Poll Everywhere

pollev.com/naomila

How is course setup going for you?

Vote for *each* of CSE Linux environment, text editor, and Gitlab/git.

A. Done! Went (relatively) smoothly.

B. Done! Was tough to set up.

C. Still working on it.

D. Haven't tried to set it up yet.

CSE333 Systems Programming

Memory, Data, Parameters

Instructors:

Naomi Alterman

Teaching Assistants:

Ann Baturytski	Barbora Buzkova	Mendel Carroll
Camden Harris	Hannah Hempstead	Rishabh Jain
Irene Lau	Jonathan Nister	Advay Patil
Aviel Wood	Angela Wu	Jennifer Xu

Administrivia

- Pre-quarter survey due Friday, 11:59 PM (link on course website)
- Exercise 1 due Friday morning, 11:00 AM
  - Submission via Gitlab (contact us if you don't have access)
    - Set up an SSH key and clone repos ASAP
    - Clone your repo before section tomorrow!
  - Make sure your solution compiles & runs properly on the CSE Linux environment before submitting
  - No late days for exercises
- Style and linting
  - We're going to push our class linting tool, `cpplint.py`, to your exercise repos today
  - Style grading will initially be lenient and get stricter as the quarter goes on

333 Workflow Aids/Upgrades

- See **Linux → Text Editors** on website for how to configure vim or VS Code for use in this class
  - From vi/vim, can compile and execute code without ever leaving the editor using "`:!<cmd>`"
  - For VS Code, can connect to attu remotely and take advantage of the IDE features
  - From either text editor, you will want to get comfortable navigating and editing multiple files *simultaneously*
- We will learn the basics of Makefiles to simplify the compilation steps into the command `make`
- *Required* as of 26wi: Husky OnNet VPN for off-campus `attu` access

Lecture Outline

- **C Declarations and Definitions**
  - Toolchain considerations
- Memory Management (351 refresher)
- C Data Considerations
- C Parameters

Printing in C

- `int printf(const char* format, ...);`
  - How do we remind ourselves how this works?
  - DOCUMENTATION 😺 !
    - Online: https://www.cplusplus.com/reference/cstdio/printf/
    - Terminal: `man 3 printf`
  - Very important to use correct format specifier for the value you want to print, otherwise implicit casting will occur

specifier	Output	Example
d *or* i	Signed decimal integer	392
u	Unsigned decimal integer	7235
o	Unsigned octal	610
x	Unsigned hexadecimal integer	7fa
X	Unsigned hexadecimal integer (uppercase)	7FA
f	Decimal floating point, lowercase	392.65
F	Decimal floating point, uppercase	392.65
e	Scientific notation (mantissa/exponent), lowercase	3.9265e+2
E	Scientific notation (mantissa/exponent), uppercase	3.9265E+2
g	Use the shortest representation: %e or %f	392.65
G	Use the shortest representation: %E or %F	392.65
a	Hexadecimal floating point, lowercase	-0xc.90fep-2
A	Hexadecimal floating point, uppercase	-0XC.90FEP-2
c	Character	a
s	String of characters	sample
p	Pointer address	b8000000

Error Handling

- Errors and Exceptions
  - C does not have exception handling (no `try/catch`)
  - Errors are returned as **integer error codes** from functions
    - Because of this, error handling is ugly and inelegant
    - For readability, CONSTANT_NAMES are defined to abstract away the actual integer values – need to look up in documentation
  - Global variable **`errno`** holds value of last system error
- Status codes and signals
  - Processes exit (*e.g.*, `return` from **`main`**) with status code
    - Standard codes found in `stdlib.h`:
      `EXIT_SUCCESS` (usually 0) and `EXIT_FAILURE` (non-zero)
  - "Crashes" trigger signals from OS (*e.g.*, SIGSEGV for segfault)

Function Definitions

- Generic format:

```
ReturnType FuncName(type param1, …, type paramN) {
   // statements
}
```

```
// sum of integers from 1 to max
int sumTo(int max) {
  int i, sum = 0;

  for (i = 1; i <= max; i++) {
    sum += i;
  }

  return sum;
}
```

Function Ordering

- You *shouldn't* call a function that hasn't been declared yet

Note: code examples from slides are posted on the course website for you to experiment with!

sum_badorder.c

```
int main(int argc, char** argv) {
  printf("sumTo(5) is: %d\n", sumTo(5));
  return EXIT_SUCCESS;
}

// sum of integers from 1 to max
int sumTo(int max) {
  int i, sum = 0;

  for (i = 1; i <= max; i++) {
    sum += i;
  }
  return sum;
}
```

Solution 1: Reverse Ordering

- Simple solution; however, imposes ordering restriction on writing functions (who-calls-what?)

sum_betterorder.c

```
// sum of integers from 1 to max
int sumTo(int max) {
  int i, sum = 0;

  for (i = 1; i <= max; i++) {
    sum += i;
  }
  return sum;
}

int main(int argc, char** argv) {
  printf("sumTo(5) is: %d\n", sumTo(5));
  return EXIT_SUCCESS;
}
```

Solution 2: Function Declaration

STYLE TIP

- Teaches the compiler the arguments and return types; function definitions can then be in a logical order
  - Function comment usually by the *prototype*

Declared

sum_declared.c

```
// sum of integers from 1 to max
int sumTo(int max);  // func prototype

int main(int argc, char** argv) {
  printf("sumTo(5) is: %d\n", sumTo(5));
  return EXIT_SUCCESS;
}

int sumTo(int max) {
  int i, sum = 0;
  for (i = 1; i <= max; i++) {
    sum += i;
  }
  return sum;
}
```

Defined

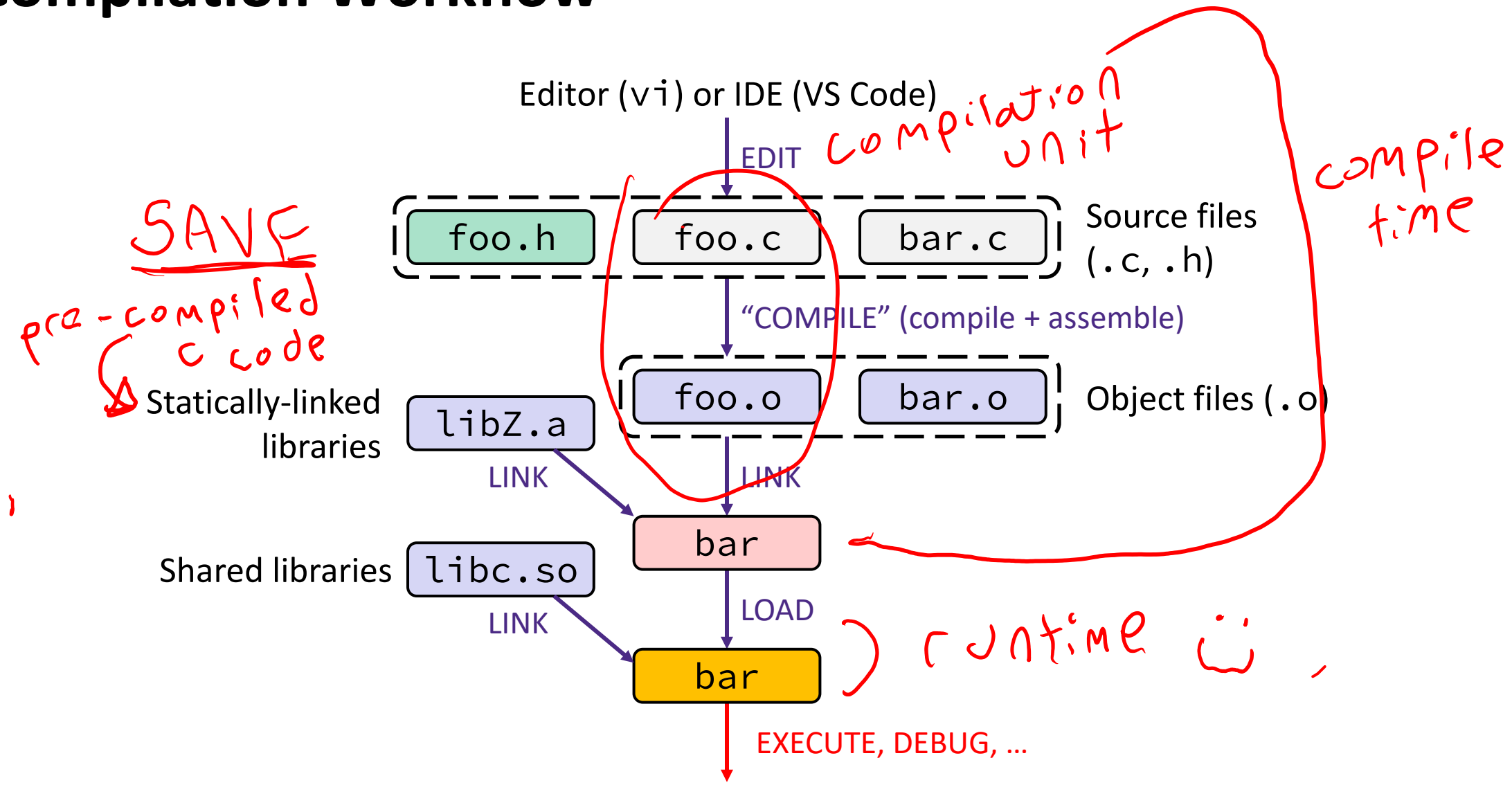
Function Declaration vs. Definition

- C/C++ make a careful distinction between these two

- Definition: The thing itself
  - *e.g.*, code for function, variable definition that creates storage
  - Must be **exactly one** definition of each thing (no duplicates)

- Declaration: Description of a thing
  - *e.g.*, function prototype, external variable declaration
    - Often in header files and incorporated via `#include`
    - Should also `#include` declaration in the file with the actual definition to check for consistency
  - Needs to appear in **all files** that use that thing
    - Should appear before first use

C Compilation Workflow



Multi-file C Programs

Note: This example has poor style for code split. More on multiple files in Lecture 5.

C source file 1 (sumstore.c)

```
void SumStore(int x, int y, int* dest) {
  *dest = x + y;
}
```

C source file 2 (sumnum.c)

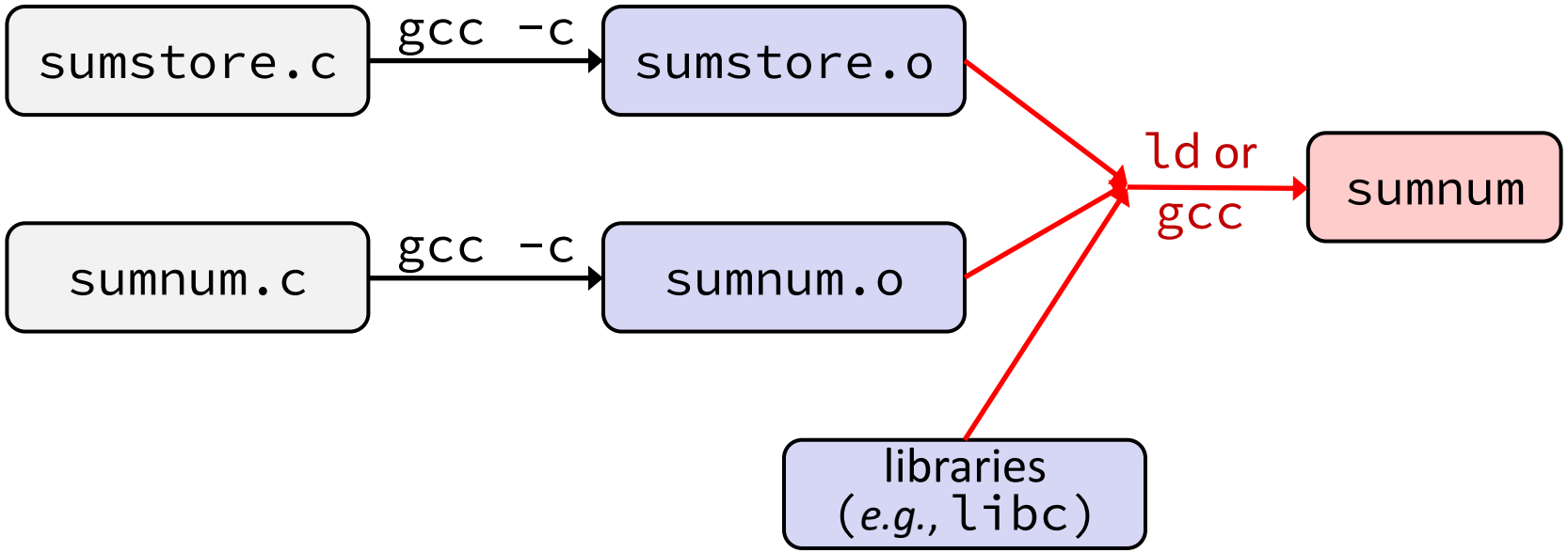
```
#include <stdio.h>
#include <stdlib.h>

void SumStore(int x, int y, int* dest);

int main(int argc, char** argv) {
  int z, x = 351, y = 333;
  SumStore(x, y, &z);
  printf("%d + %d = %d\n", x, y, z);
  return EXIT_SUCCESS;
}
```

Compile together:

```
$ gcc -o sumnum sumnum.c sumstore.c
```

Compiling Multi-file Programs

- The **linker** combines multiple object files plus statically-linked libraries to produce an executable
  - Includes many standard libraries (*e.g.*, `libc`, `crt1`)
    - A *library* is just a pre-assembled collection of `.o` files

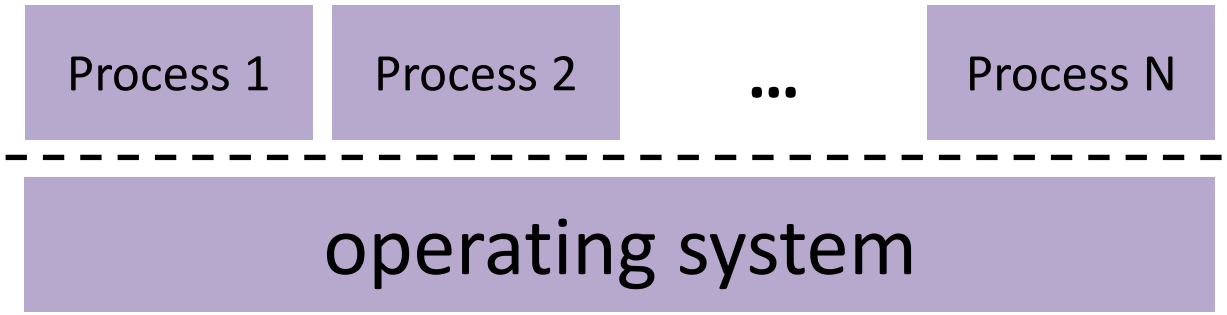


Lecture Outline

- C Declarations and Definitions
- **Memory Management** (351 refresher)
- C Data Considerations
- C Parameters

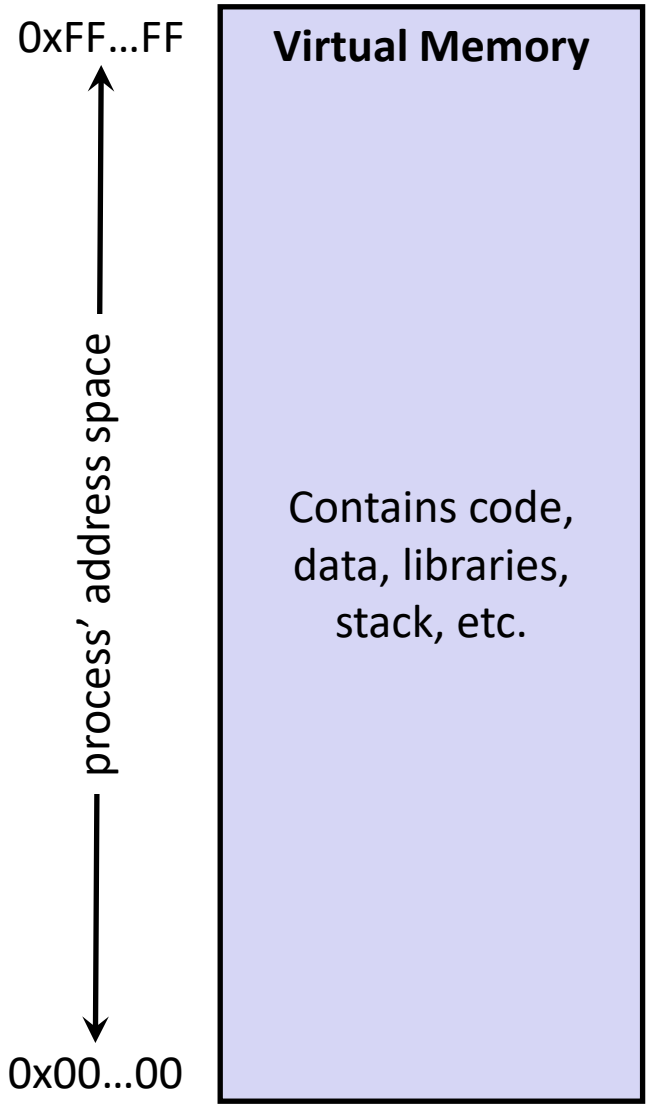
OS and Processes

- 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*: ~100 times per second



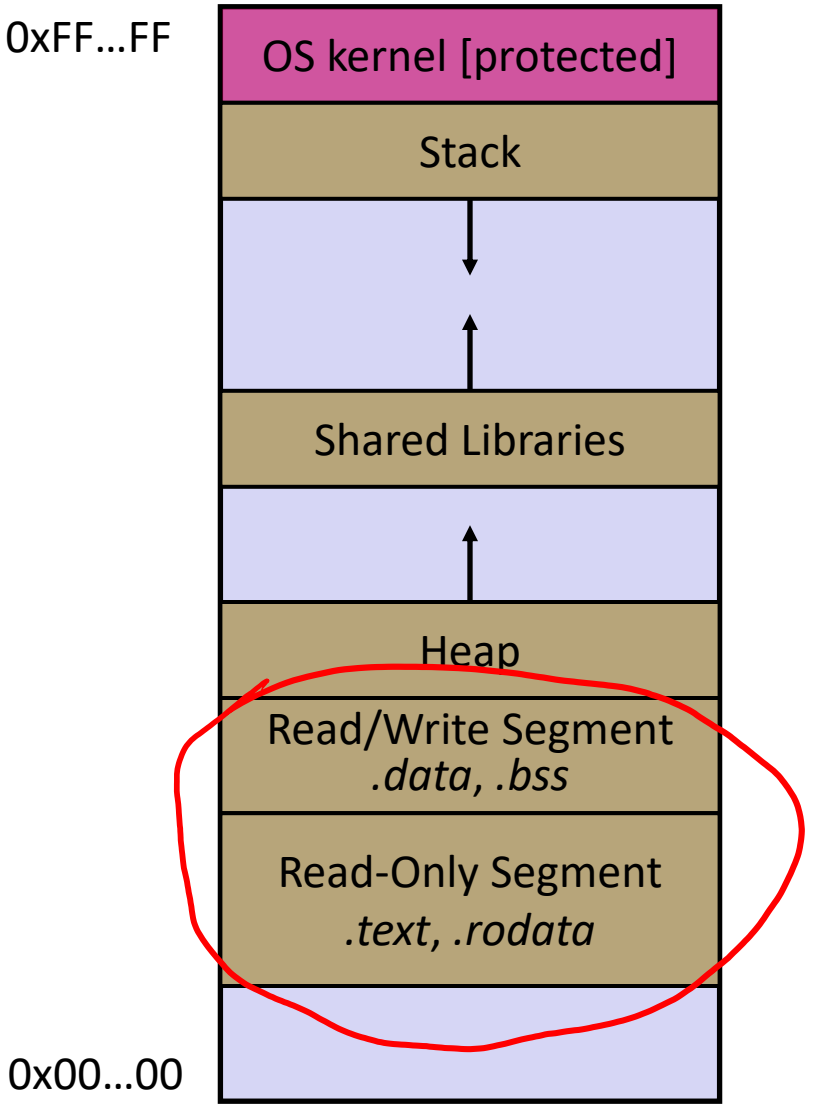
Processes and Virtual Memory

- 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



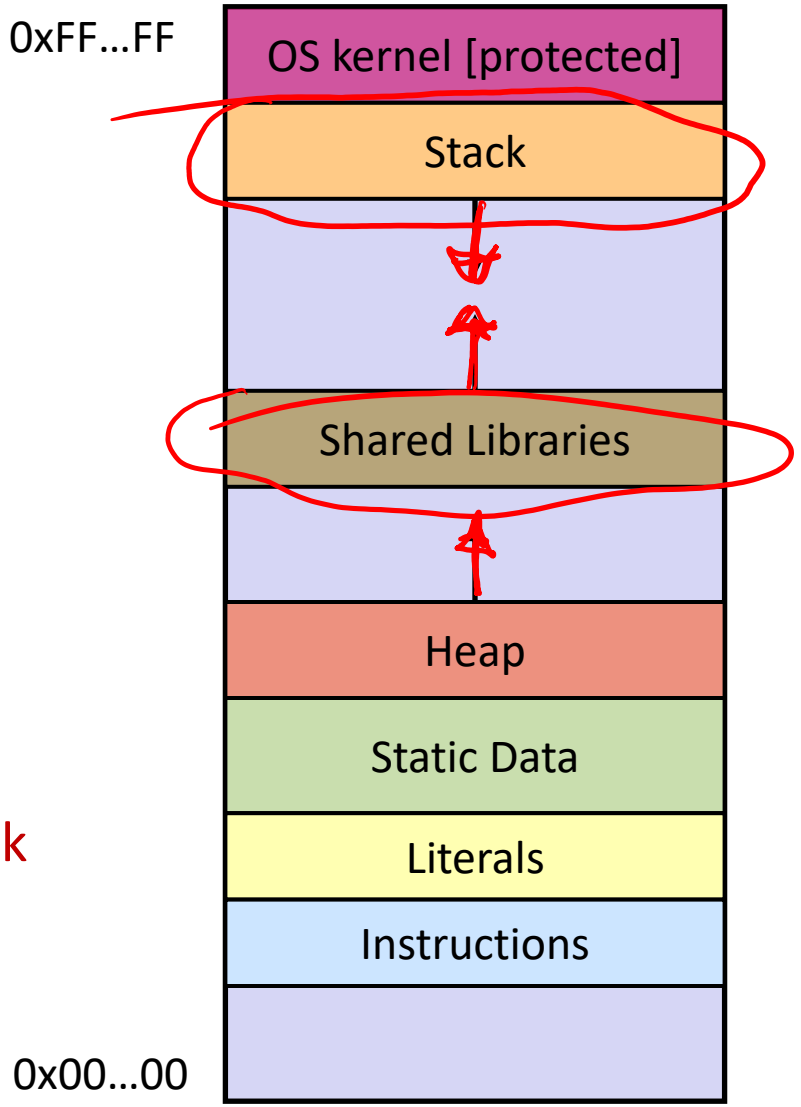
Loading

- 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



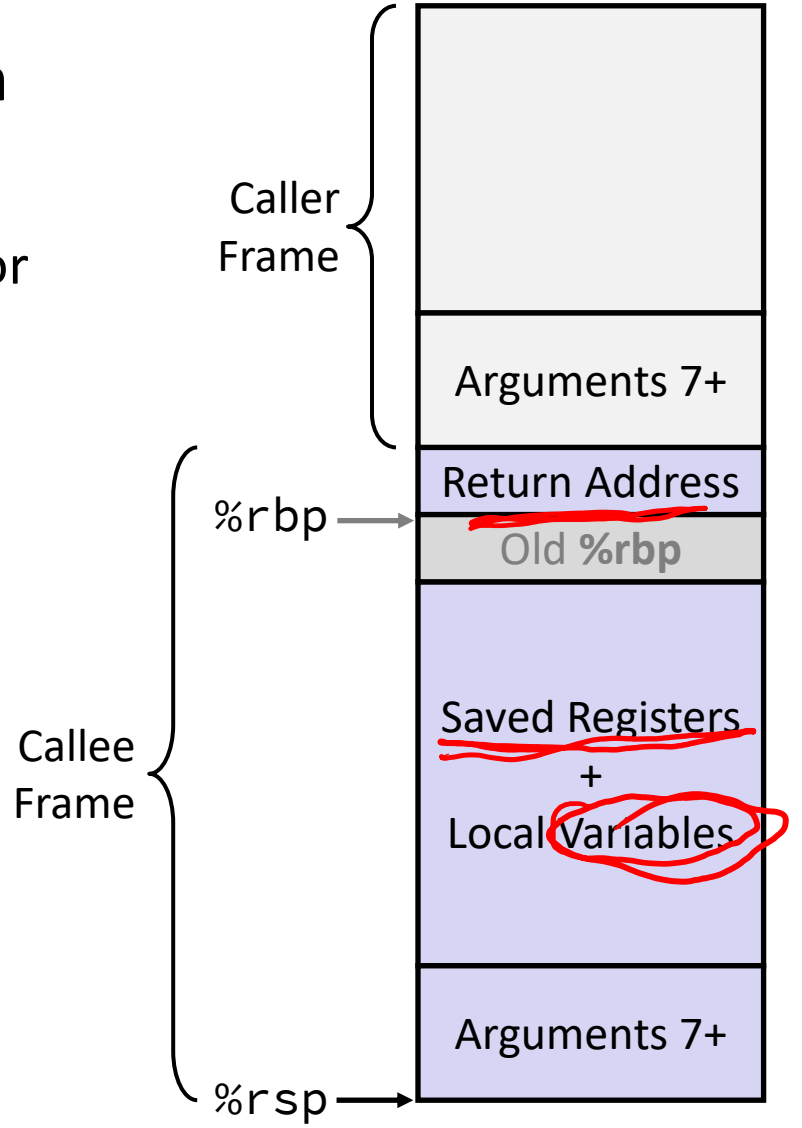
Memory Management

- *Local* variables on the Stack
  - **Automatically-**allocated and deallocated via calling conventions (`push`, `pop`, `mov`)
- *Global* and *static* variables in Data
  - **Statically-**allocated when the process starts and deallocated when it exits
- `malloc`-ed data on the Heap
  - **Dynamically**-allocated by process
  - Must call `free()` to free, otherwise a memory leak



Review: The Stack

- Used to store data associated with function calls
  - 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

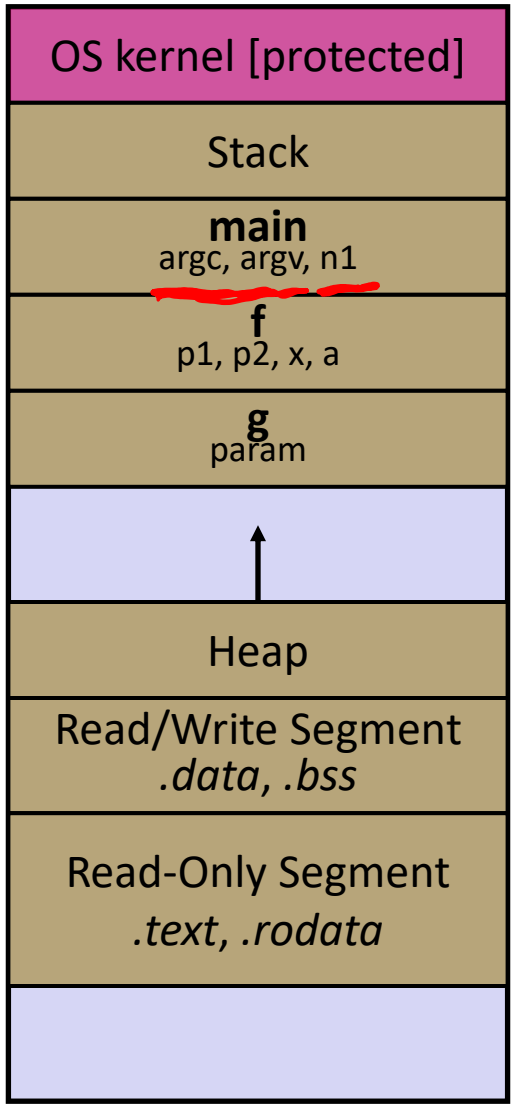


Stack in Action (1/4)

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

stack.c

```
#include <stdlib.h>

int f(int, int);
int g(int);

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

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

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

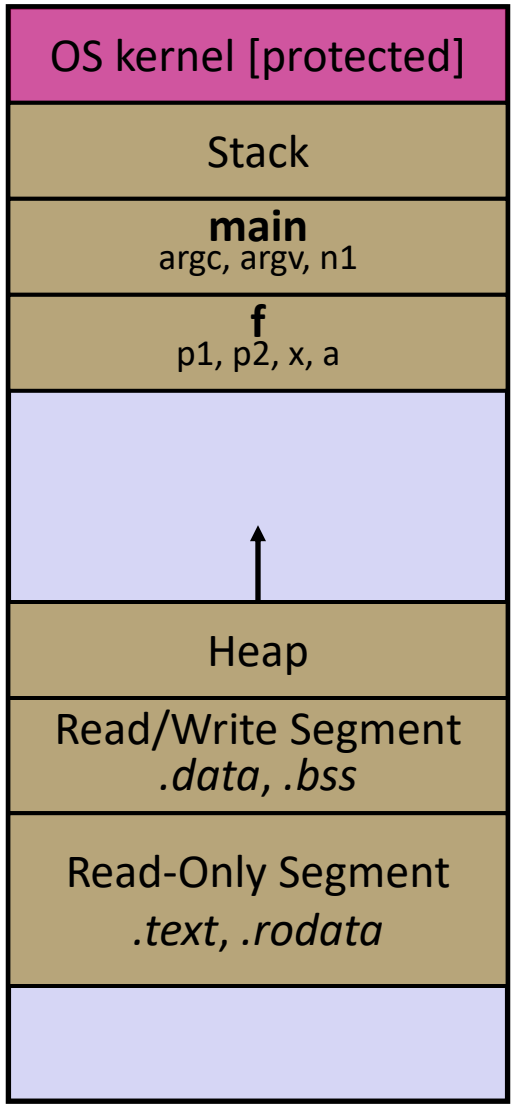


Stack in Action (2/4)

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

stack.c

```
#include <stdlib.h>

int f(int, int);
int g(int);

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

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

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

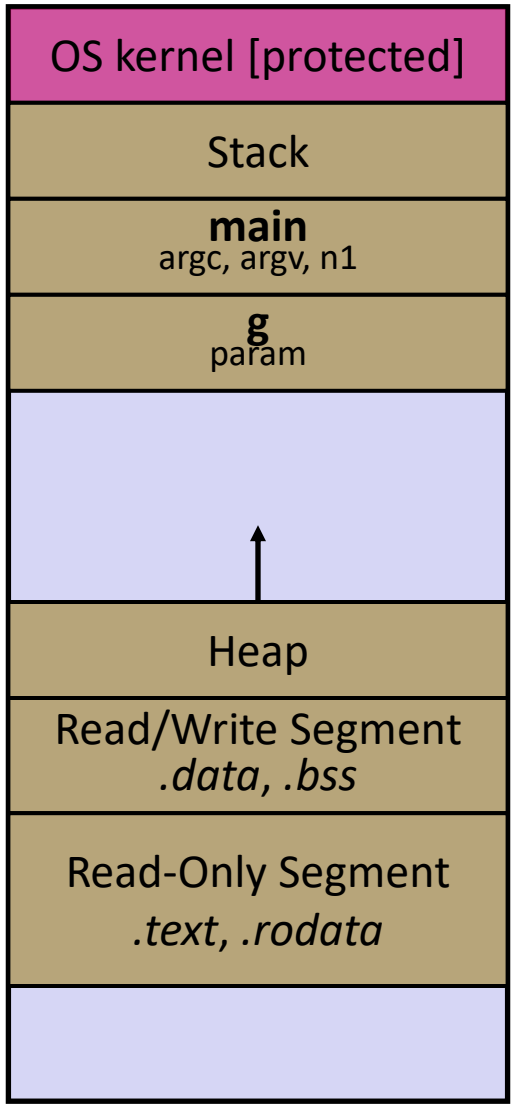


Stack in Action (3/4)

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

stack.c

```
#include <stdlib.h>

int f(int, int);
int g(int);

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

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

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



Stack in Action (4/4)

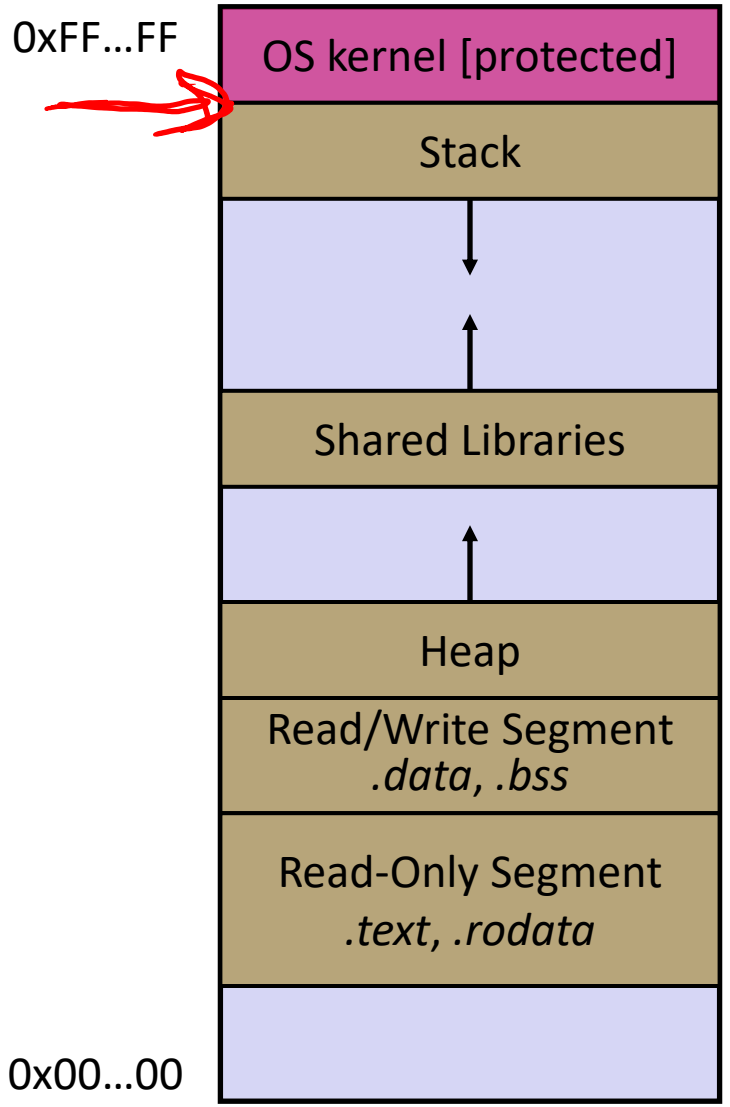
Note: arrow points to *next* instruction to be executed (like in gdb).

stack.c

```c
#include <stdlib.h>

int f(int, int);
int g(int);

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

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

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

Neato trivia: Address Space Layout Randomization

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



Lecture Outline

- C Declarations and Definitions
- Memory Management (351 refresher)
- **C Data Considerations**
- Parameters

C Primitive Types and Memory

- Integer types
  - `char`, `int`
- Floating point
  - `float`, `double`
- Modifiers
  - `short` [int]
  - `long` [int, double]
  - `signed` [char, int]
  - `unsigned` [char, int]

Do not memorize, these aren't strict sizes!

C Data Type	32-bit	64-bit	printf
char	1	1	%c
short int	2	2	%hd
unsigned short int	2	2	%hu
int	4	4	%d / %i
unsigned int	4	4	%u
long int	4	8	%ld
long long int	8	8	%lld
float	4	4	%f
double	8	8	%lf
long double	12	16	%Lf
pointer	4	8	%p

C99 Extended Integer Types

- Solves the conundrum of "how big is an `long int`?"

```
#include <stdint.h>

void foo(void) {
  int8_t  a;  // exactly 8 bits, signed
  int16_t b;  // exactly 16 bits, signed
  int32_t c;  // exactly 32 bits, signed
  int64_t d;  // exactly 64 bits, signed
  uint8_t w;  // exactly 8 bits, unsigned
  ...
}
```

```
void sumstore(int x, int y, int* dest) {
```

```
void sumstore(int32_t x, int32_t y, int32_t* dest) {
```

Arrays

- Definition: `type name[size]` allocates `size*sizeof(type)` bytes of *contiguous* memory
  - By default, array values are "mystery" data (*i.e.*, uninitialized)
  - Normal usage is a compile-time constant for `size`
    e.g., `int scores[175];`

- Size of an array
  - Not stored anywhere – array does not know its own size!
    - `sizeof(array)` only works in the 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*]

```
int n = 175;
int 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 used as identifier for "collection of data"
  - Array name produces the address of the start of the array
    - Cannot be assigned to / changed
  - `name[index]` specifies an element of the array and can be used as an assignment target or as a value in an expression
    - Is actually `*(name+index)` with pointer arithmetic (Lecture 3)

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

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 discussed 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 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
  - (will need to either wait for Lecture 4 or review malloc/free on your own)