# Memory and Arrays

## CSE 333 Autumn 2019

**Instructor:** Hannah C. Tang

**Teaching Assistants:**

| | | |
|---|---|---|
| Dao Yi | Farrell Fileas | Lukas Joswiak |
| Nathan Lipiarski | Renshu Gu | Travis McGaha |
| Yibo Cao | Yifan Bai | Yifan Xu |

## Poll Everywhere

pollev.com/cse333

# About how long did Exercise 0 take?

A. 0-1 Hours
B. 1-2 Hours
C. 2-3 Hours
D. 3-4 Hours
E. 4+ Hours
F. I didn't submit / I prefer not to say

# Exercises

- Congratulations on writing your first standalone program for 333!
- Exercise 0
  - Sample solution will be posted this afternoon
  - Grades back next week – reference system is the CSE Linux environment
  - If you haven't been added to Gradescope yet, email your ex0 submission to Hannah ASAP

# Administrivia

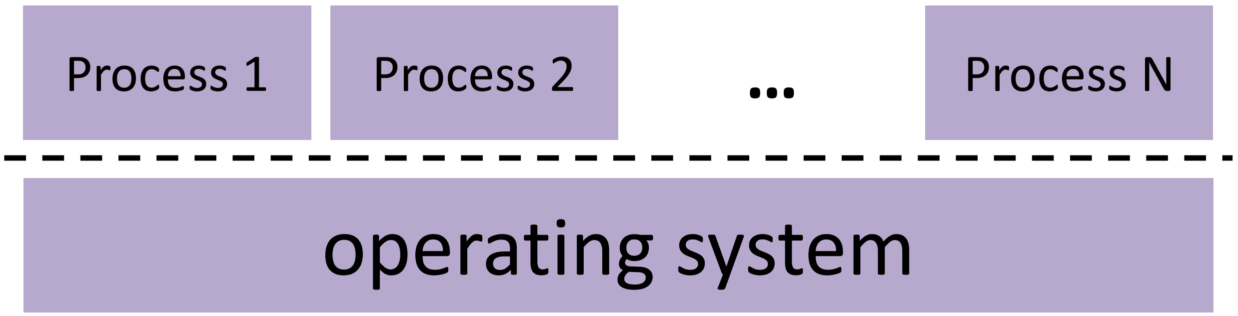
- No Panopto :(
- Exercise 1 out today and due Monday
- Homework 0 due Monday; Homework 1 released today
- EXTRA SLOTS OPENING UP!
  - Email Hannah with your UW ID *by tonight* so we can get an accurate count

# Lecture Outline

- **C's Memory Model (refresher)**
- Pointers (refresher)
- Arrays

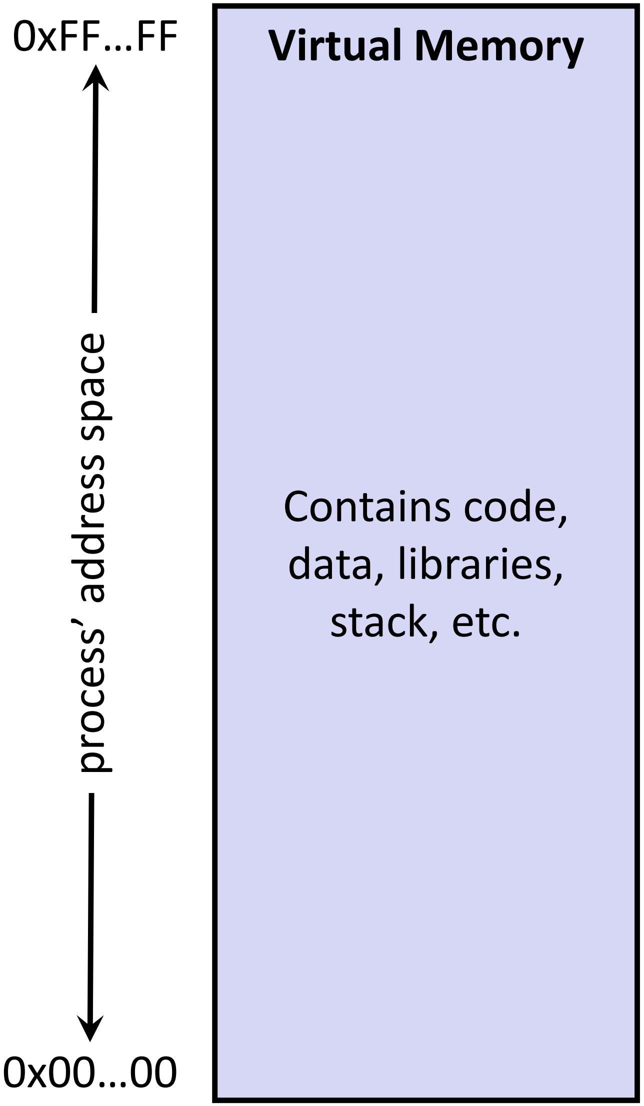
# OS and Processes

- The OS lets you run multiple applications at once
  - An application runs within an OS "process"
  - The OS time slices each CPU between runnable processes
    - This happens *very quickly*



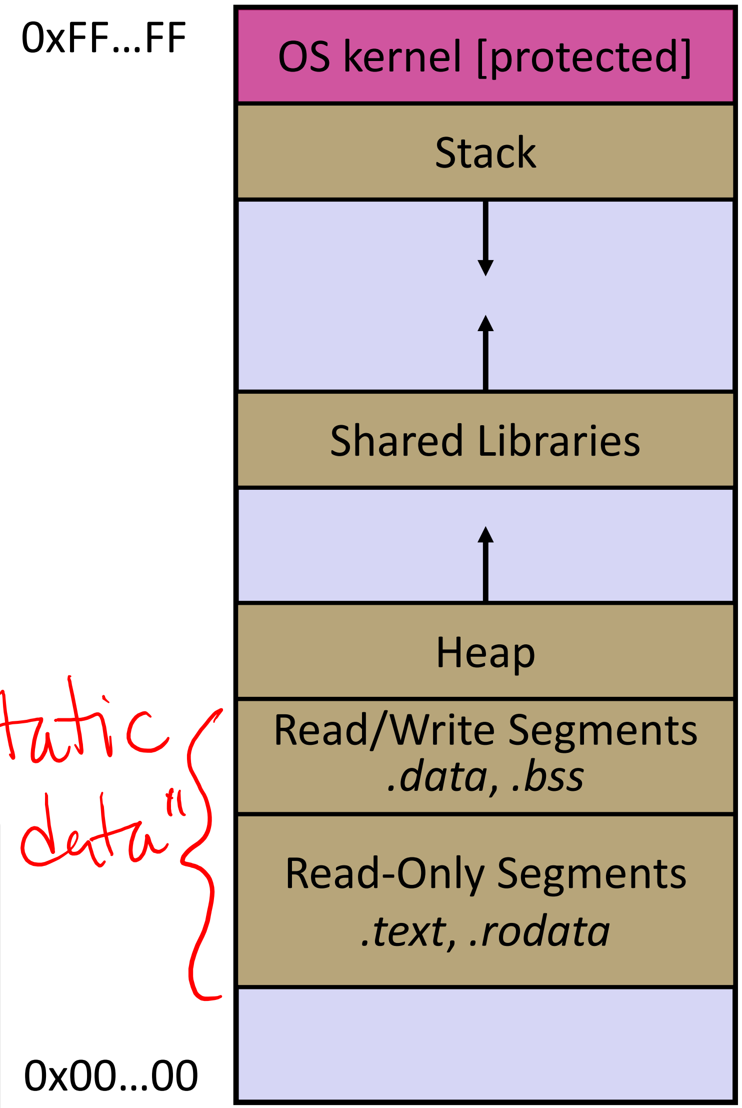
# Processes and Virtual Memory

- The OS gives each process the illusion of its own private memory
  - Called the process' address space
  - Contains the process' virtual memory, visible only to it (via translation)
  - $2^{64}$ bytes on a 64-bit machine



# Loading

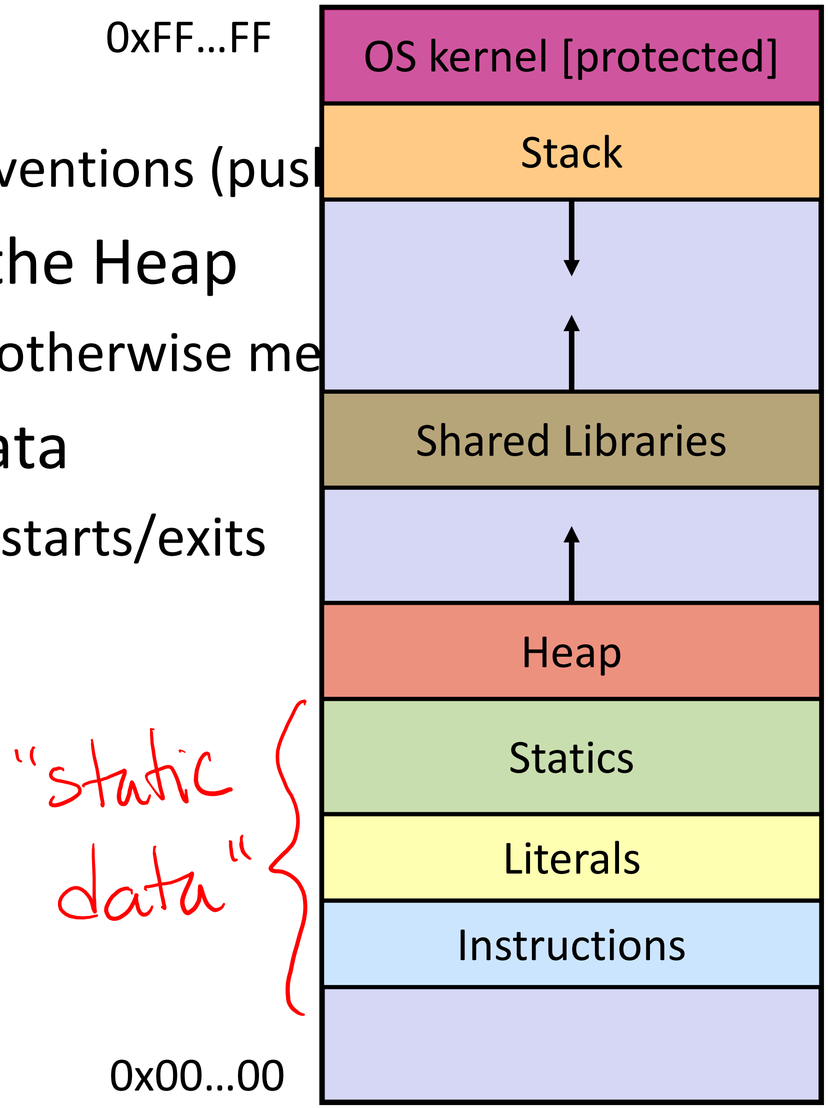
- When the OS loads a program it:
  1) Creates an address space
  2) Inspects the executable file to see what's in it
  3) (Lazily) copies regions of the file into the right place in the address space
  4) Does any final linking, relocation, or other needed preparation




```
char *greeting = "Hello World";
int main(void) {
  ...
  greeting = "Farewell, cruel world";
  return 0;
}
```

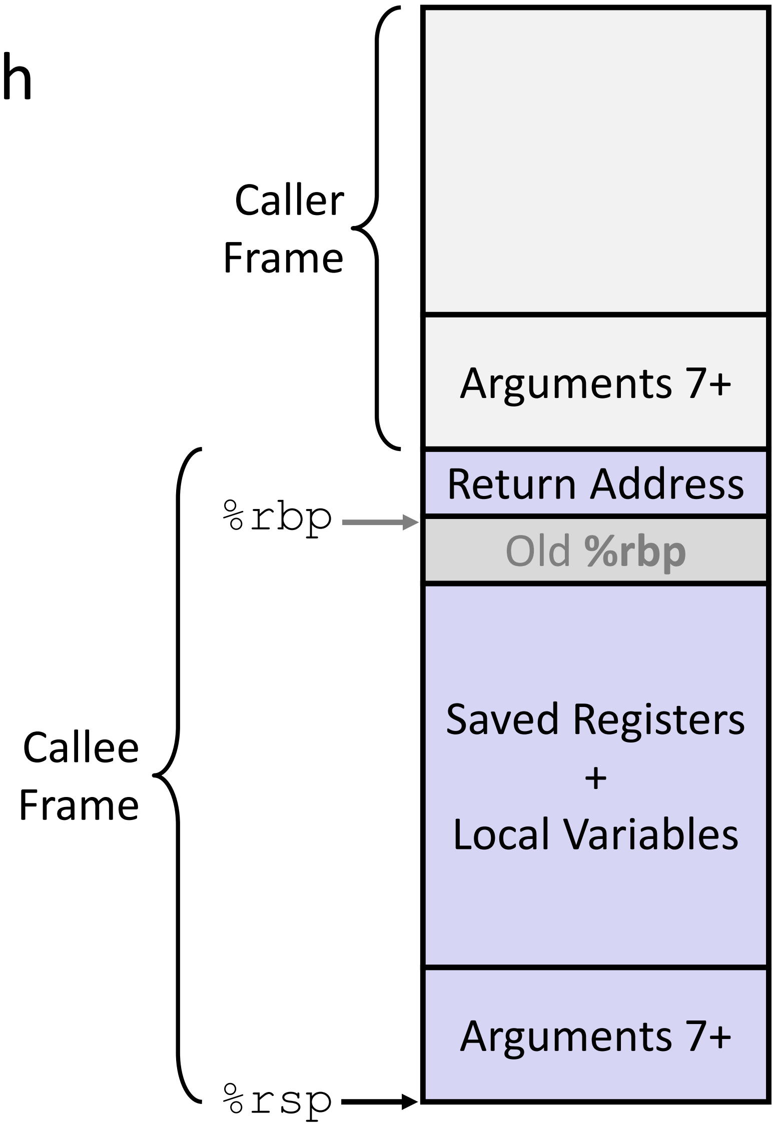
# Memory Management

- Local variables on the Stack
  - Allocated and freed via calling conventions (pus
- Dynamically-allocated data on the Heap
  - malloc() to request; free() to free, otherwise me
- Global and static variables in Data
  - Allocated/freed when the process starts/exits



# Review: The Stack

- Used to store data associated with each function call
  - Compiler-inserted code manages stack frames for you
- Stack frame (x86-64) includes:
  - Address to return to
  - Saved registers
    - Based on calling conventions
  - Local variables
  - Argument build
    - Only if > 6 used



# Stack in Action

Note: arrow points to *next* instruction to be executed (like in gdb).

stack.c

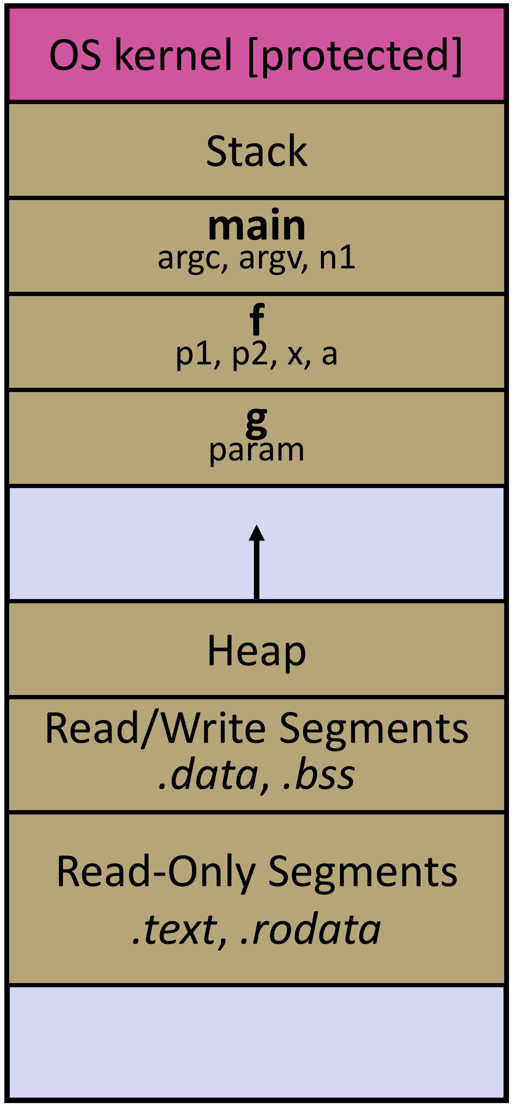
```
#include <stdint.h>

int32_t f(int32_t, int32_t);
int32_t g(int32_t);

int main(int argc, char **argv) {
  int32_t n1 = f(3,-5);
  n1 = g(n1);
  return EXIT_SUCCESS;
}

int32_t f(int32_t p1, int32_t p2) {
  int32_t x;
  int32_t a[3];
  ...
  x = g(a[2]);
  return x;
}

int32_t g(int32_t param) {
  return param * 2;
}
```



# Stack in Action

Note: arrow points to *next* instruction to be executed (like in gdb).

stack.c

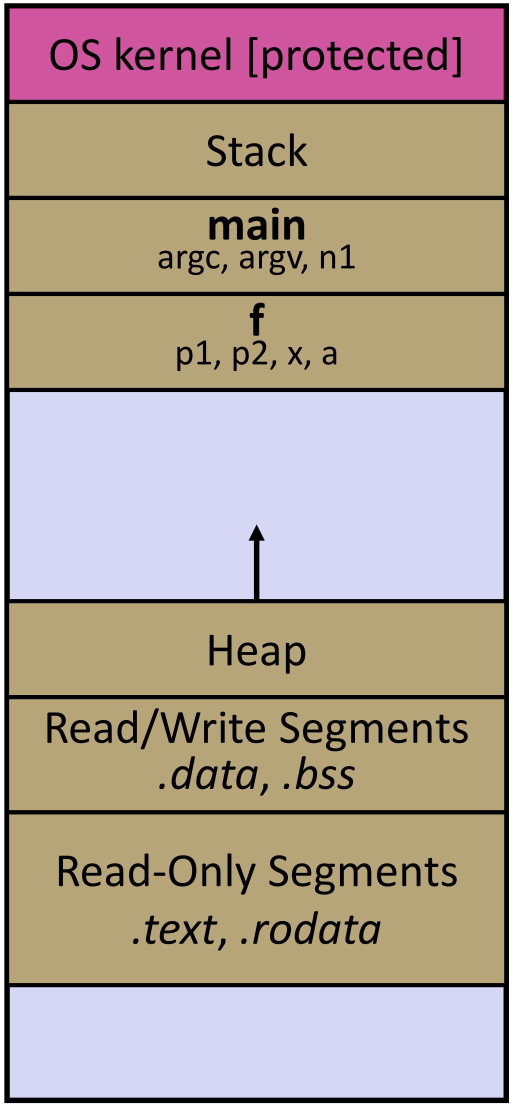
```
#include <stdint.h>

int32_t f(int32_t, int32_t);
int32_t g(int32_t);

int main(int argc, char **argv) {
  int32_t n1 = f(3,-5);
  n1 = g(n1);
  return EXIT_SUCCESS;
}

int32_t f(int32_t p1, int32_t p2) {
  int32_t x;
  int32_t a[3];
  ...
  x = g(a[2]);
→ return x;
}

int32_t g(int32_t param) {
  return param * 2;
}
```



# Stack in Action

Note: arrow points to *next* instruction to be executed (like in gdb).

stack.c

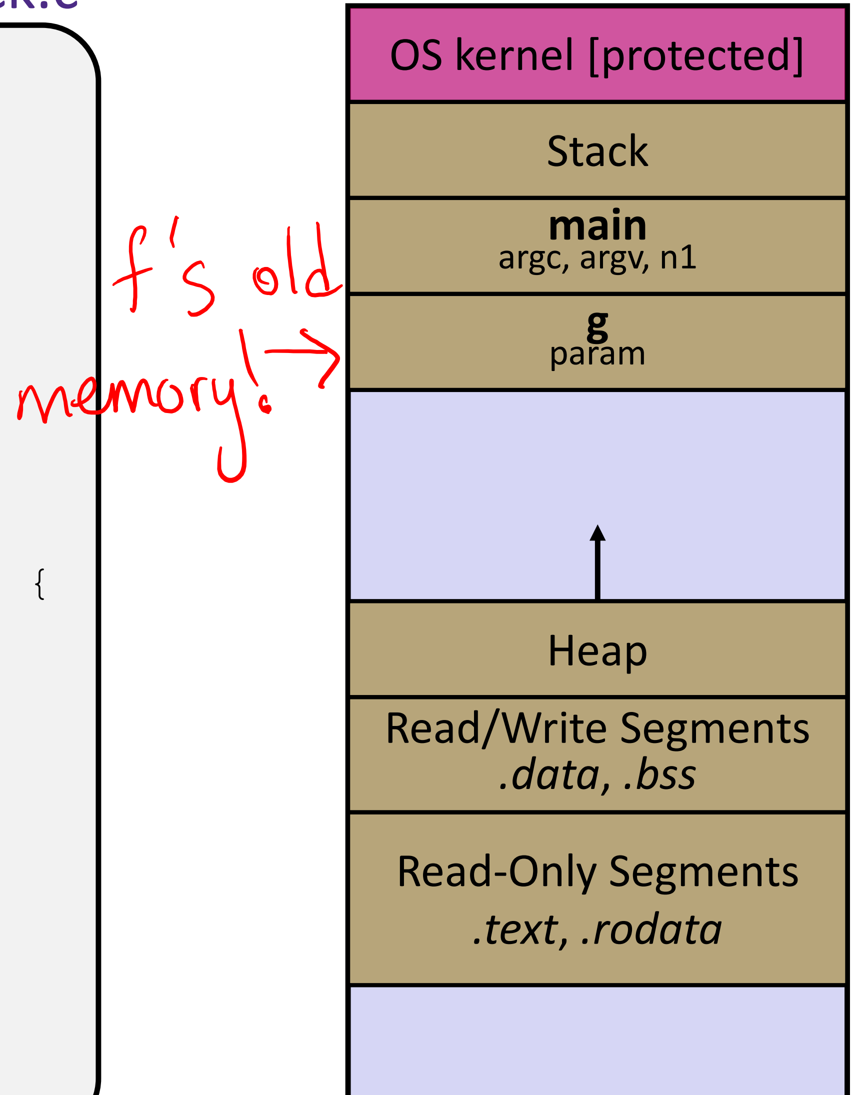
```c
#include <stdint.h>

int32_t f(int32_t, int32_t);
int32_t g(int32_t);

int main(int argc, char **argv) {
  int32_t n1 = f(3,-5);
  n1 = g(n1);
  return EXIT_SUCCESS;
}

int32_t f(int32_t p1, int32_t p2) {
  int32_t x;
  int32_t a[3];
  ...
  x = g(a[2]);
  return x;
}

int32_t g(int32_t param) {
  return param * 2;
}
```



# Stack in Action

Note: arrow points to *next* instruction to be executed (like in `gdb`).

stack.c

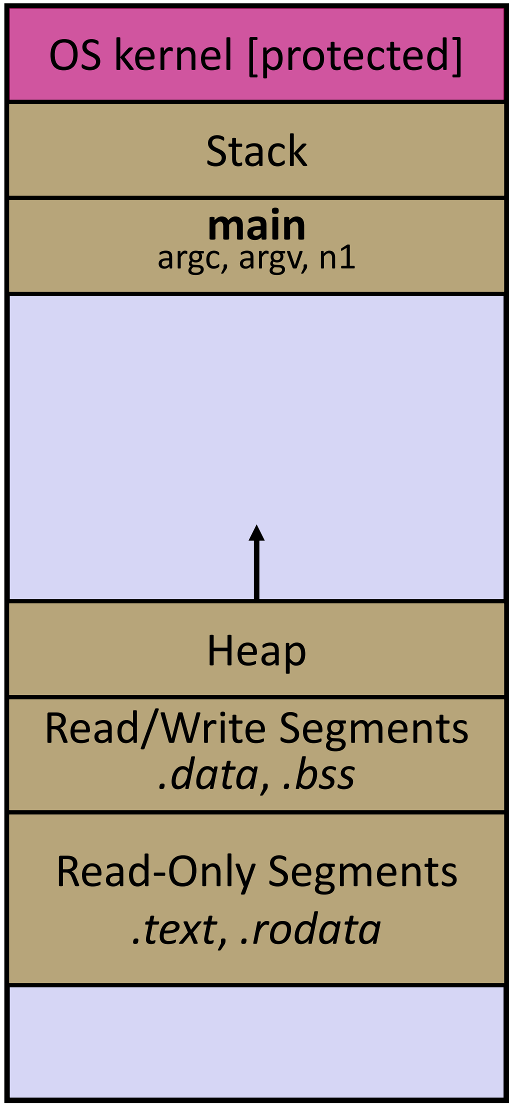
```
#include <stdint.h>

int32_t f(int32_t, int32_t);
int32_t g(int32_t);

int main(int argc, char **argv) {
  int32_t n1 = f(3,-5);
  n1 = g(n1);
→ return EXIT_SUCCESS;
}

int32_t f(int32_t p1, int32_t p2) {
  int32_t x;
  int32_t a[3];
  ...
  x = g(a[2]);
  return x;
}

int32_t g(int32_t param) {
  return param * 2;
}
```



# Lecture Outline

- C's Memory Model (refresher)
- **Pointers (refresher)**
- Arrays

# Pointers

- Variables that store addresses
  - It points to somewhere in the process' virtual address space
  - `&foo` produces the virtual address of `foo`
- Generic definition: `type* name;` or `type *name;`
  - Recommended: do not define multiple pointers on same line: `int *p1, p2;` not the same as `int *p1, *p2;`
  - Instead, use:

```
int *p1;
int *p2;
```

- *Dereference* a pointer using the unary `*` operator
  - Access the memory referred to by a pointer

# Pointer Example


pointy.c

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

int main(int argc, char **argv) {
  int32_t x = 351;
  int32_t *p;      // p is a pointer to a int

  p = &x;        // p now contains the addr of x
  printf("&x is %p\n", &x);
  printf(" p is %p\n",  p);
  printf(" x is %d\n",  x);

  *p = 333;   // change the value of x
  printf(" x is %d\n",  x);

  return EXIT_SUCCESS;
}
```

# Something Curious

- What happens if we run `pointy.c` several times?

```
bash$ gcc -Wall -std=c11 -o pointy pointy.c
```

Run 1:

```
bash$ ./pointy
&x is 0x7ffff9e28524
 p is 0x7ffff9e28524
 x is 351
 x is 333
```

Run 2:

```
bash$ ./pointy
&x is 0x7fffe847be34
 p is 0x7fffe847be34
 x is 351
 x is 333
```

Run 3:

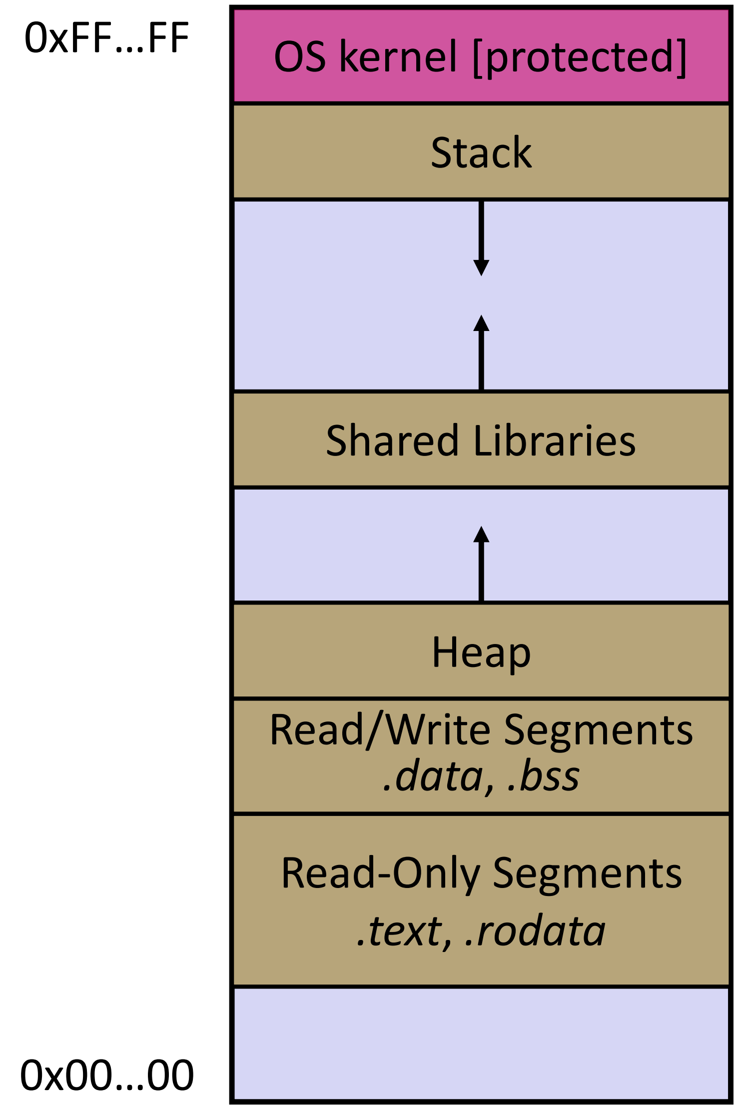
```
bash$ ./pointy
&x is 0x7fffe7b14644
 p is 0x7fffe7b14644
 x is 351
 x is 333
```

Run 4:

```
bash$ ./pointy
&x is 0x7fffff0dfe54
 p is 0x7fffff0dfe54
 x is 351
 x is 333
```

# Address Space Layout Randomization

- Linux uses *address space layout randomization* (ASLR) for added security
  - Randomizes:
    - Base of stack
    - Shared library location (`mmap`)
  - Makes Stack-based buffer overflow attacks tougher
  - Makes debugging tougher
  - Can be disabled (`gdb` does this by default); Google if curious



# Lecture Outline

- C’s Memory Model (refresher)
- Pointers (refresher)
- **Arrays**

# Arrays

- Definition: `type name[size]`
  - Allocates `size*sizeof(type)` bytes of *contiguous* memory
  - Normal usage is a compile-time constant for `size` (*e.g.* `int32_t scores[175];`)
  - Initially, array values are "garbage"

- Number of elements in an array
  - Not stored anywhere!
    - `sizeof(array)` only works in variable scope of array definition
  - Recent versions of C (but *not* C++) allow for variable-length arrays
    - Uncommon and can be considered bad practice [*we won't use*]

```
int32_t n = 175;
int32_t scores[n];   // OK in C99
```

# Using Arrays

- 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 is an identifier for "collection of elements"
  - `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 array's start
    - Cannot be assigned to / changed
  - Elements are contiguous – array is a single block of memory

```
int32_t primes[6] = {2, 3, 5, 6, 11, 13};
primes[3] = 7;
primes[100] = 0; // memory smash!
```

# Poll Everywhere

pollev.com/cse333

**Challenge Question:** The code snippets both use a variable-length array. What will happen when we compile with C99+?

```
int32_t m = 175;
int32_t scores[m];

void foo(int32_t n) {
  ...
}
```

```
int32_t m = 175;

void foo(int32_t n) {
  int32_t scores[n];
  ...
}
```

| | | |
|---|---|---|
| A. | Compiler Error | Compiler Error |
| B. | Compiler Error | No Compiler Error |
| C. | No Compiler Error | Compiler Error |
| D. | No Compiler Error | No Compiler Error |
| E. | I'm not sure … | |

# Multi-dimensional Arrays

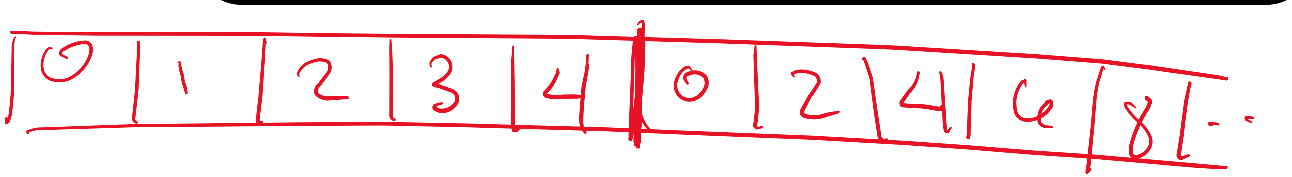
- Generic 2D format:

```
type name[rows][cols] = {{values},…,{values}};
```

  - Still allocates a single, contiguous chunk of memory
  - C is *row-major*

```
// a 2-row, 3-column array of doubles
double grid[2][3];

// a 3-row, 5-column array of ints
int32_t matrix[3][5] = {
  {0, 1, 2, 3, 4},
  {0, 2, 4, 6, 8},
  {1, 3, 5, 7, 9}
};
```



# Arrays as Parameters

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

```c
int32_t sumAll(int32_t a[]);  // prototype

int main(int argc, char **argv) {
  int32_t numbers[] = {9, 8, 1, 9, 5};
  int32_t sum = sumAll(numbers);
  return 0;
}

int32_t sumAll(int32_t a[]) {
  int32_t i, sum = 0;
  for (i = 0; i < ...???
}
```

# Solution 1: Declare Array Size

```
int32_t sumAll(int32_t a[5]);  // prototype

int main(int argc, char **argv) {
  int32_t numbers[] = {9, 8, 1, 9, 5};
  int32_t sum = sumAll(numbers);
  printf("sum is: %d\n", sum);
  return 0;
}

int32_t sumAll(int32_t a[5]) {
  int32_t i, sum = 0;
  for (i = 0; i < 5; i++) {
    sum += a[i];
  }
  return sum;
}
```

must match

- Problem: loss of generality/flexibility

# Solution 2: Pass Size as Parameter

- This is the standard idiom in C programs

```
// prototype
int32_t  sumAll(int32_t a[], int32_t size);

int main(int argc, char **argv) {
  int32_t numbers[] = {9, 8, 1, 9, 5};
  int32_t sum = sumAll(numbers, 5);
  printf("sum is: %d\n", sum);
  return 0;
}

int32_t sumAll(int32_t a[], int32_t size) {
  int32_t i, sum = 0;
  for (i = 0; i < size; i++) {
    sum += a[i];
  }
  return sum;
}
```

look familiar?

arraysum.c

# Parameters: reference vs. value

- There are two fundamental parameter-passing schemes in programming languages
- Call-by-value
  - Parameter is a local variable initialized with a copy of the calling argument when the function is called; manipulating the parameter only changes the copy, *not* the calling argument
  - **C**, **Java**, C++ (most things)
- Call-by-reference
  - Parameter is an alias for the supplied argument; manipulating the parameter manipulates the calling argument
  - C++ references (we'll see more later)

# Arrays: Call-By-Value or Call-By-Reference?

- **Technical answer:** a `T[]` array parameter is "decayed" to a pointer of type `T*`, and the *pointer* is passed by value
  - So it acts like a call-by-reference array (if callee changes the array parameter elements it changes the caller's array)
  - But it's really a call-by-value pointer (the callee can change the pointer parameter to point to something else(!))

```
void copyArray(int32_t src[],
    int32_t dst[],
    int32_t size) {
  int32_t i;
  for (i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```

```
void copyArray2(int32_t src[],
    int32_t dst[]
    int32_t size) {
  int32_t i;
  int32_t copy[size];
  for (i = 0; i < size; i++) {
    copy[i] = src[i];
  }
  dst = copy;   // doesn't change
                // caller's array
}
```

# Returning an Array

- Local variables, including arrays, are allocated on the Stack
  - They "disappear" when a function returns!
  - Can't safely return local arrays from functions
    - Can't return an array as a return value – why not?

# Solution: Arrays as Output Parameters

- Create the "returned" array in the caller
  - Pass it as an output parameter to `copyarray()`
    - A pointer parameter that allows the called function to store values that the caller can use
  - Works because arrays are "passed" as pointers
    - "Feels" like call-by-reference, *but technically it's not*

call-by-value-of-reference ?!?!

```
void copyArray(int32_t src[], int32_t dst[], int32_t size) {
  int32_t i;

  for (i = 0; i < size; i++) {
    dst[i] = src[i];
  }
}
```

# Other Uses for Output Parameters

- Output parameters are common in library functions
  - `long int strtol(char *str, char **endptr, int base);`
  - `int sscanf(char *str, char *format, ...);`

```
int32_t   num, i;
char *pEnd, *str1 = "333 rocks";
char  str2[10];

// converts "333 rocks" into long -- pEnd is conversion end
num = (int32_t) strtol(str1, &pEnd, 10);

// reads string into arguments based on format string
num = sscanf("3 blind mice", "%d %s", &i, str2);
```

outparam.c

# Extra Exercises

- Some lectures contain "Extra Exercise" slides
  - Extra practice for you to do on your own without the pressure of being graded
  - You may use libraries and helper functions as needed
    - Early ones may require reviewing 351 material or looking at documentation for things we haven't reviewed in 333 yet
  - Always good to provide test cases in `main()`
- Solutions for these exercises will be posted on the course website
  - You will get the most benefit from implementing your own solution before looking at the provided one

# Extra Exercise #1

- Write a function that:
  - Accepts an array of 32-bit unsigned integers and a length
  - Reverses the elements of the array in place
  - Returns nothing (`void`)

# Extra Exercise #2

- Write a function that:
  - Accepts a string as a parameter
  - Returns:
    - The first white-space separated word in the string as a newly-allocated string
    - AND the size of that word