project 1 & 2

- Project 1
  - Unix “Shell” – command interpreter (e.g. sh, bash, etc)
  - Excellent way to learn about how system calls are supported and used.
  - Done individually
  - Code review

- Project 2
  - Unix “Shell” – the real deal
  - Redirection, pipelines, background/foreground processing, job control
  - Groups of two.

PennOS

- Best way to learn about an operating systems is to build one.
- Build all the main features of an OS (in emulation)
- Will either be done in Groups of 4 or 2 (because we haven't decided yet, we will announce closer to the midterm.)
- By the end of the project, you will:
  - Learn about how different subsystems in Unix interact with each other
  - Learn about priority scheduling, file systems, user shell interactions
  - Become a really good and confident systems programmer

PennOS

- There is a paper on this: http://netdb.cis.upenn.edu/papers/pennos.pdf at an ACM OS journal.

- **Group evaluation done by the end of semester.**
  - **Team members with lower than 15% contribution to the group will get their course grade downgraded.**
  - **Team members who do almost nothing will get a failing grade in the course**

HW Policies

- **Students who did not contribute to group projects will get F grade regardless of overall score.**

- Late Policy
  - You are given 5 late tokens.
  - Tokens are counted per student and can only be used on some assignments.
  - Two tokens used at max per assignment
  - Each token grants 48 hours of extra time
  - If there are extenuating circumstances, please let me know. I can be lenient, we can work something out

Collaboration Policy Violation

- You will be caught:
  - Careful grading of all written homeworks by teaching staff
  - Measure of Software Similarity (MOSS): http://theory.stanford.edu/~aiken/moss/
  - Successfully used in several classes at Penn

- Zero on the assignment, zero for class participation (3%). F grade if caught twice.
  - First-time offenders will be reported to Office of Student Conduct with no exceptions. Possible suspension from school
  - Your friend from last semester who gave the code will have their grade retrospectively downgraded.

Collaboration Policy Violation

- Generative AI
  - I am skeptical of its usefulness for your learning and for your success in the course
  - Some articles on the topic:
    - https://www.aisnakeoil.com/p/chatgpt-is-a-bullshit-generator-but
    - https://www.aisnakeoil.com/p/gpt-4-and-professional-benchmarks
  - Not banned, but not recommended. Use your best judgement.
- You will not help your overall grade and happiness:
  - Quizzed individually during project demo, exams on project in finals
  - If you can't explain your code in OH, we can turn you away.
    - This is different than being confused on a bug or with C, this is ok
  - Personal lifelong satisfaction from completing PennOS

Course Grading

- Breakdown:
  - Project 0 penn-parser: (8%)
  - Project 1 penn-shredder: (6%)
  - Project 2 penn-shell: (15%)
  - Project 3 PennOS: (34%)
  - Exams (34%)
    - 17% each (probably)
  - Check-in Quizzes(3%)

- Final Grade Calculations:
  - I would LOVE to give everyone an A+ if it is earned
  - Final grade cut-offs will be decided privately at the end of the Semester. What is used in previous semesters is in the syllabus

Course Infrastructure

- Course Website: www.seas.upenn.edu/~cis3800/24sp/
  - Materials, Schedule, Syllabus …
- Docker or Speclab
  - Coding environment for hw's
- Gradescope
  - Used for HW Submissions
- Poll Everywhere
  - Used for lecture polls
- Ed Discussion
  - Course discussion board

Getting Help

- Ed
  - Announcements will be made through here
  - Ask and answer questions
  - Sign up if you haven't already!
- Office Hours:
  - Can be found on calendar on front page of course website
  - Starts next week for all TAs
- 1-on-1's:
  - Can schedule 1-on-1's with Travis
  - Should attend OH and use Ed when possible, but this is an option for when OH and Ed can't meet your needs

We Care

- I am still figuring things out, but we do care about you and your experience with the course
  - Please reach out to course staff if something comes up and you need help

- PLEASE DO NOT CHEAT OR VIOLATE ACADEMIC INTEGRITY
  - We know that things can be tough, but please reach out if you feel tempted. We want to help
  - Read more on academic integrity in the syllabus

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- Any questions, comments or concerns so far?

Lecture Outline

- Introduction & Logistics
  - Course Overview
  - Assignments & Exams
  - Policies
- **C refresher**
  - **Pointers**
  - Arrays

I Will go through parts of this relatively fast.

Review this on your own

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- Does this C code compile?
  - The format specifiers (e.g. "%d\n") are fine

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

int main(int argc, char* argv[]) {
  int x = 5;
  printf("%d\n", x);
  char* string = get_string();
  printf("%s\n", string);
  return EXIT_SUCCESS;
}

char* get_string() {
  return "Hello, World!";
}
```

Demo: hello_print.c

Poll Everywhere

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  return EXIT_SUCCESS;
}

char* get_string() {
  return "Hello, World!";
}
```

get_string needs to be declared before it is used

You don't have to put all the variables at the top of the function

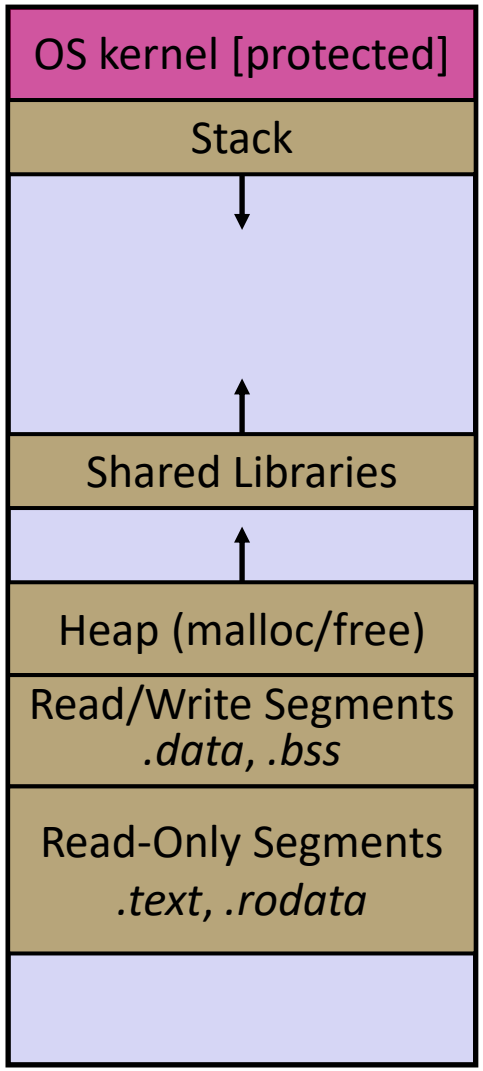
Demo: hello_print.c

Demo: Downloading & Running

- Commands:
  - curl -o 00-code.zip https://www.seas.upenn.edu/~cis3800/24sp/code/00-code.zip
  - unzip 00-code.zip
  - cd 00-code
- To compile:
  - Make
- To run:
  - ./<program name>
  - E.g.
    - ./get_input

Aside: Memory

- Where all data, code, etc are stored for a program
- Broken up into several segments:
  - The stack
  - The heap
  - The kernel
  - Etc.
- Each "unit" of memory has an address



Aside: Memory as a giant array

- In CIS 2400 we introduced memory as a giant array of bytes, with each byte having its own address:

- Our variables live in memory

```
int main(int argc, char* argv[]) {
  char a = 'a';
  char b = 'b';
  return 0;
}
```

0x0	0x1	0x2

…

0x55	0x56	0x57	0x58	0x59	0x5A	0x5B	0x5C	0x5D	0x
		'a'	'b'						

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 = 595;
int *ptr = &a;
*ptr = 2; // 'a' now holds 2
```

Pointers as References

- The exact value stored in a pointer almost never matters, we treat them more like references
- In this class we will never hardcode in an address into a pointer. We will never do something like :

```
int *ptr = 0x7fffff5194;
```

  - Read as: "`ptr` contains the address 0x7fffff5194"
  - *with the exception of NULL
- Instead, we write code that is more often like:

```
int example = 5;
int *ptr = &a;
```

  - Read as: "`ptr` refers to the integer `example`"
  - Or "`ptr` contains the address of the integer `example`"

NULL

- `NULL` is a memory location that is guaranteed to be invalid
  - In C on Linux, `NULL` is `0x0` and an attempt to dereference `NULL` *causes a segmentation fault*
- Useful as an indicator of an uninitialized (or currently unused) pointer or allocation error
  - It's better to cause a segfault than to allow the corruption of memory!

```c
int main(int argc, char** argv) {
  int* p = NULL;
  *p = 1;  // causes a segmentation fault
  return EXIT_SUCCESS;
}
```

Pointer Example

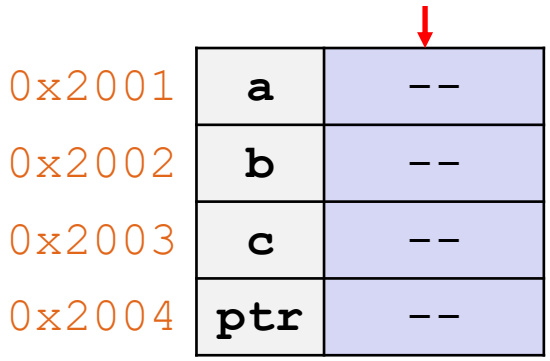
```
int main(int argc, char** argv) {
  int a, b, c;
  int* ptr;   // ptr is a pointer to an int

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

  *ptr = 7;
  c = a + b;

  return 0;
}
```

Initial values are garbage



In real code, you should always initialize variables

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

Pointer Example

```
int main(int argc, char** argv) {
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  *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

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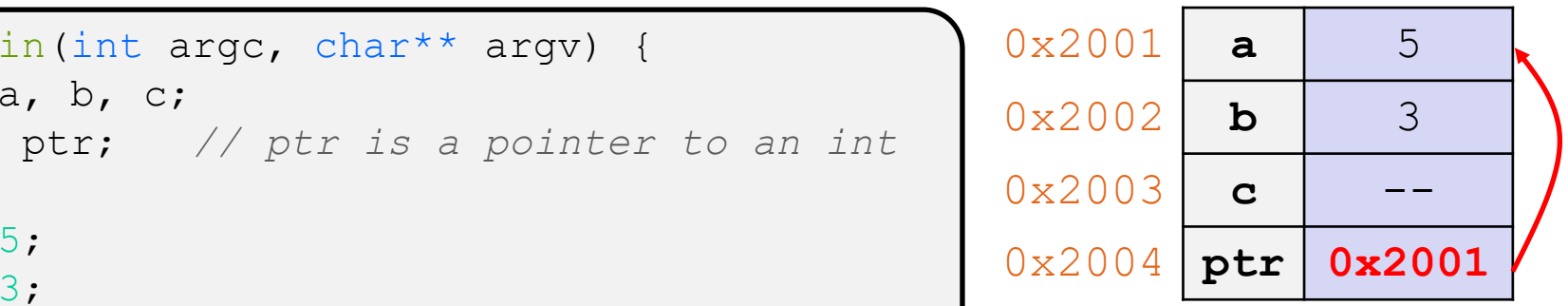

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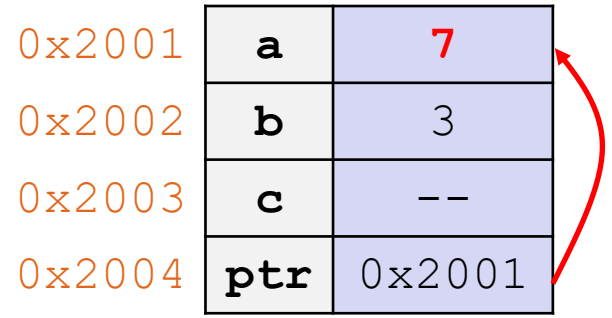

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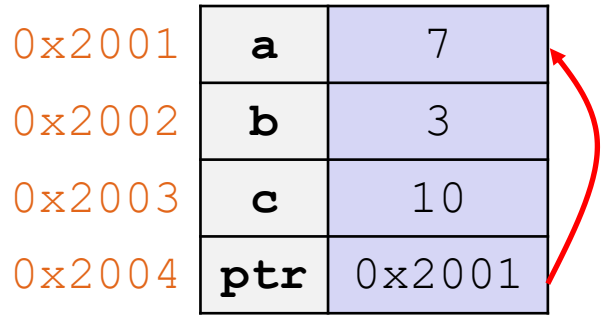
}
```



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

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- What does this code print?

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

void modify_int(int x) {
  x = 5;
}

int main() {
  int num = 3;
  modify_int(num);
  printf("%d\n", num);
  return EXIT_SUCCESS;
}
```

Poll Everywhere

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- What does this code print?

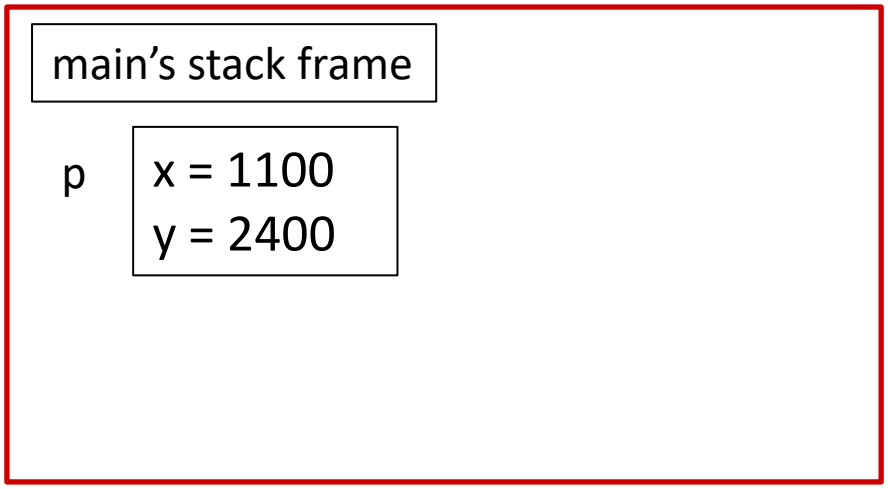
- How could we fix it?
  E.g. make modify point actually modify a point

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

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

void modify_point(Point p) {
  p.x = 3800;
  p.y = 4710;
}

int main() {
  Point p = {1100, 2400};
  modify_point(p);
  printf("%d, %d\n", p.x, p.y);
  return EXIT_SUCCESS;
}
```

Demo: pass_by.c

- Everything in C is pass-by value (e.g. a copy is passed to the function)
- HOWEVER, we can pass a copy of a pointer (e.g. a reference to something) to mimic pass-by-reference.
- Demo pass_by.c
  - Note: most lecture code will be available on the course website

Visualization: faulty pass by reference

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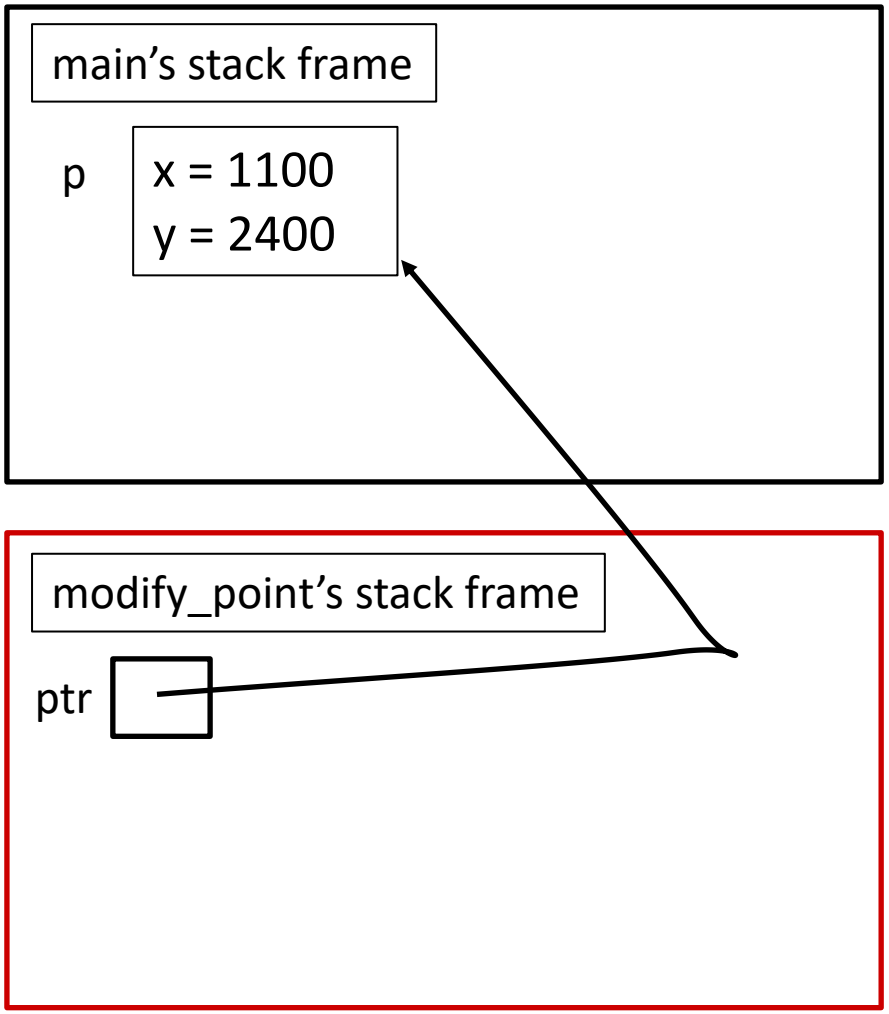


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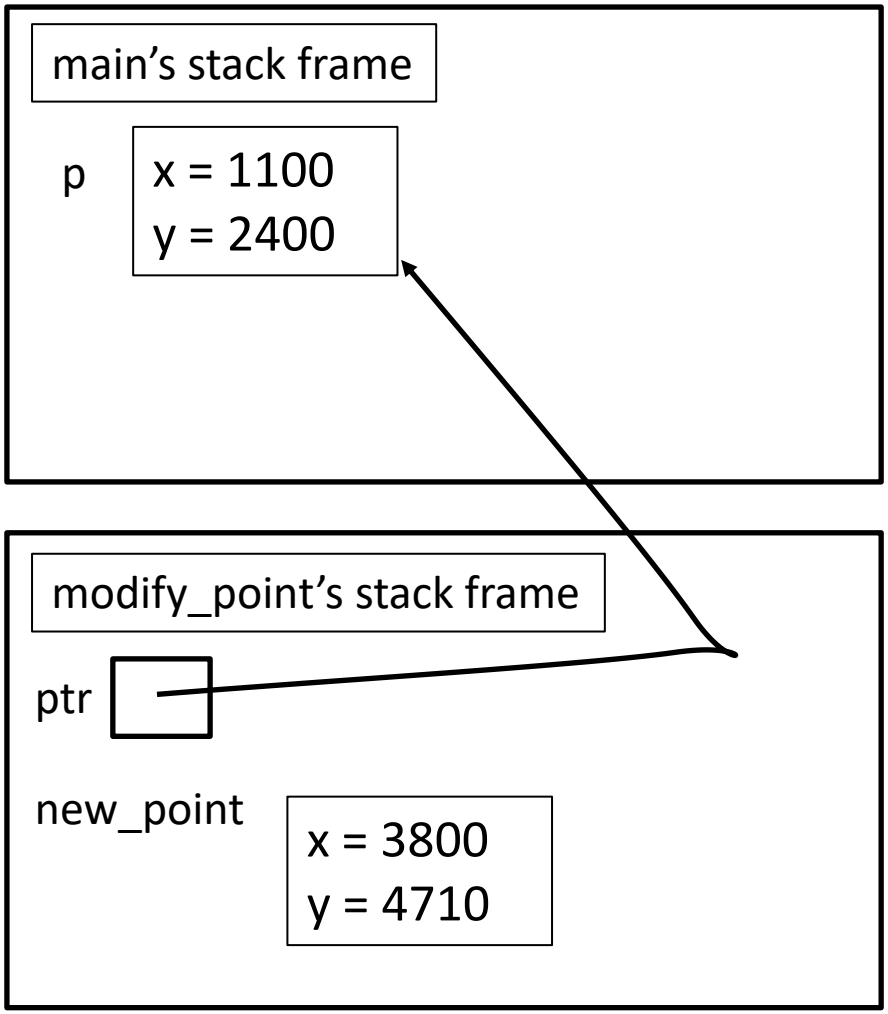


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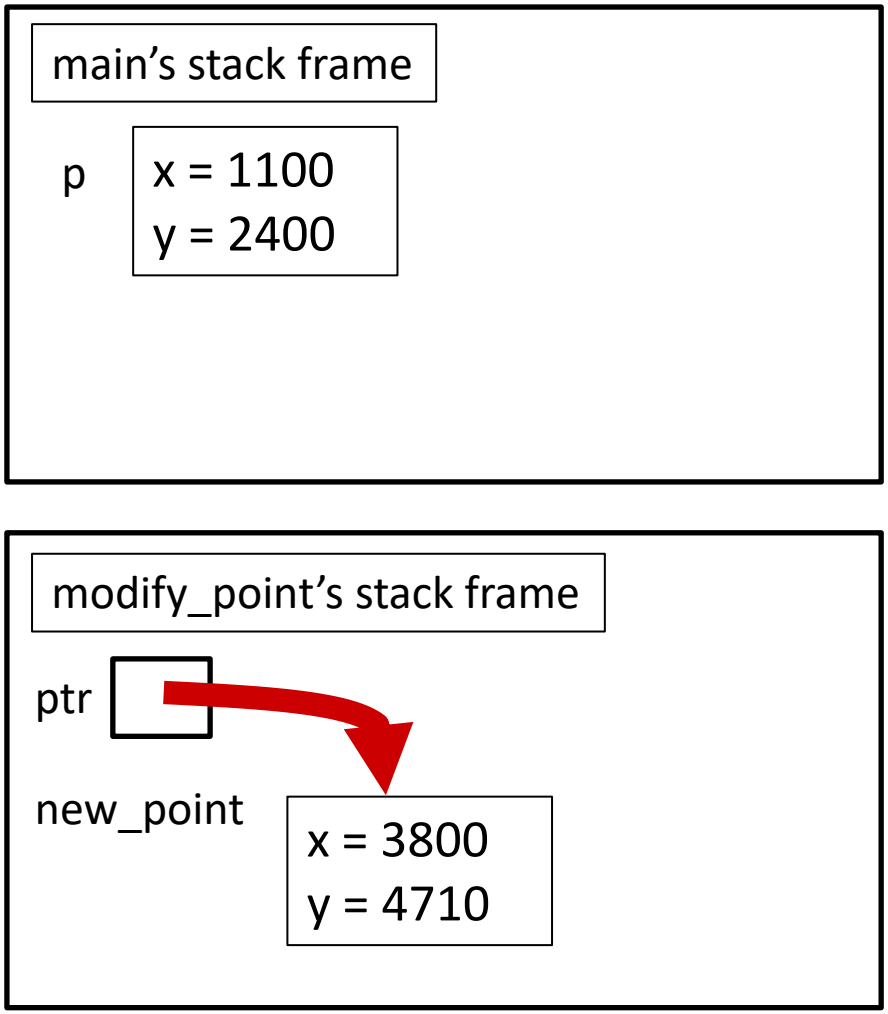


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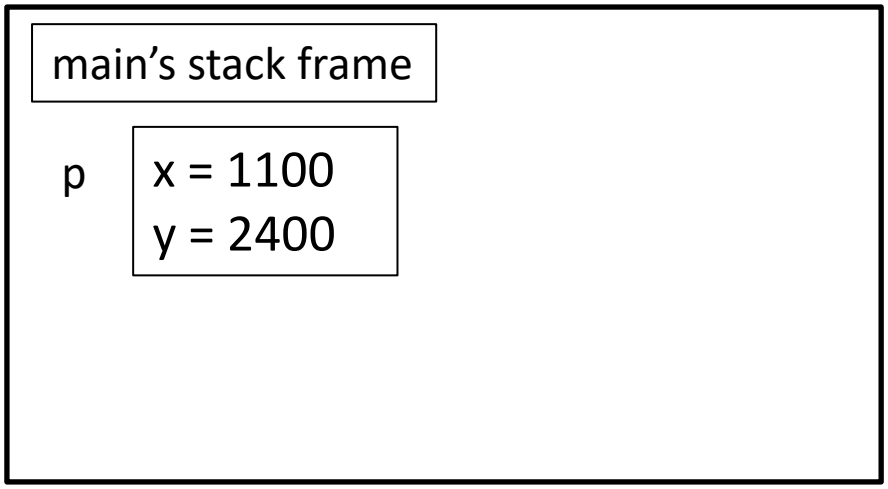


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```

Gap slide

- Slide to make clear that we are moving onto a new example (that looks very similar)

Visualization: fixed pass by reference

Buggy version said:
`ptr = &new_point`

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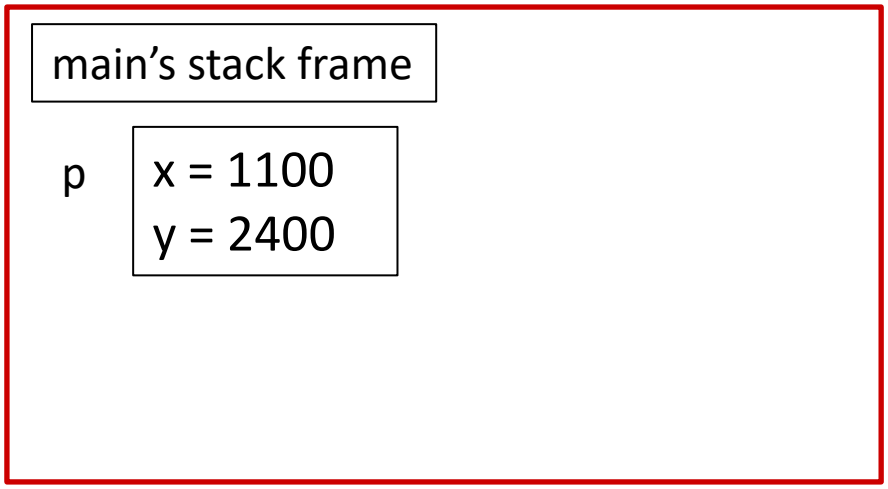


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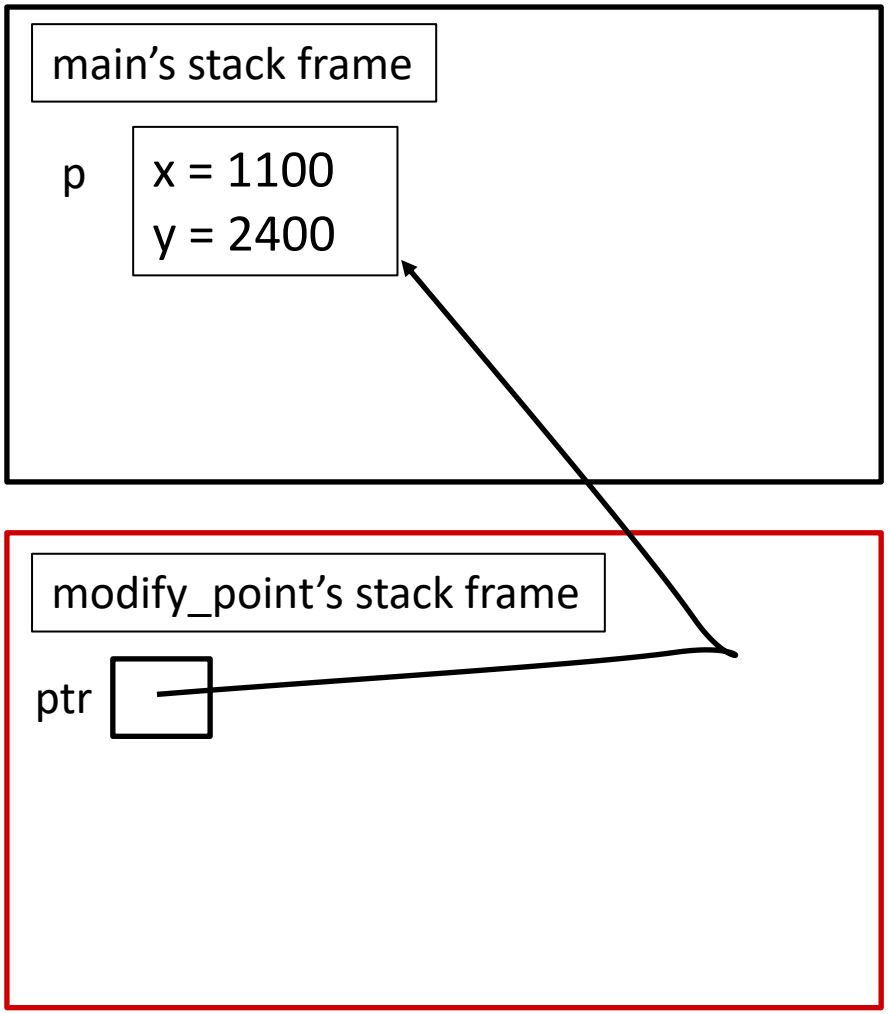


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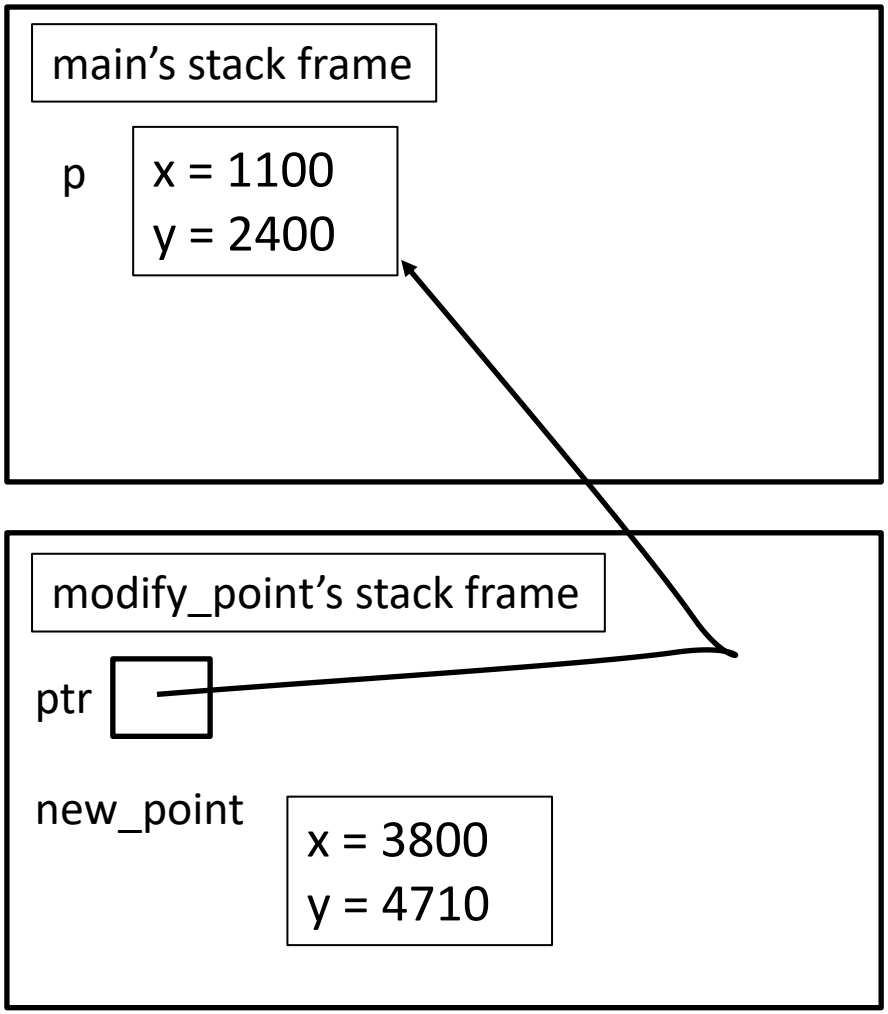


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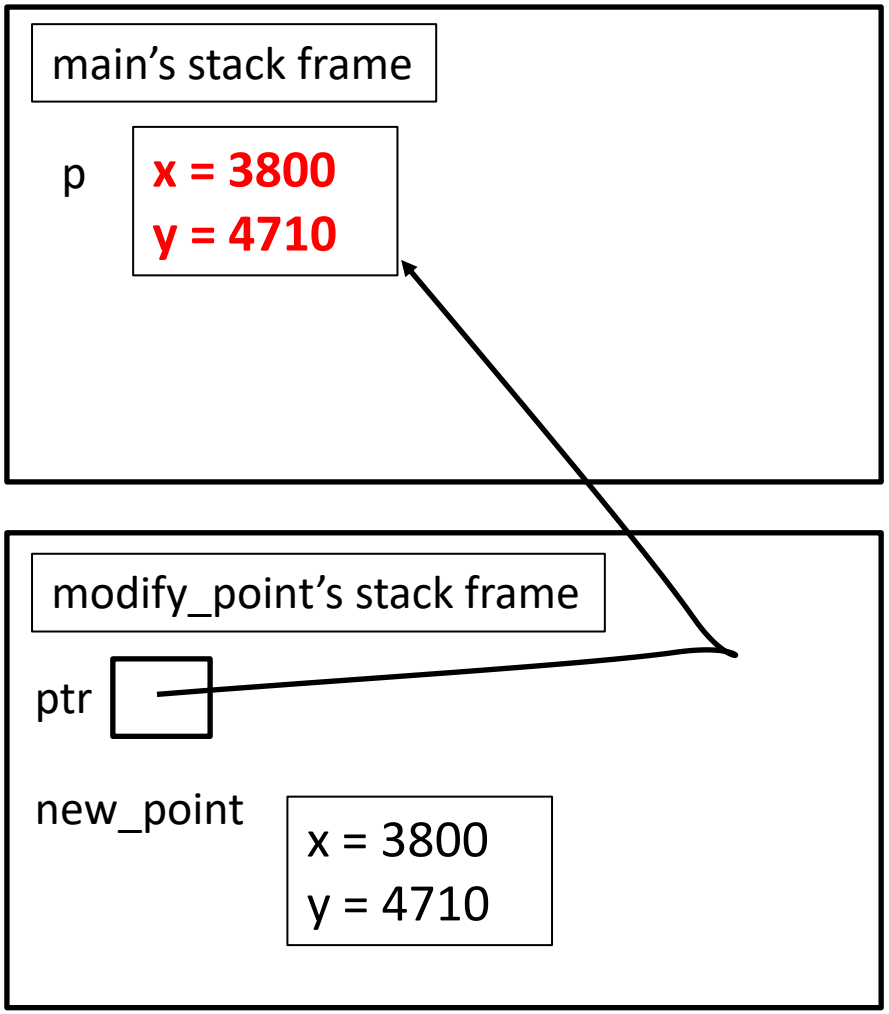


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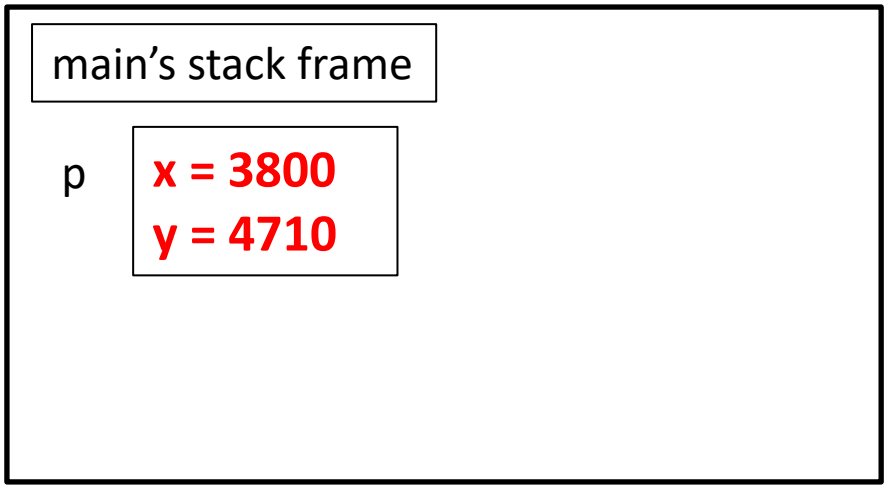


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```

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);
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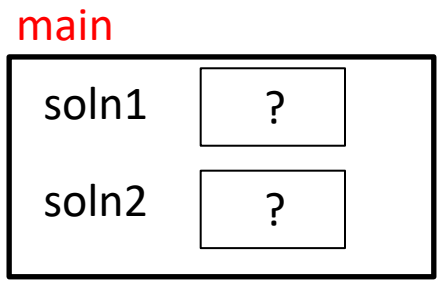

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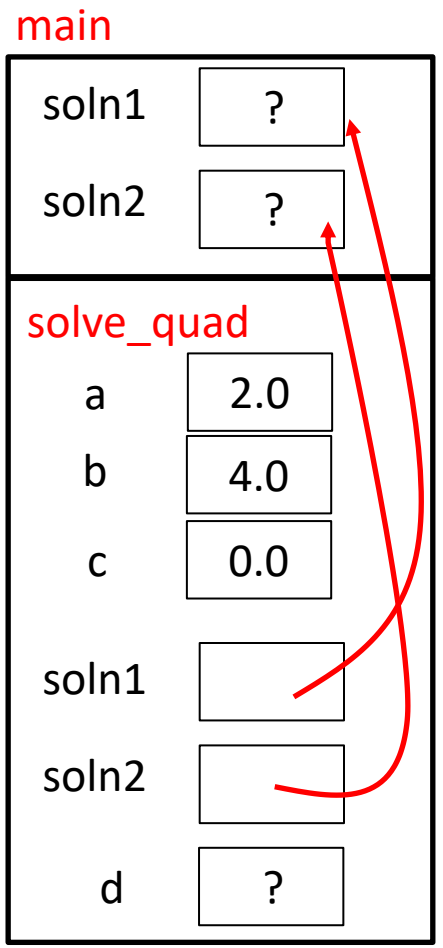

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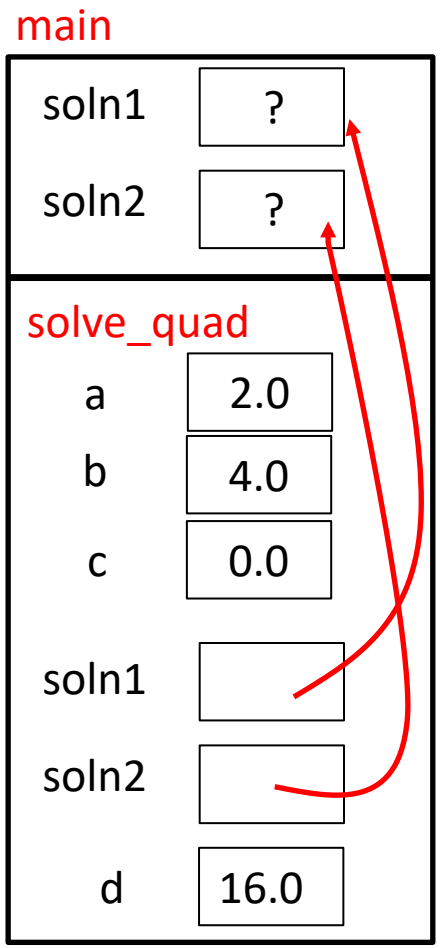

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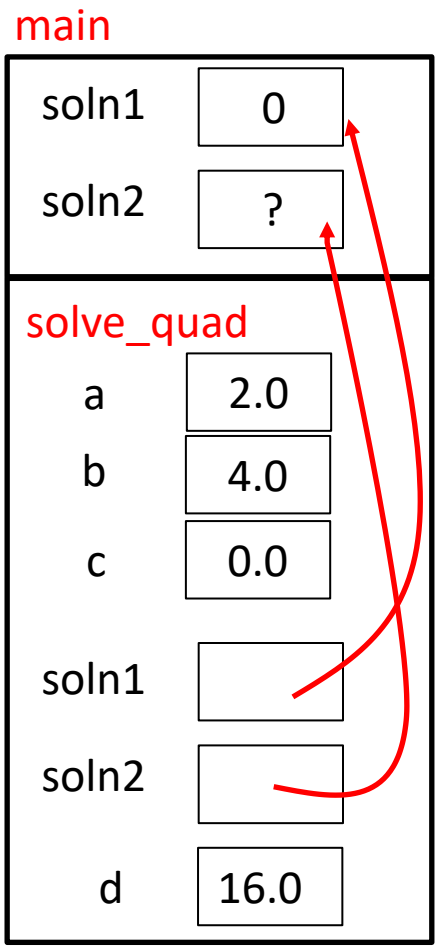

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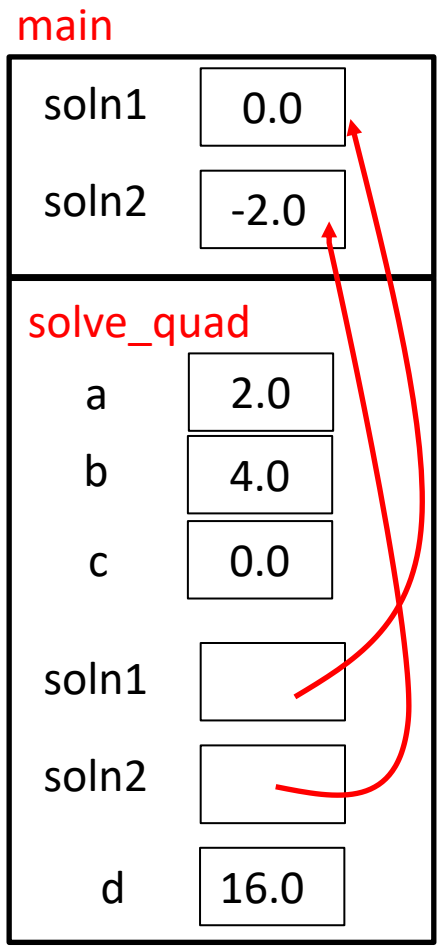

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  // ...
}
```

main

soln1	0.0
soln2	-2.0

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

- We can do arithmetic on addresses to iterate through arrays.

```c
int a[] = {0, 3, 5, 9};
int size = 4;

int sum = 0;
int* ptr = a; // &(a[0])
for (int i = 0; i < size; i++) {
  sum += ptr[i];
}
```

```c
int a[] = {0, 3, 5, 9};
int size = 4;

int sum = 0;
int* ptr = a; // &(a[0])
int* end = ptr + size;
for (; ptr != end; ptr++) {
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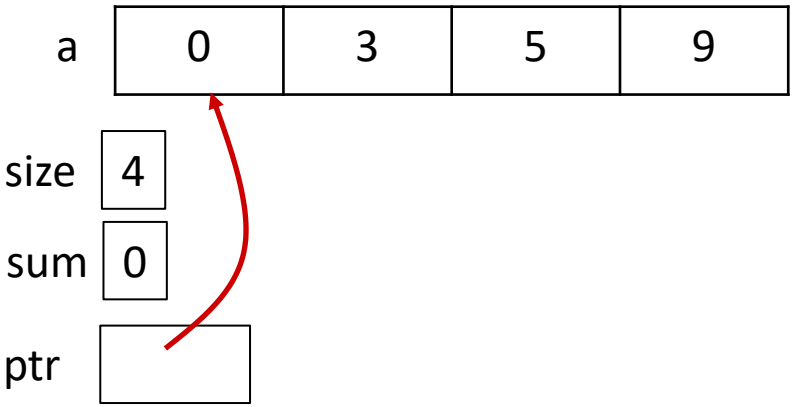

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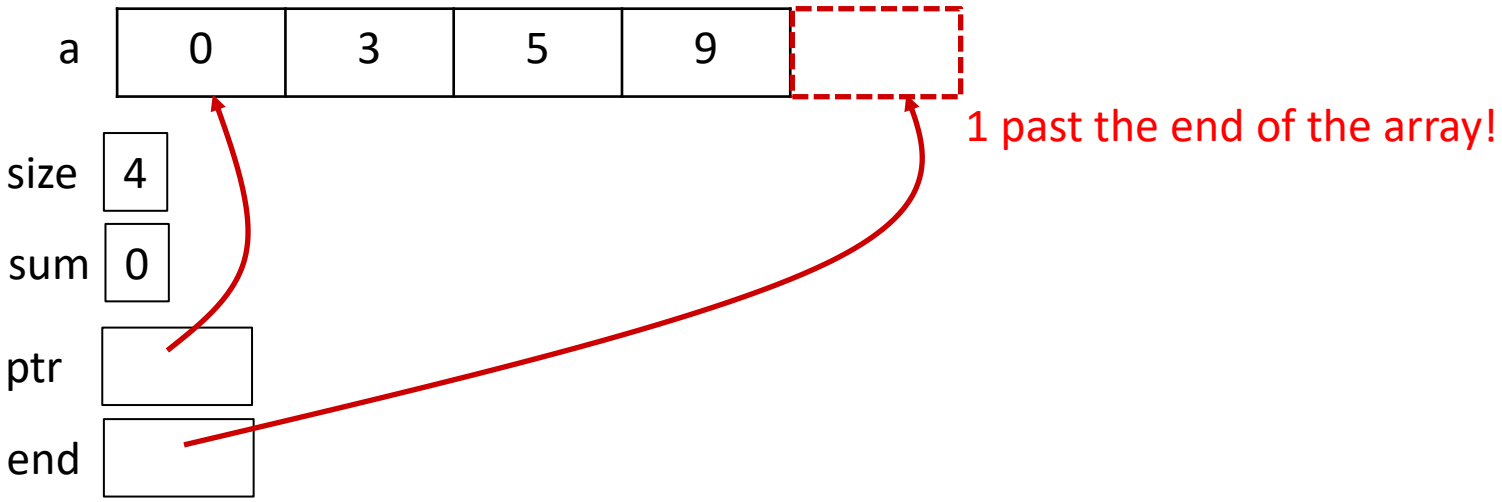

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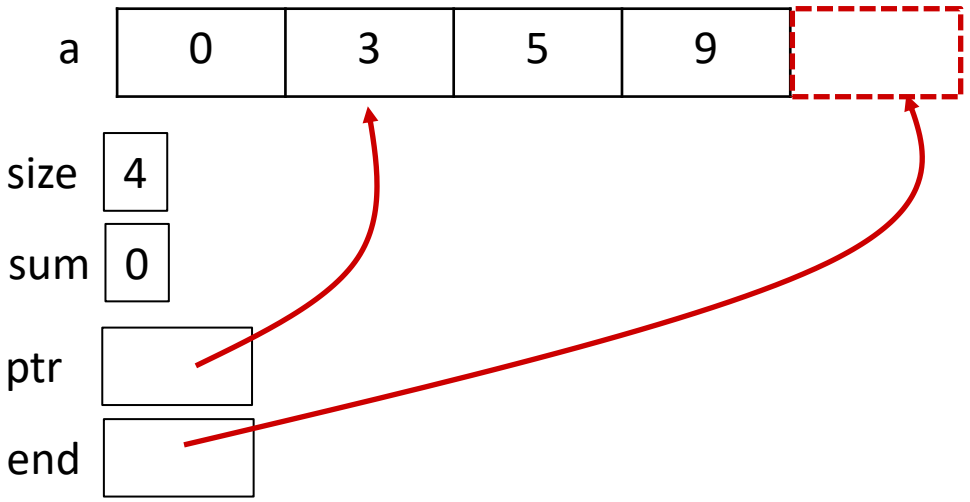

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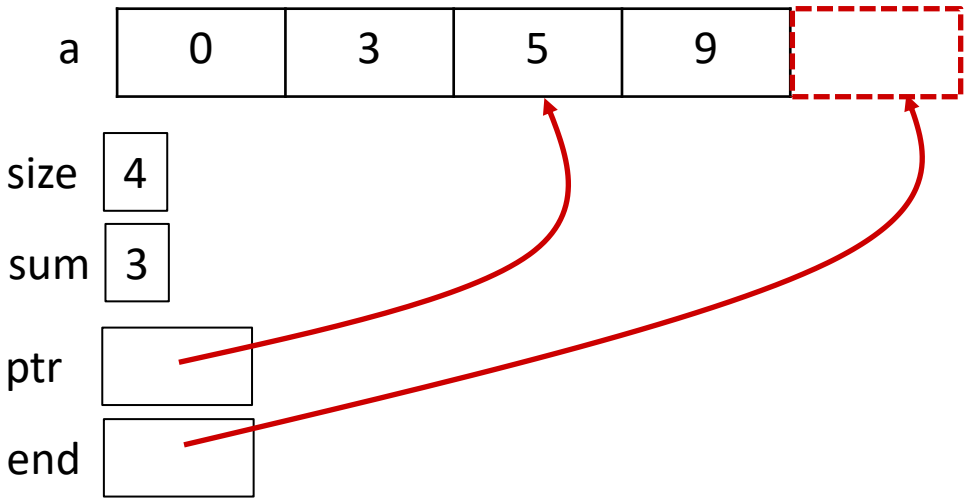

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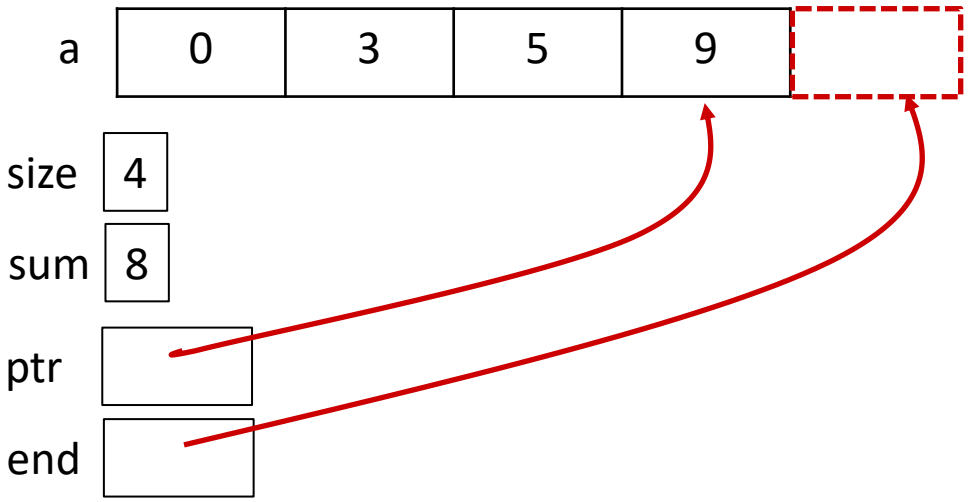

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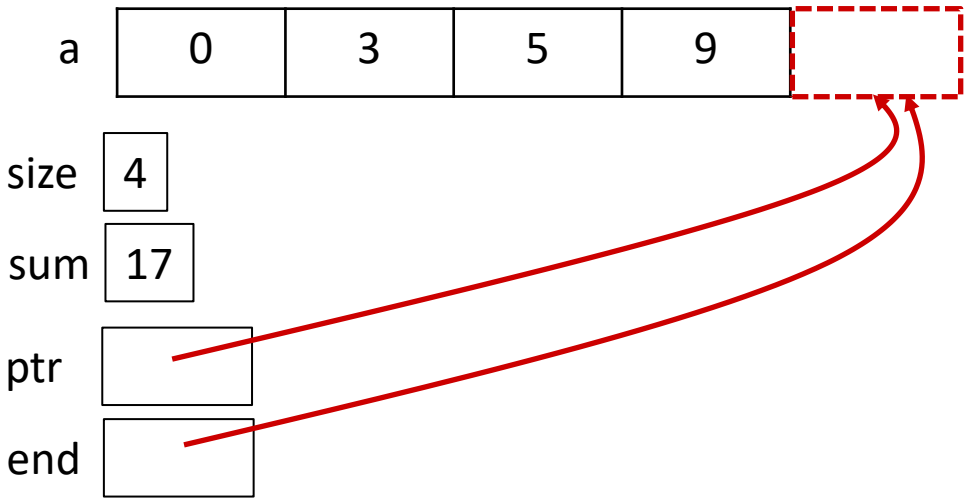

Strings without Objects

- 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'

Demo: get_input.c

- Lets code together a small program that:
  - Reads at max 100 characters from stdin (user input)
  - Truncates the input to only the first word
  - Prints that word out
  - Not allowed to use scanf, FILE*, printf, etc

Poll Everywhere

pollev.com/tqm

- There is something wrong with this function
- What is it? How do we fix this function w/o changing the function signature

```c
#define MAX_INPUT_SIZE 100

char* read_stdin() {
  char str[MAX_INPUT_SIZE];

  ssize_t res = read(STDIN_FILENO, str, MAX_INPUT_SIZE);

  // error checking
  if (res <= 0) {
    return NULL;
  }

  return str;
}
```

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- There is something wrong with this function
- What is it? How do we fix this function w/o changing the function signature

```c
#define MAX_INPUT_SIZE 100

char* read_stdin() {
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  if (res <= 0) {
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  return str;
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Poll Everywhere

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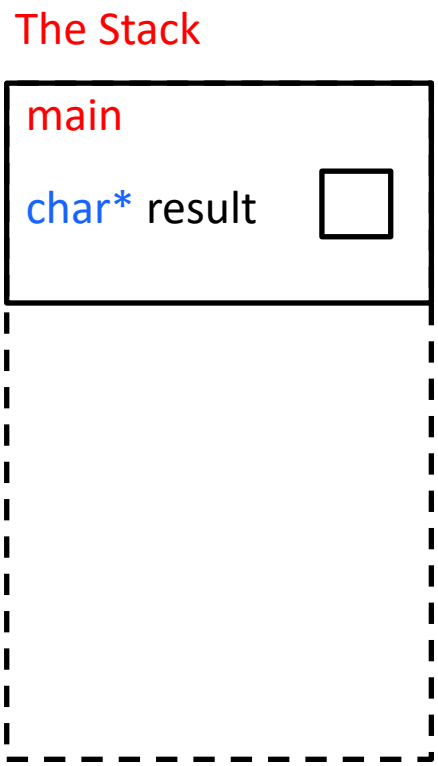


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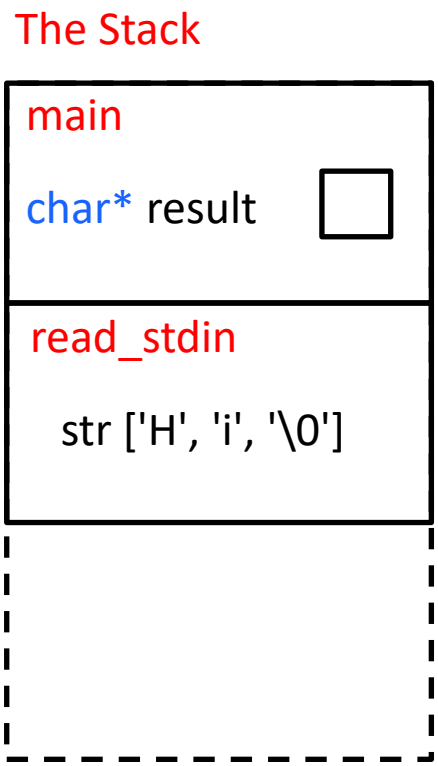


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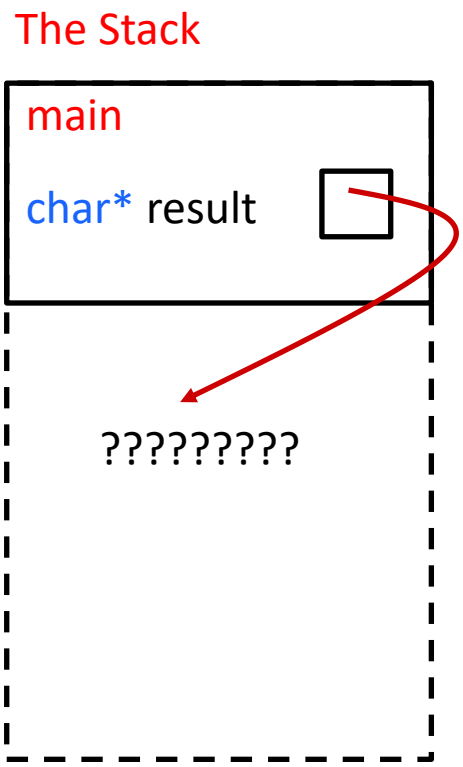


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  // error checking
  if (res <= 0) {
    return NULL;
  }

  return str;
}
```

`static` function variables

- Functions can declare a variable as static

```c
#include <stdio.h>  // for printf
#include <stdlib.h> // for EXIT_SUCCESS

int next_num();

int main(int argc, char** argv) {
  printf("%d\n", next_num()); // prints 1
  printf("%d\n", next_num()); // then 2
  printf("%d\n", next_num()); // then 3
  return EXIT_SUCCESS;
}

int next_num() {
  // marking this variable as static means that
  // the value is preserved between calls to the function
  // this allows the function to "remember" things
  static int counter = 0;
  counter++;
  return counter;
}
```

This is how some functions (like one in proj0) can "remember" things.

Can be thought of as a global variable that is "private" to a function

Memory Allocation

- So far, we have seen two kinds of memory allocation:

```c
int counter = 0;    // global var

int main() {
  counter++;
  printf("count = %d\n",counter);
  return 0;
}
```

- `counter` is ***statically***-allocated
  - Allocated when program is loaded
  - Deallocated when program exits

```c
int foo(int a) {
  int x = a + 1;      // local var
  return x;
}

int main() {
  int y = foo(10);    // local var
  printf("y = %d\n",y);
  return 0;
}
```

- `a`, `x`, `y` are ***automatically***-allocated
  - Allocated when function is called
  - Deallocated when function returns

Aside: `sizeof`

- **`sizeof`** operator can be applied to a variable or a type and it evaluates to the size of that type in bytes
- Examples:
  - **`sizeof(int)`** – returns the size of an integer
  - **`sizeof(double)`** – returns the size of a double precision number
  - **`struct my_struct s;`**
    - **`sizeof(s)`** – returns the size of the struct s
  - **`my_type *ptr`**
    - **`sizeof (*ptr)`** – returns the size of the type pointed to by ptr

- Very useful for Dynamic Memory

What is Dynamic Memory Allocation?

- We want Dynamic Memory Allocation
  - Dynamic means “at run-time”
  - The compiler and the programmer don’t have enough information to make a final decision on how much to allocate
  - Your program explicitly requests more memory at run time
  - The language allocates it at runtime, maybe with help of the OS

- Dynamically allocated memory persists until either:
  - A garbage collector collects it (automatic memory management)
  - Your code explicitly deallocates it (manual memory management)

- C requires you to manually manage memory
  - More control, and more headaches

Heap API

- Dynamic memory is managed in a location in memory called the "Heap"
  - The heap is managed by user-level runetime library (libc)
  - Interface functions found in `<stdlib.h>`
- Most used functions:
  - **`void *malloc(size_t size);`**
    - Allocates memory of specified size
  - **`void free(void *ptr);`**
    - Deallocates memory
- Note: **`void*`** is “generic pointer”. It holds an address, but doesn’t specify what it is pointing at.
- Note 2: **`size_t`** is the integer type of **`sizeof()`**

malloc()

- `void *malloc(size_t size);`
- **malloc** allocates a block of memory of the requested size
  - Returns a pointer to the first byte of that memory
    - And returns `NULL` if the memory allocation failed!
  - You should assume that the memory initially contains garbage
  - You'll typically use `sizeof` to calculate the size you need

```
// allocate a 10-float array
float* arr = malloc(10*sizeof(float));
if (arr == NULL) {
  return errcode;
}
...   // do stuff with arr
```

ALWAYS CHECK FOR NULL

free()

- Usage: `free(pointer);`
- Deallocates the memory pointed-to by the pointer
  - Pointer *must* point to the first byte of heap-allocated memory (*i.e.* something previously returned by **malloc**)
  - Freed memory becomes eligible for future allocation
  - `free(NULL);` does nothing.
  - The bits in the pointer are *not changed* by calling free
    - Defensive programming: can set pointer to NULL after freeing it

```
float* arr = malloc(10*sizeof(float));
if (arr == NULL)
  return errcode;
...             // do stuff with arr
free(arr);
arr = NULL;     // OPTIONAL
```

The Heap

- The Heap is a large pool of available memory to use for Dynamic allocation
- This pool of memory is kept track of with a small data structure indicating which portions have been allocated, and which portions are currently available.
- **`malloc`**:
  - searches for a large enough unused block of memory
  - marks the memory as allocated.
  - Returns a pointer to the beginning of that memory
- **`free`**:
  - Takes in a pointer to a previously allocated address
  - Marks the memory as free to use.

Dynamic Memory Example

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  if (ptr == NULL)
    return EXIT_FAILURE;
  ...              // do stuff with ptr
  free(ptr);
}
```

addr	var	value
0x2001	**ptr**	--
...	...	--
0x4000	**HEAP START**	USED
0x4001		USED
0x4002		
0x4003		
0x4004		
0x4005		
0x4006		
0x4007		
0x4008		USED
0x4009		USED

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Fixed read_stdin()

```c
#define MAX_INPUT_SIZE 100

char* read_stdin() {
  char str = (char*) malloc(sizeof(char) * MAX_INPUT_SIZE);
  if (str == NULL) {
    return NULL;
  }

  ssize_t res = read(STDIN_FILENO, str, MAX_INPUT_SIZE);

  // error checking
  if (res <= 0) {
    return NULL;
  }

  return str;
}
```

Dynamic Memory Pitfalls

- Buffer Overflows
  - E.g. ask for 10 bytes, but write 11 bytes
  - Could overwrite information needed to manage the heap
  - Common when forgetting the null-terminator on malloc'd strings
- Not checking for **`NULL`**
  - Malloc returns NULL if out of memory
  - Should check this after every call to malloc
- Giving **`free()`** a pointer to the middle of an allocated region
  - Free won't recognize the block of memory and probably crash
- Giving free() a pointer that has already been freed
  - Will interfere with the management of the heap and likely crash
- **`malloc`** does NOT initialize memory
  - There are other functions like **`calloc`** that will zero out memory

Memory Leaks

- The most common Memory Pitfall
- What happens if we malloc something, but don't free it?
  - That block of memory cannot be reallocated, even if we don't use it anymore, until it is **`free`**d
  - If this happens enough, we run out of heap space and program may slow down and eventually crash
- Garbage Collection
  - Automatically "frees" anything once the program has lost all references to it
  - Affects performance, but avoid memory leaks
  - Java has this, C doesn't

Poll Everywhere

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- Which line below is first to (most likely) cause a crash?
  - Yes, there are a lot of bugs, but not all cause a crash ☺
  - See if you can find all the bugs!

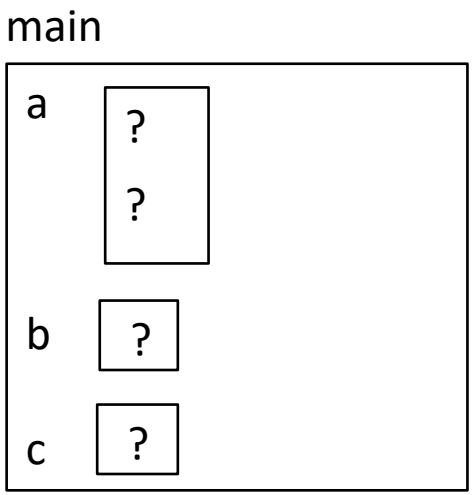
```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char** argv) {
  int a[2];
  int* b = malloc(2*sizeof(int));
  int* c;

1   a[2] = 5;
2   b[0] += 2;
3   c = b+3;
4   free(&(a[0]));
5   free(b);
6   free(b);
7   b[0] = 5;

  return 0;
}
```

Memory Corruption - What Happens?



heap:

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int main(int argc, char** argv) {
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  free(&(a[0]));  // free something not malloc'ed
  free(b);
  free(b);     // double-free the same block
  b[0] = 5;    // use a freed (dangling) pointer

  // any many more!
  return 0;
}
```

Note: Arrow points to *next* instruction.

memcorrupt.c

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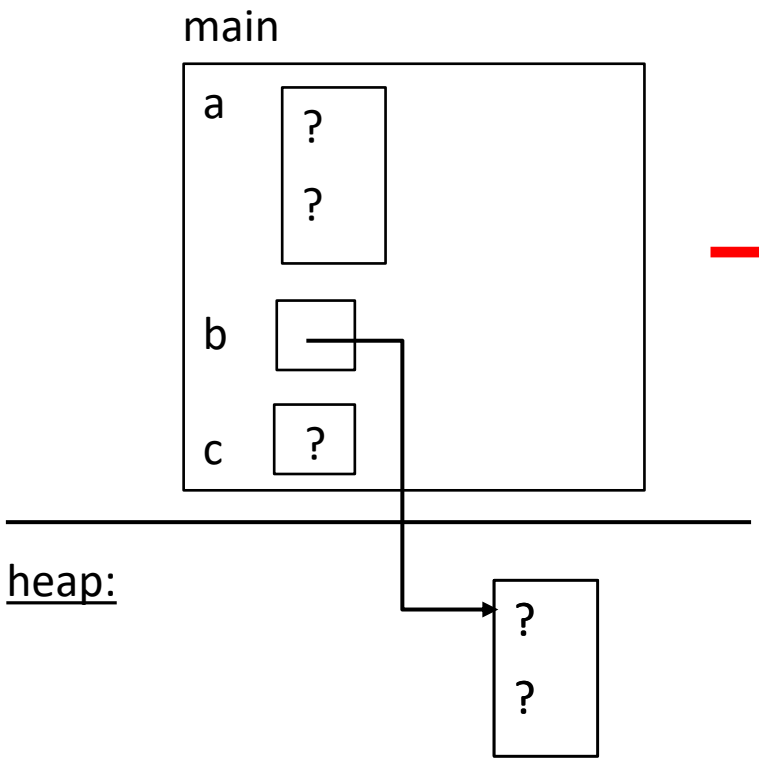


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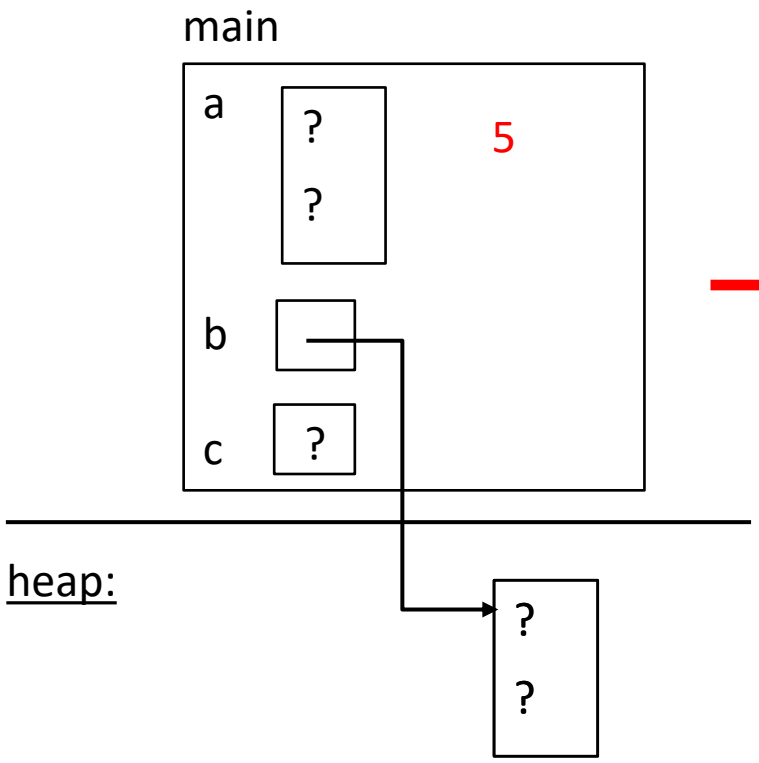


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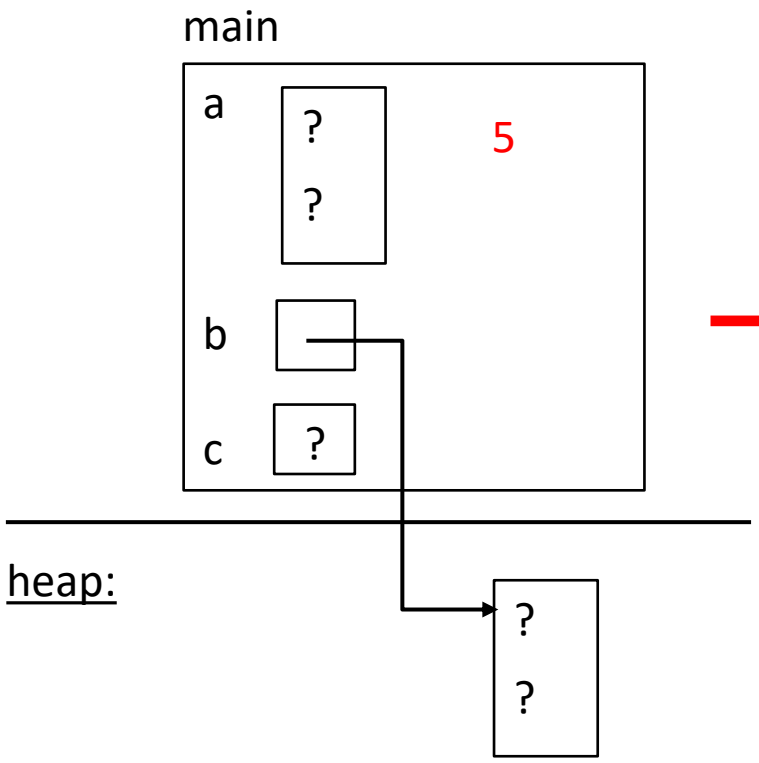


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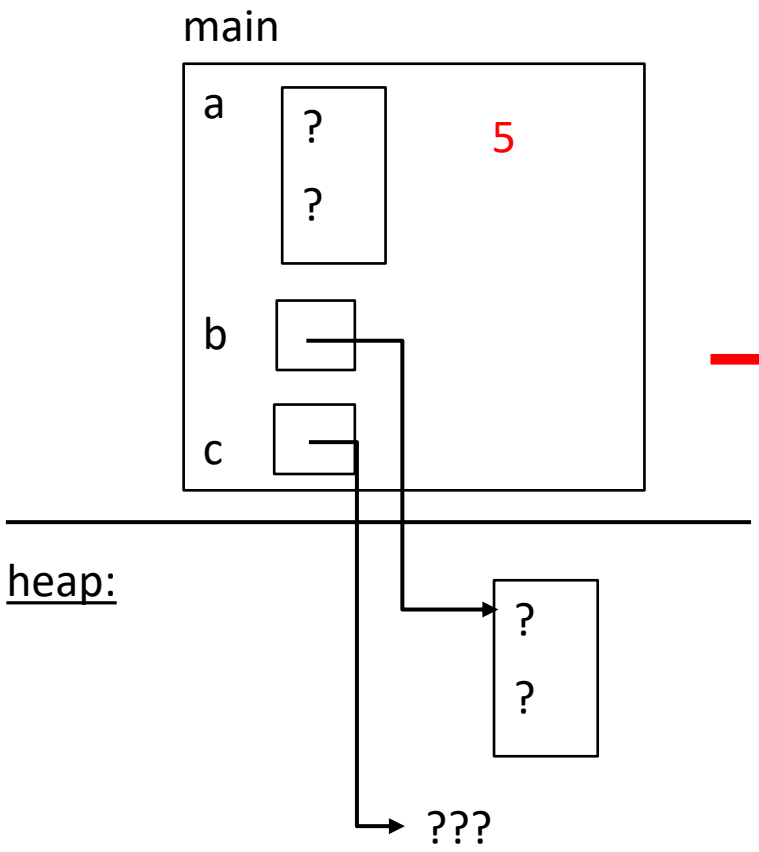


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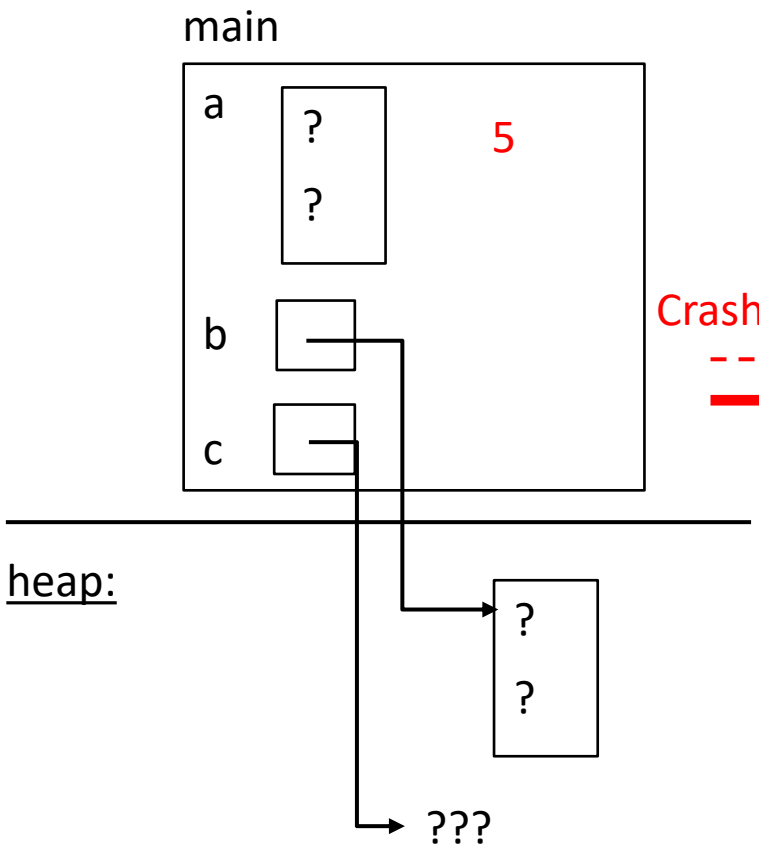


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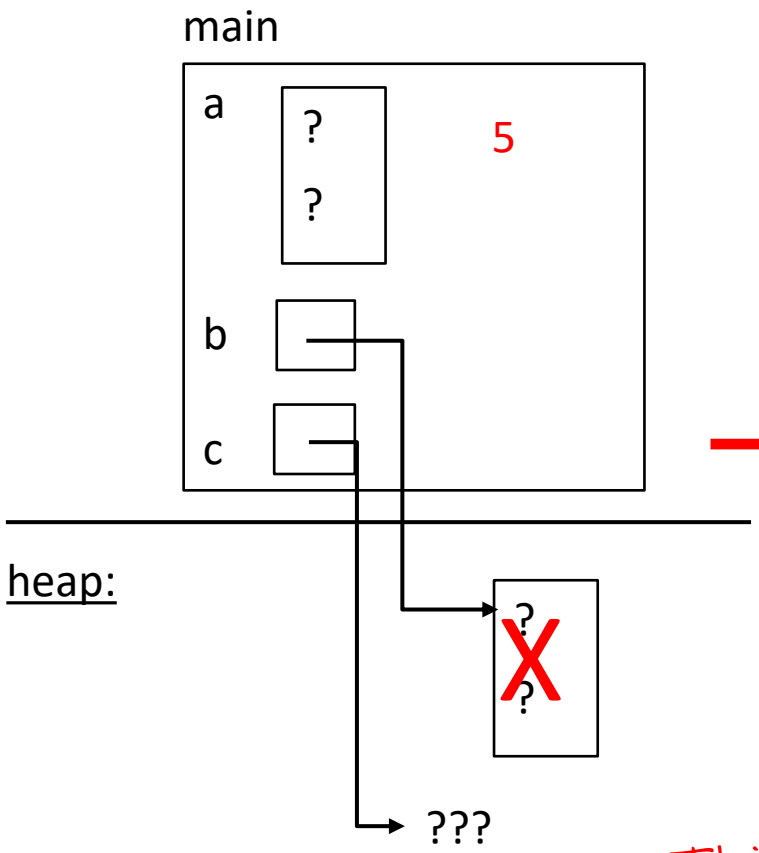


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This "double free" would also cause the program to crash

memcorrupt.c

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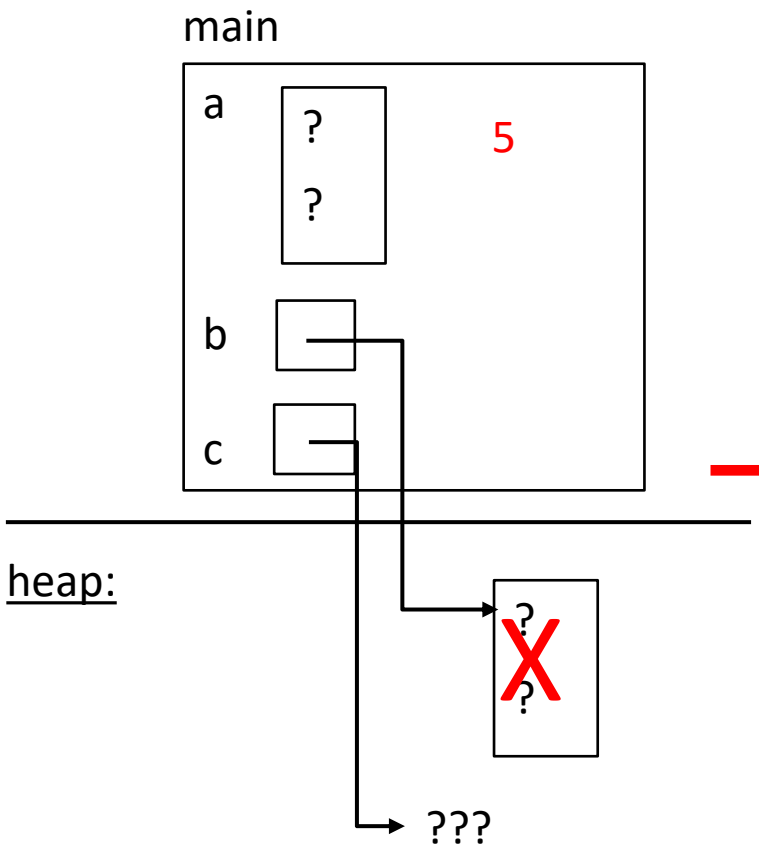


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memcorrupt.c

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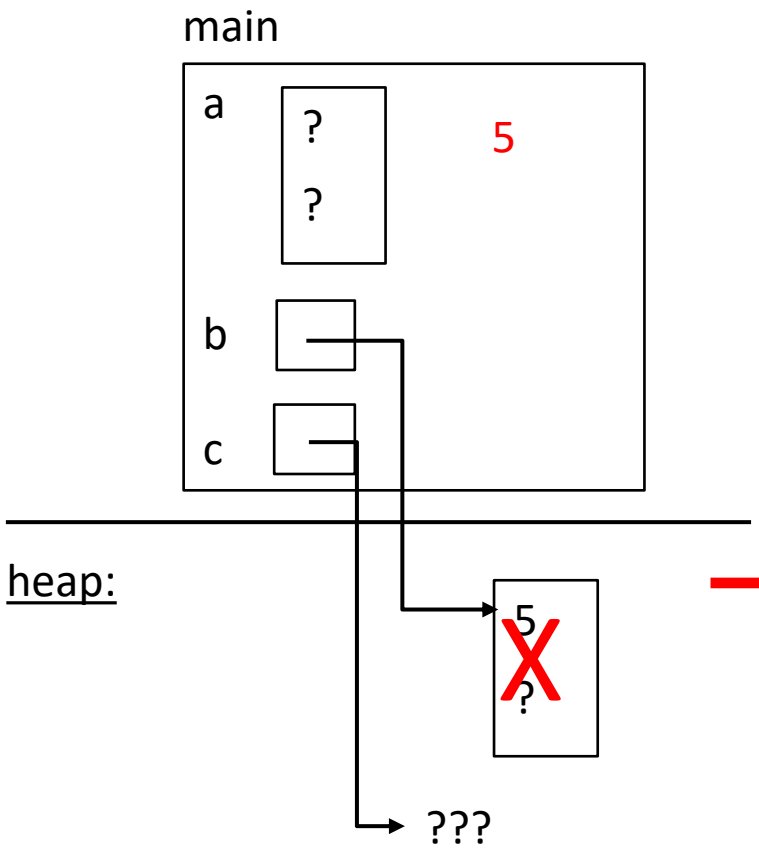


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memcorrupt.c