Poll Everywhere

pollev.com/cse333a

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.**

Systems Programming

Memory, Data, Parameters

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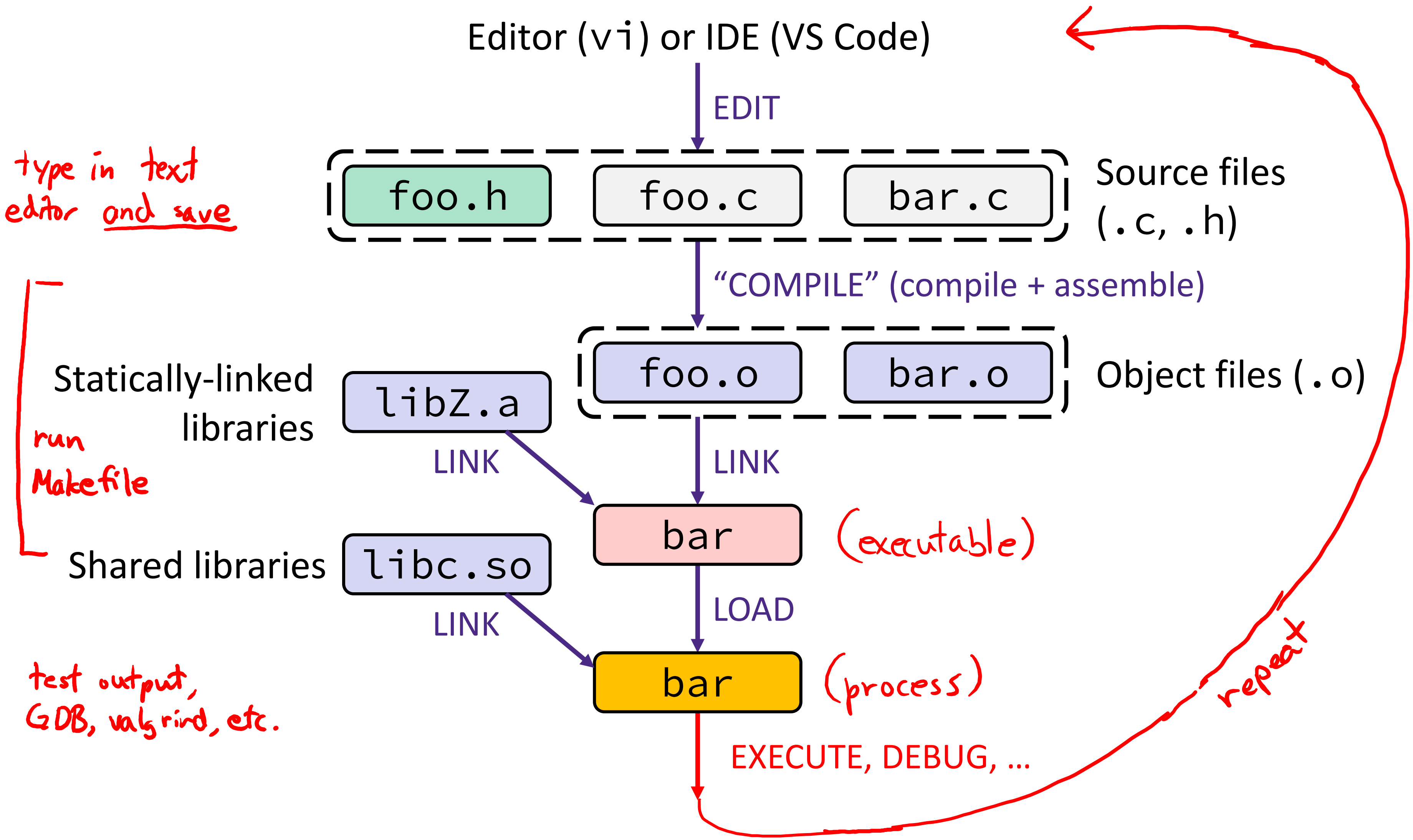
Relevant Course Information (1/2)

- Pre-quarter survey due Friday, 11:59 pm (Canvas)
- Exercise 0 was due at 11:00 am today
  - No late days for exercises
  - Solutions have been released
  - Style issues Ed post will be released soon
  - Ex 0 grades will be released before Ex 2 is due
- Exercise 1 due Friday morning, 11:00 am
  - Submission via Gradescope (contact us if you don't have access)
  - Make sure your solution compiles & runs properly on the CSE Linux environment before submitting

Relevant Course Information (2/2)

- Starting with Exercise 2 (released Friday), all submissions will be done via Gitlab tagging
  - We will submit to Gradescope from your repo for you
  - Gitlab email sent when repos created – no action needed
    - Make a private Ed post if you don't have your repos yet
  - Set up an SSH key and clone repos ASAP
  - Clone your repo before section tomorrow!

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) {   ← defined here
  *dest = x + y;
}
```

C source file 2 (sumnum.c)

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

void SumStore(int x, int y, int* dest);   ← declared here

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

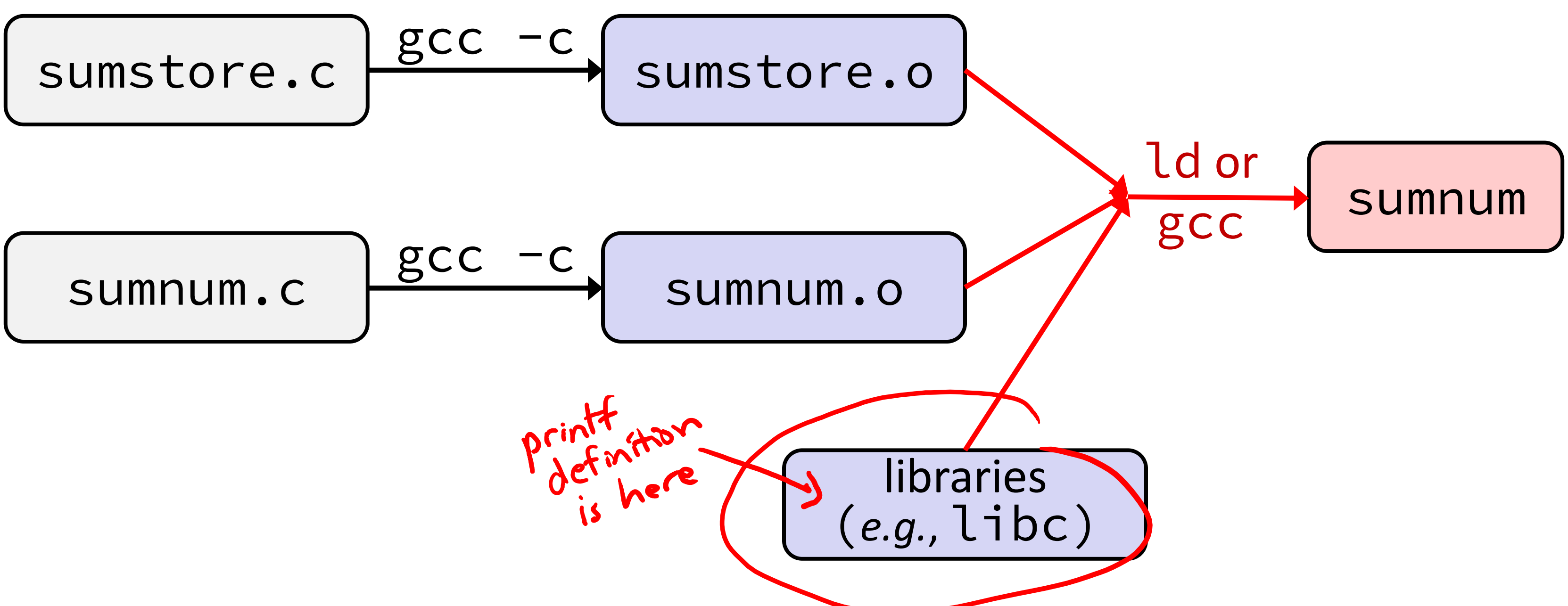
Compile together:

both files included during compilation

```
$ 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



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Which of the following statements are FALSE?

A. With the standard `main` syntax, it is always safe to use `argv[0]` ← will be the name of the executable

B. Your program's returned status code is unimportant

C. Using function declarations is beneficial to both single- and multi-file C programs
single : flexible ordering of functions
multi : use definitions in other files

D. Defined error constants need to be looked up in function documentation, man pages, or header files like errno.h

E. We're lost…

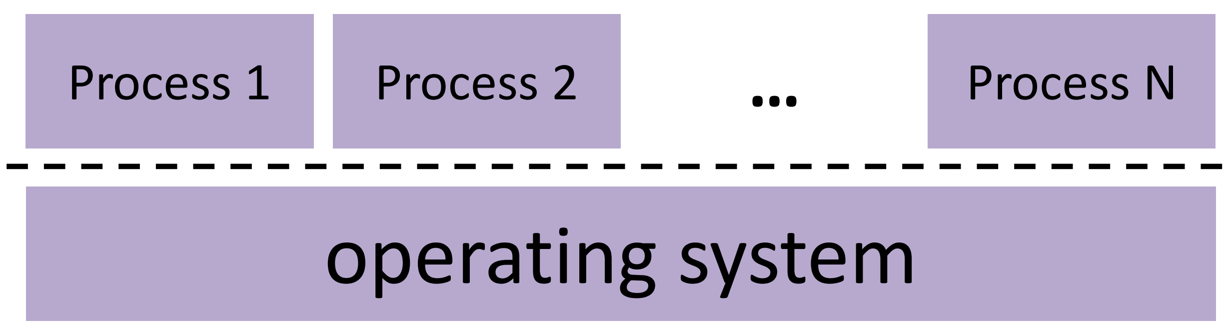
Lecture Outline (1/3)

- **Memory Management** (351 refresher)
- C Data Considerations
- C Parameters
  - Arrays and Pointers as Parameters

OS and Processes

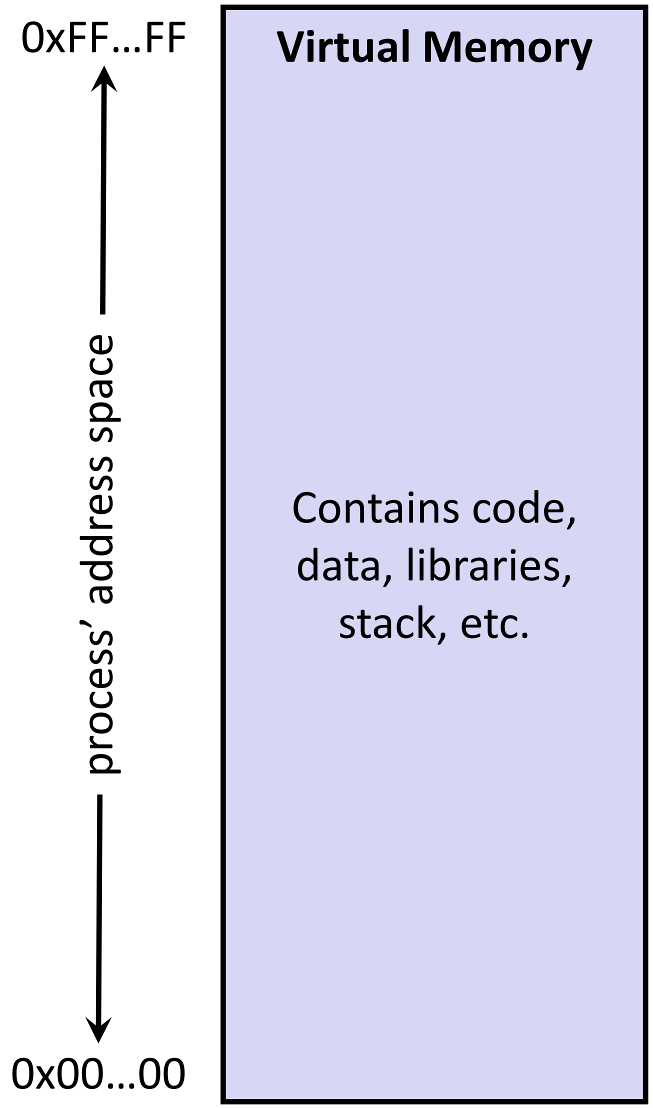
- The OS lets you run multiple applications at once
  - An application runs within an OS "process"
  - The OS time slices each CPU between runnable processes
    - This happens *very quickly*: ~100 times per second

context switching



Processes and Virtual Memory

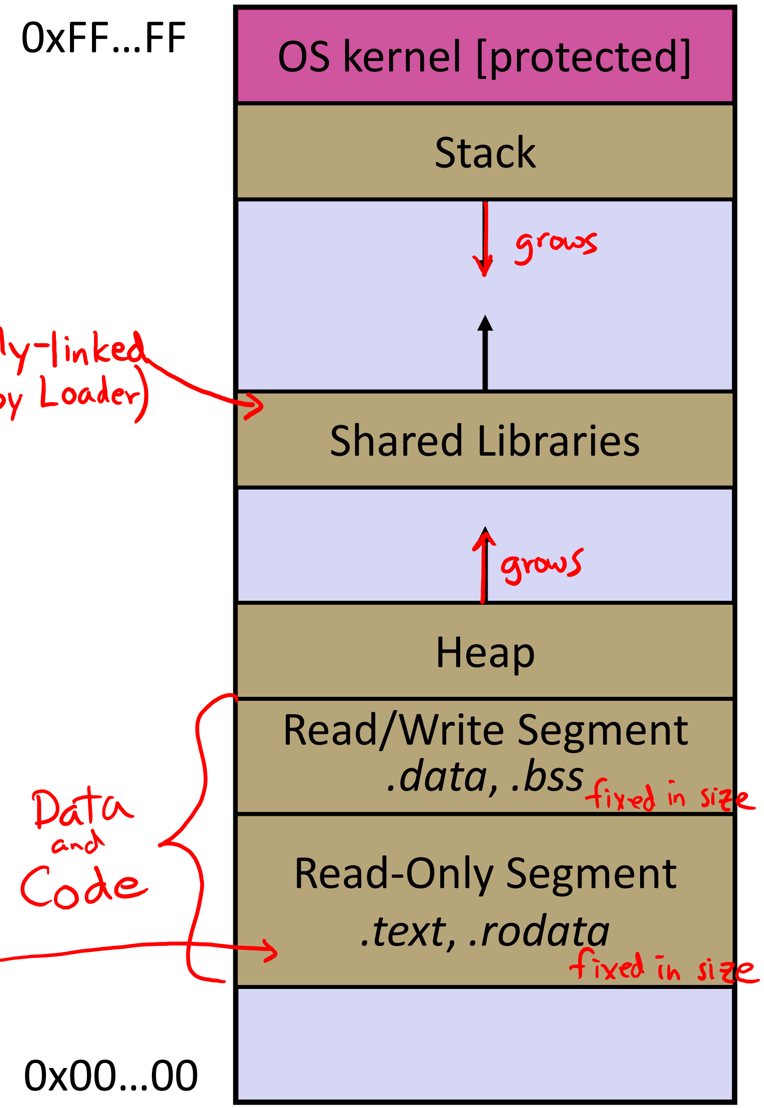
- The OS gives each process the illusion of its own private memory
  - Called the process' address space
  - Contains the process' virtual memory, visible only to it (via translation)
  - 2^{64} bytes on a 64-bit machine



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

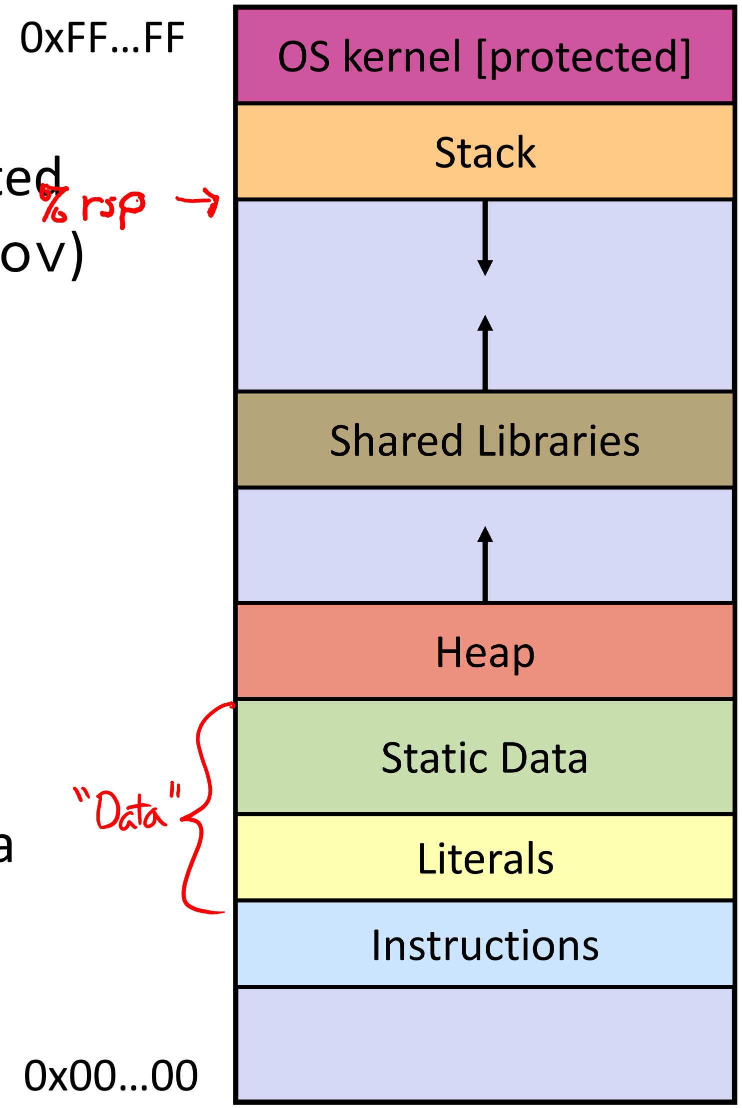
dynamically-linked libraries (by Loader)



statically-linked libraries (by Linker)

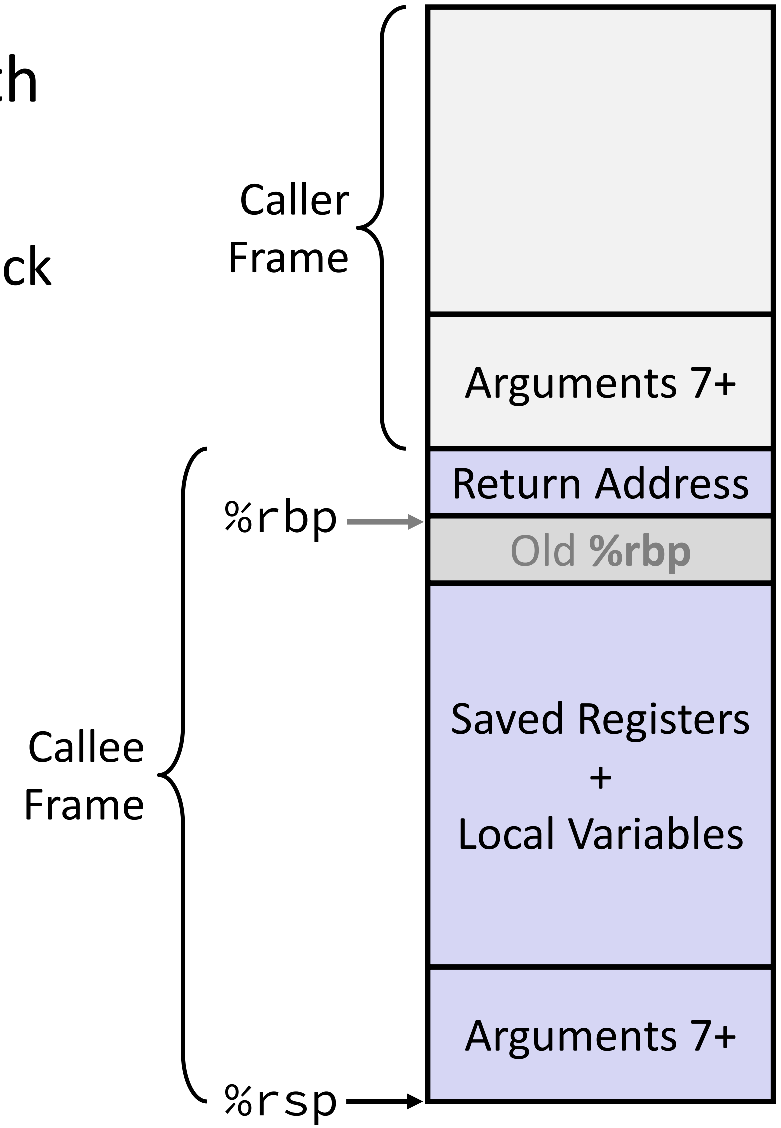
Memory Management

- *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

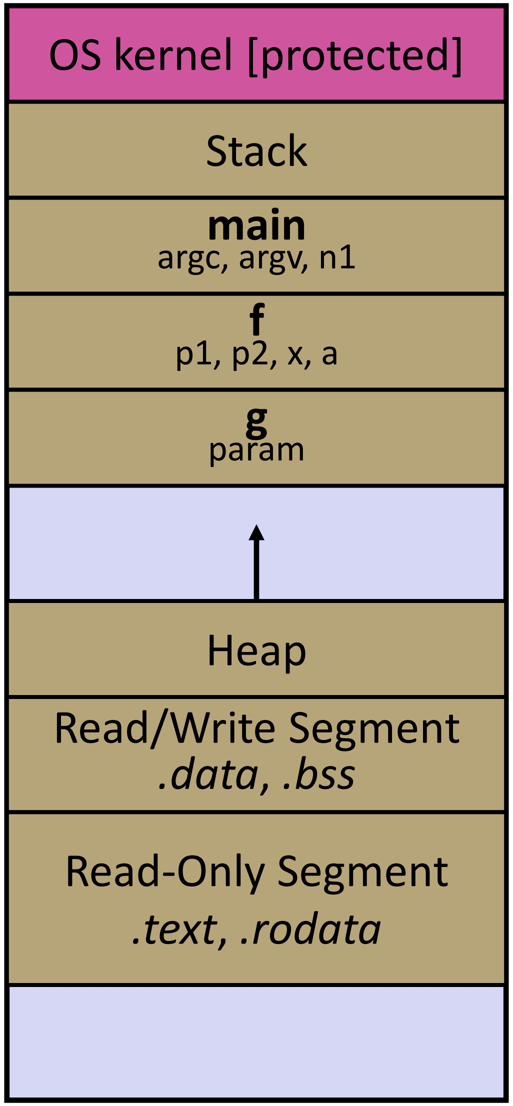


Stack in Action (1/4)

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;
}
```

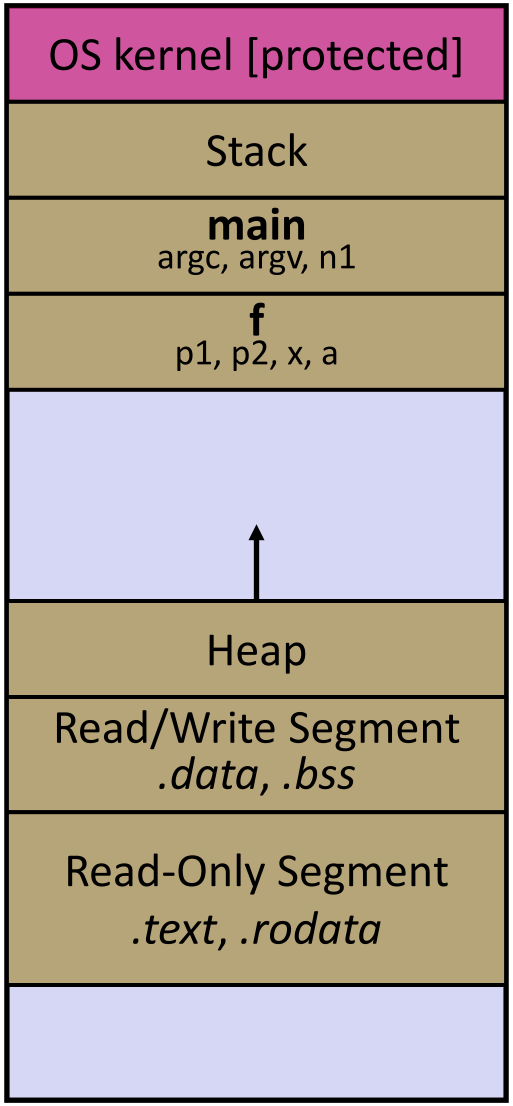


Stack in Action (2/4)

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;
}
```

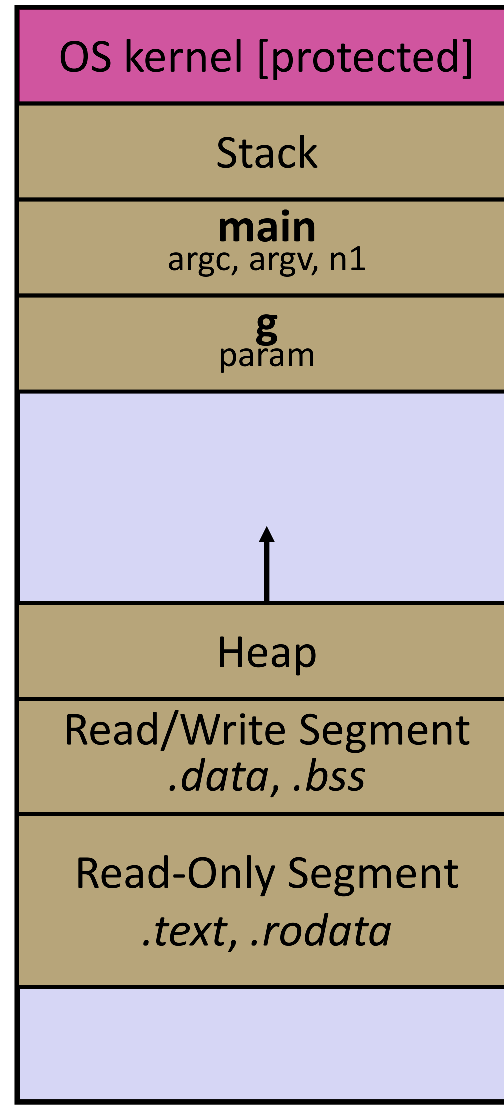


Stack in Action (3/4)

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;
}
```

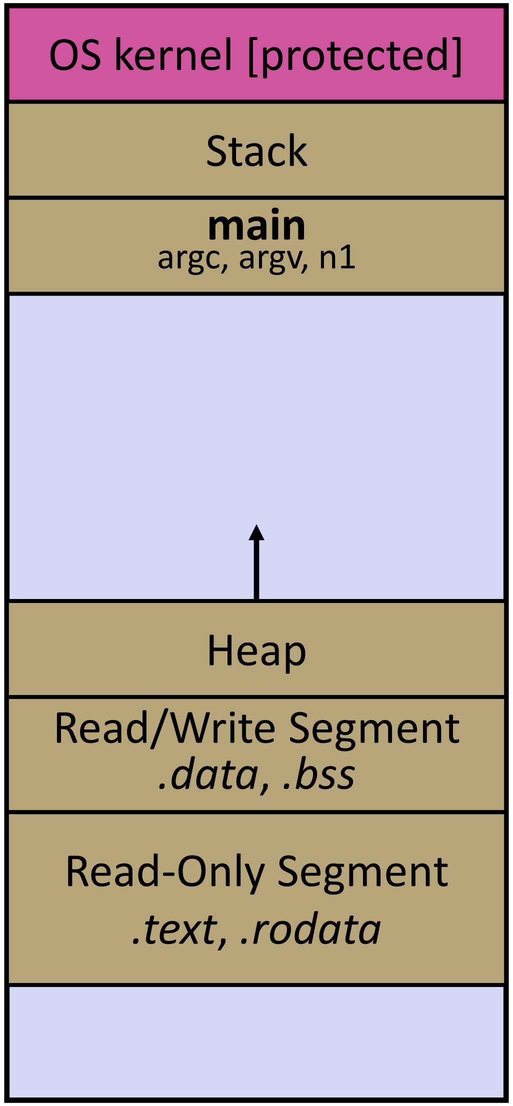


Stack in Action (4/4)

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

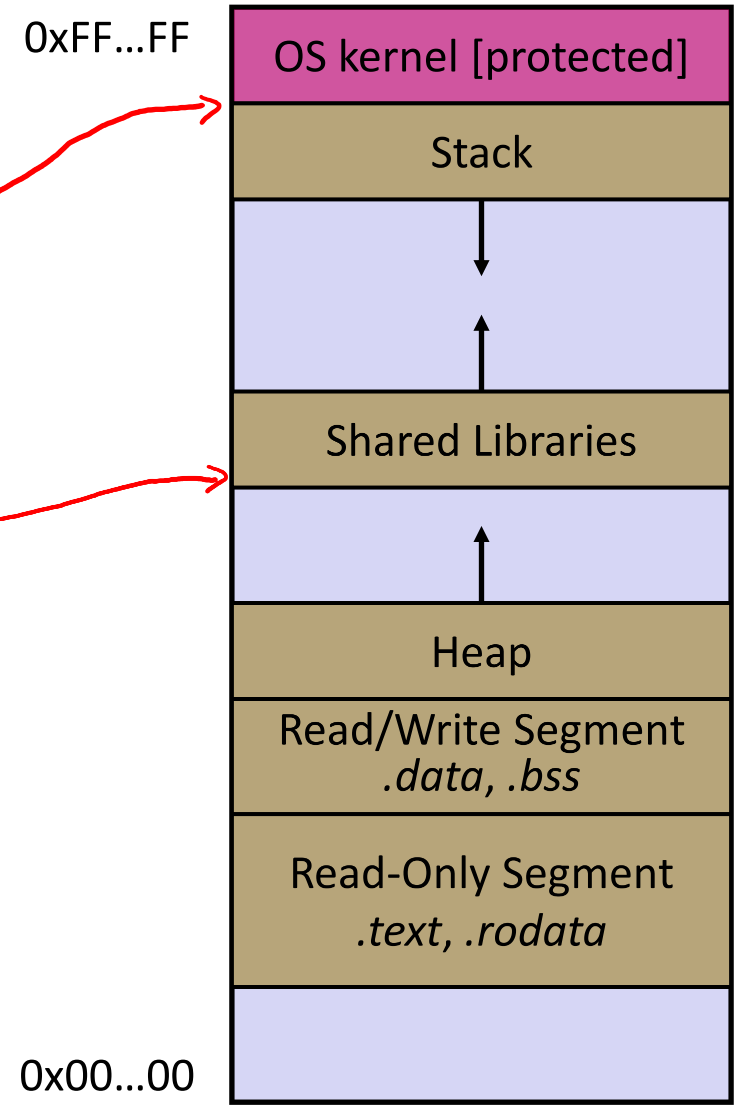
stack.c

```
#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;
}
```



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 (2/3)

- 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

STYLE TIP

C99 Extended Integer Types

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

```
#include <stdint.h>  ← types defined here

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
  ...
}
```

fine for generic C code

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

needed for "system" code – use appropriately

```
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

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"
  - 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)

not necessary

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

(hope for segfault)

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
int matrix[3][5] = {
  {0, 1, 2, 3, 4},
  {0, 2, 4, 6, 8},
  {1, 3, 5, 7, 9}
};
```

  - 2-D arrays normally only useful if size known in advance; otherwise, use dynamically-allocated data

Structs

- The *size* and *layout* of a struct instance is completely determined by (1) the field ordering and (2) alignment requirements
  - Can review 351 if curious
- In practical terms, wouldn't solve for these by hand; use built-in C functionality instead:
  - `sizeof(type)` returns the size in bytes
  - `offsetof(type, field)` returns offset value in bytes
    - Defined in `stddef.h`
- We'll talk more about struct usage in Lecture 4

Lecture Outline (3/3)

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

Parameters: Reference vs. Value

- There are two fundamental parameter-passing schemes in programming languages
- Call-by-value / "Pass-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 / "Pass-by-reference"
  - Parameter is an alias for the supplied argument; manipulating the parameter manipulates the calling argument
  - C++ references (we'll see these 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

get address of start of array

```
int SumAll(int a[]);  // prototype

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

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

Solution 1: Declare Array Size

```
int SumAll(int a[5]);  // prototype

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

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

- Problem: loss of generality/flexibility

Solution 2: Pass Size as Parameter

```
int SumAll(int a[], int size);  // prototype

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

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

arraysum.c

- Standard idiom in C programs!

Arrays: Call-by-what?

- Technical answer: a `T[]` array parameter is "promoted" to a pointer of type `T*`, and the *pointer* is passed by value
  - So it acts like a *call-by-reference* *__array__* – caller's array can be changed if callee modifies the array parameter elements
  - But it's really a *call-by-value* *__pointer__* – the callee's pointer parameter can be changed without affecting the caller's array
    - This is because `T[i]` is really `*(T+i)`. We aren't changing T!

```
void CopyArray(int src[], int dst[], int size) {
  int i;
  dst = src;  // doesn't copy the array, copies the address
  for (i = 0; i < size; i++) {
    dst[i] = src[i];  // copies source array to itself
  }
}
```

Array Parameters

STYLE TIP

- Array parameters are *actually* passed as pointers to the first array element
  - The `[]` syntax for parameter types is just for convenience
    - Use whichever best helps the reader

This code:

```
void f(int a[]);

int main( ... ) {
  int a[5];
  ...
  f(a);
  return EXIT_SUCCESS;
}

void f(int a[]) {
```

pointer

array

Equivalent to:

```
void f(int* a);

int main( ... ) {
  int a[5];
  ...
  f(&a[0]);
  return EXIT_SUCCESS;
}

void f(int* a) {
```

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?

returns address has to fit in %rax

```
int* CopyArray(int src[], int size) {
  int i, dst[size];   // OK in C99

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

  return dst;   // no compiler error, but wrong!
}
```

returns address of start of local array on Stack

buggy_copyarray.c

Solution: Output Parameter

- 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

no return value!

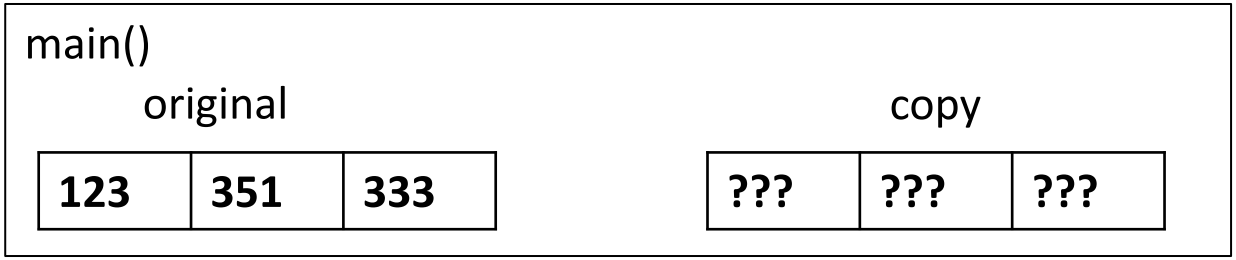
```
void CopyArray(int src[], int dst[], int size) {
  int i;

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

output parameter used to "pass" data to caller

data stored by dereferencing pointer

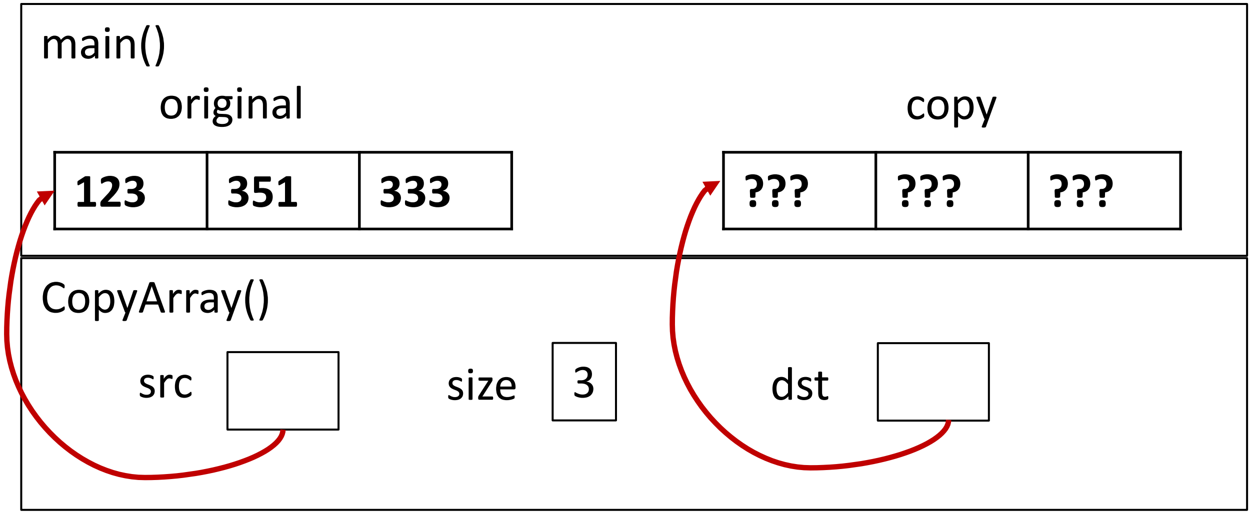
copyarray.c

Array Memory Diagram (1/3)




```c
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

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

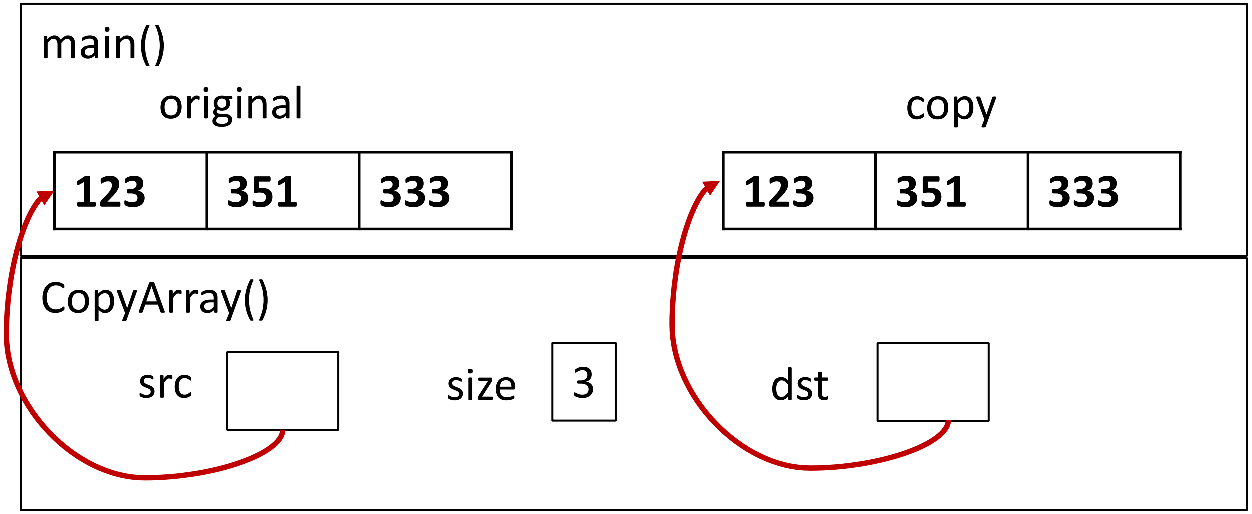
Array Memory Diagram (2/3)




```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

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

`dst[i]` is really `*(dst+i)`. We aren't changing `dst`!

Array Memory Diagram (3/3)




```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  CopyArray(original, copy, 3);
}

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

`dst[i]` is really `*(dst+i)`. We aren't changing `dst`!

Output Parameters

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

output parameters

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

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

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

333

"returns" data in 2 ways!

stores data in corresponding output params

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