Memory and Arrays
CSE 333

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Administrivia (1)

- Exercise 0 was due this morning
  - Let us know if you had any issues
    - cse333-staff@cs.washington.edu
  - Sample solution was posted earlier and linked to calendar
    - Requires CSE login; please do not distribute
      - Non-CSE students should have received guest accounts for the quarter. Let us know if you're not set up, but we'll probably need for you to contact support[at]cs to get it resolved
- Exercise 1 out today, due Friday morning @ **10 am**

Administrivia (2)

- Reference system for grading is *current* CSE lab/attu/VM
  - For both exercises and homework (project) code
  - It's your job to be sure your solution(s) work there

- If you're having any problems with attu, let us know ASAP! Support has had some issues with some attu accounts this quarter, but they should be resolved now.

Administrivia (3)

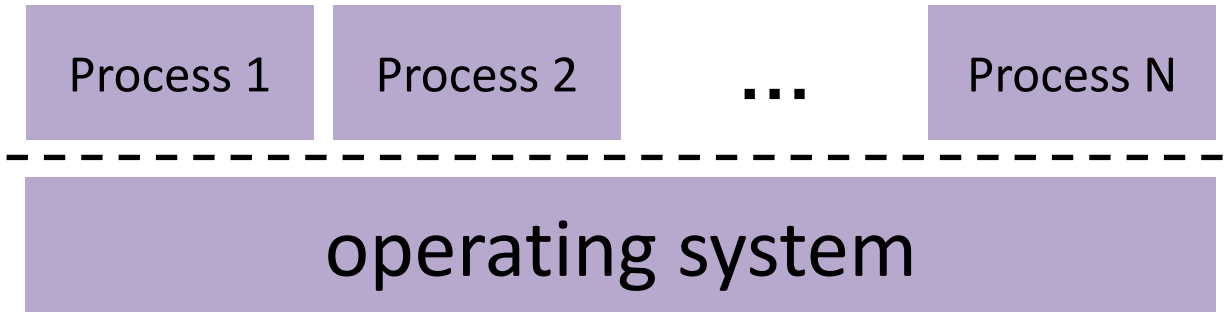
- Homework 0 out today
  - Due Monday @ **11 pm**
  - Logistics and infrastructure for projects – should be quick
- Homework 1 will be posted and pushed to repos next Wednesday (1 week from today) – read and get started as soon as it's out
  - Linked list and hash table implementations in C
  - Please read the spec and start looking at the code next week
    - For large projects, you must pace yourself so if something baffling happens, you can let it go for the day and come back to it tomorrow

Lecture Outline

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

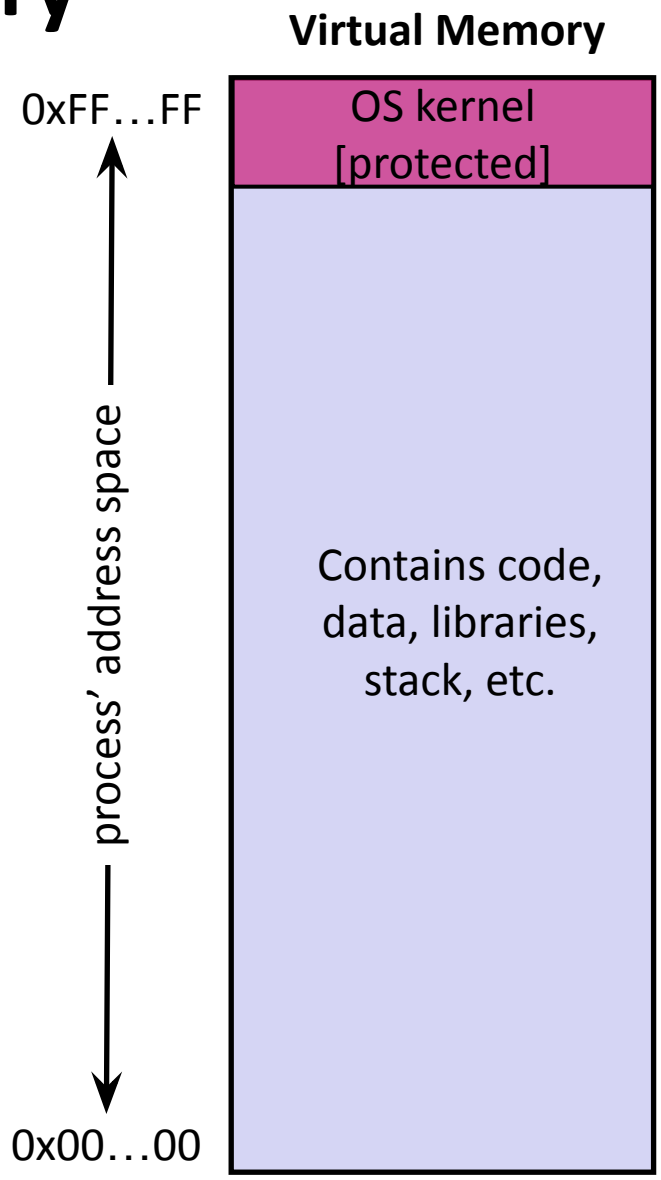
OS and Processes

- The OS lets you run multiple applications at once
  - An application runs within an OS "process"
  - The OS timeslices 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
  - Mostly unstructured from the OS's perspective



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) (As needed) copies regions of the file into the right place in the address space
  4) Does any final linking, relocation, or other needed preparation

Lecture Outline

- OS Processes (refresher)
- **C's Memory Model** (refresher)
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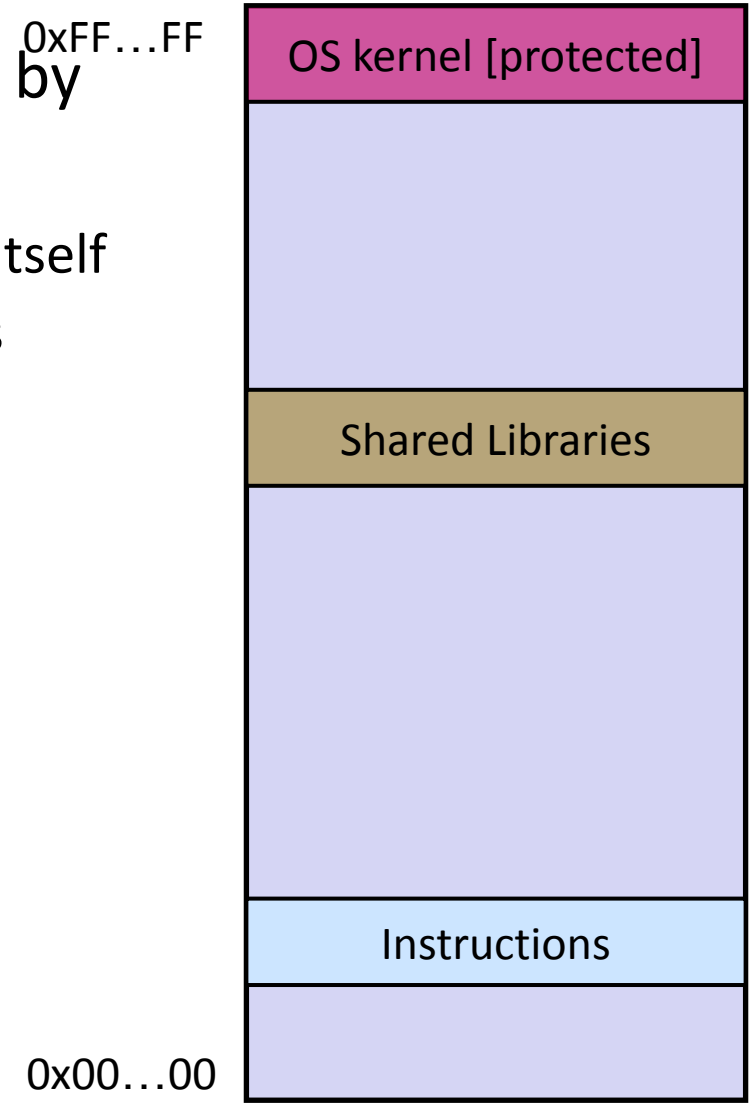
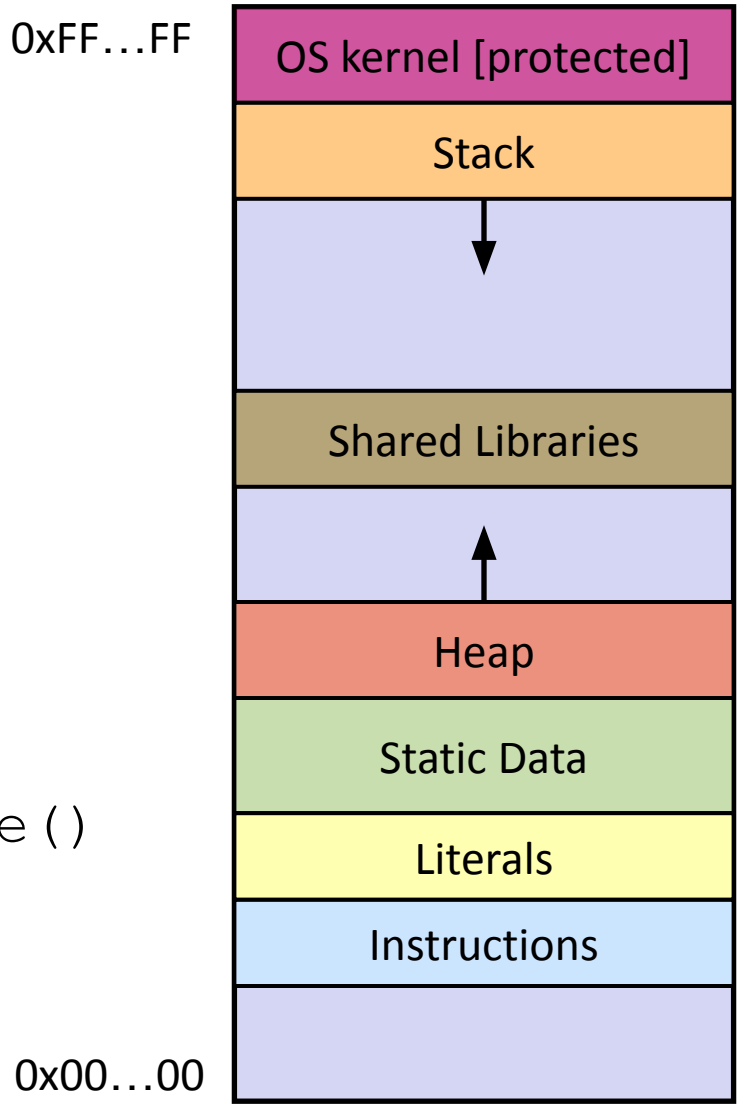
Memory Management

- Instructions are placed in memory by the OS
  - Includes instructions from the binary itself as well as dynamically loaded libraries



Memory Management

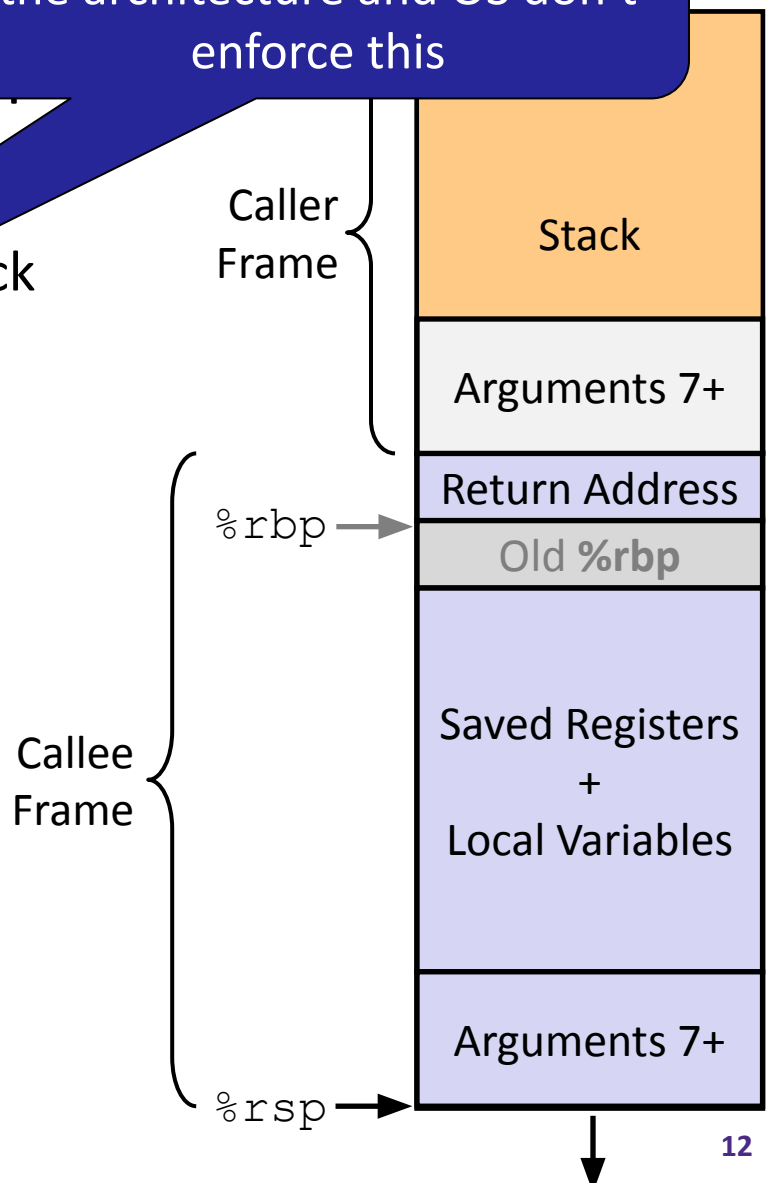
- *Local* variables on the Stack
  - **Automatically** allocated and freed via calling conventions (`push`, `pop`, `mov`)
- *Global* and *static* variables in Data
  - **Statically** alocated/freed when the process starts/exits
- ***Dynamically**-allocated* data on the Heap
  - `malloc()` to request; must call `free()` to release, otherwise memory leak



Review: The Stack

- Used to store data associated wi… function calls
  - Compiler-inserted code mana… stack frames for you
- Stack frame (x86-64) includes:
  - Address to return to
  - Saved registers
    - Based on calling conventions
  - Local variables
  - Argument values
    - Only if > 6 used

Technically, just a convention; the architecture and OS don't enforce this



Stack in Action

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

stack.c

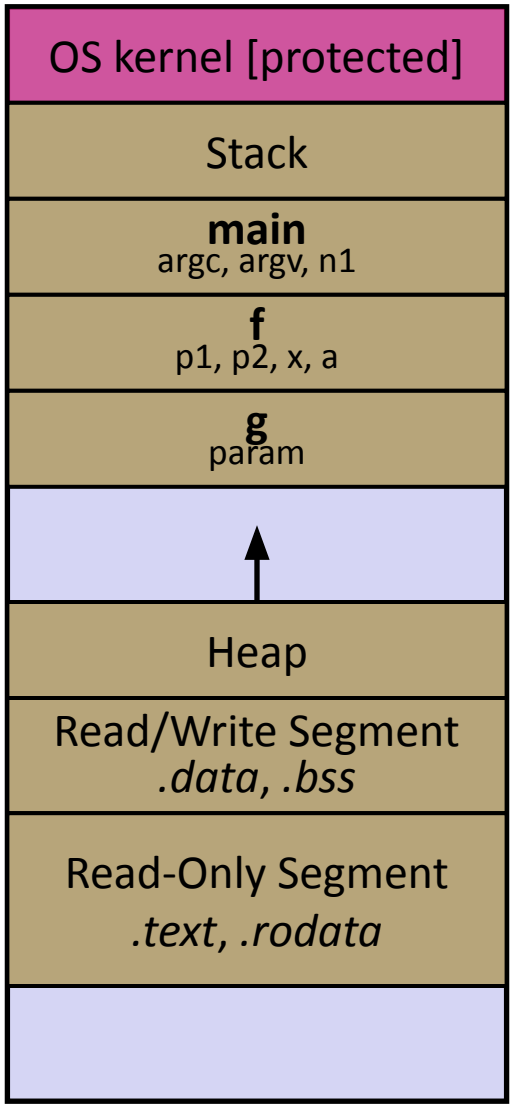
```
#include <stdint.h>

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

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

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

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



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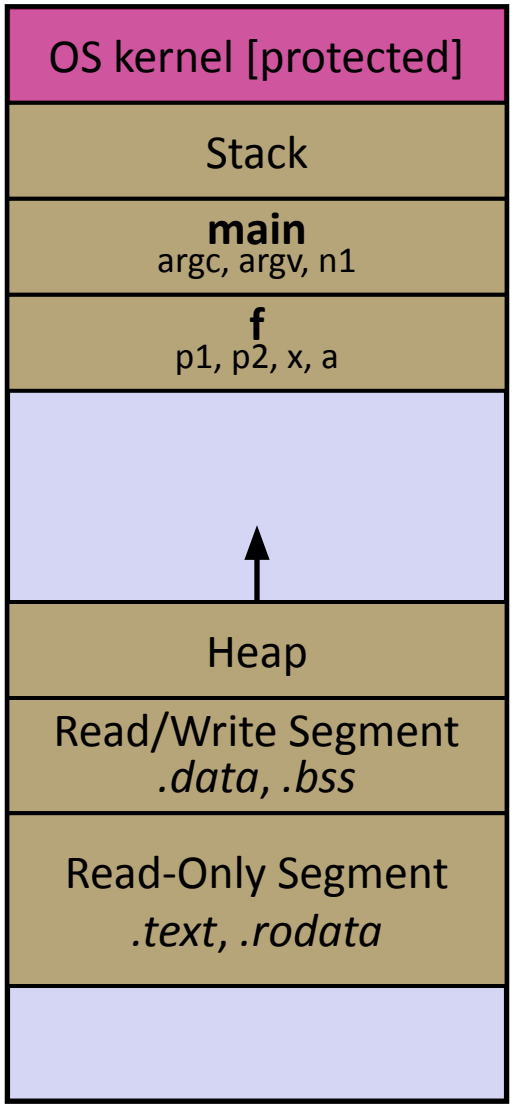
  int x;
  int a[3];
  ...
  x = g(a[2]);
  return x;
}

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



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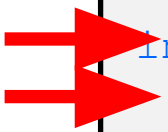
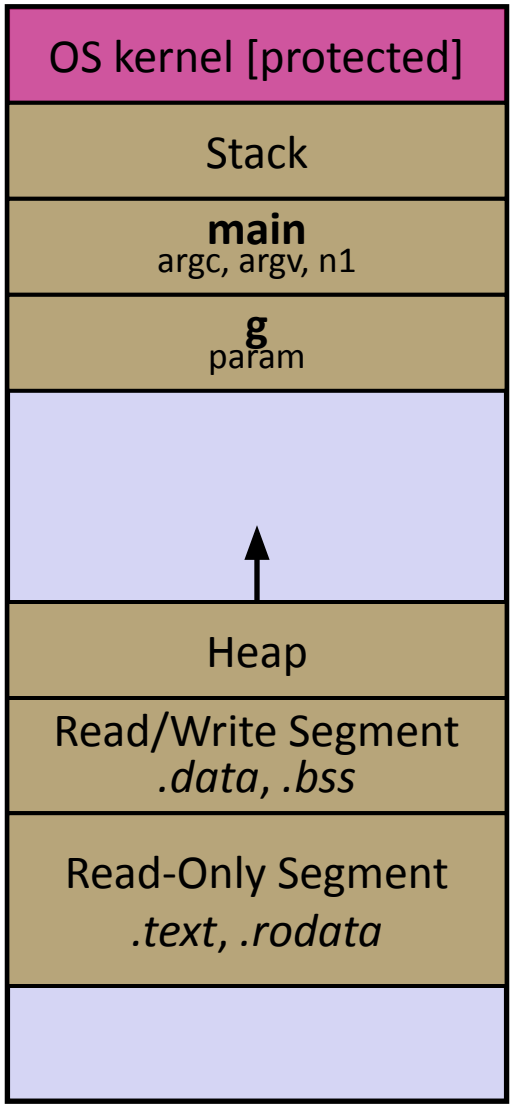
int main(int argc, char** argv) {
  int n1 = f(3,-5);
  n1 = g(n1);
}

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

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stack.c

```
#include <stdint.h>

int f(int, int);
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int main(int argc, char** argv) {
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  n1 = g(n1);
}

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  int a[3];
  ...
  x = g(a[2]);
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  return param * 2;
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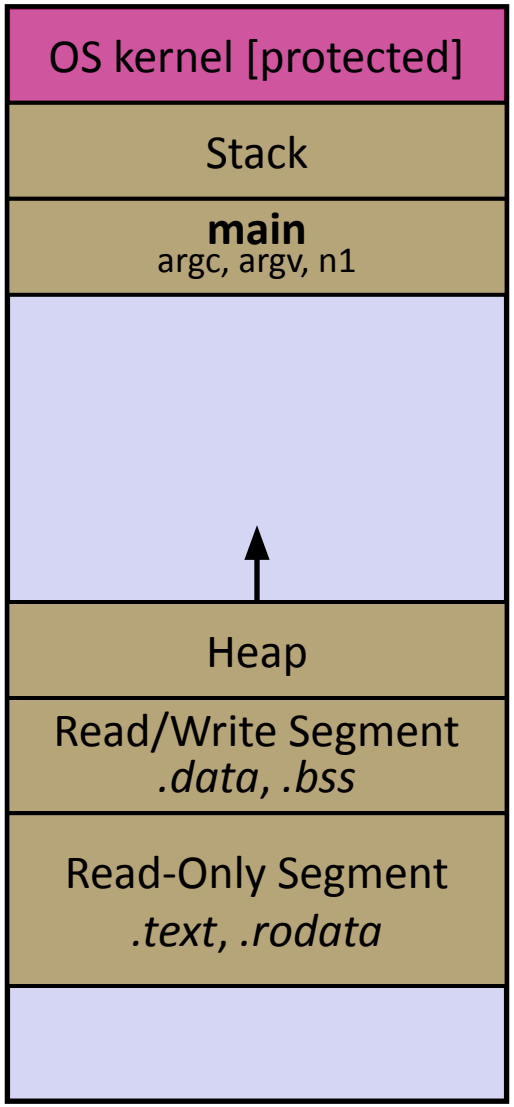
```



Lecture Outline

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

Pointers

- Variables that store addresses
  - It points to somewhere in the process' virtual address space
- 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;
    ```
- Create a pointer using the unary `&` operator
  - Example: `int* foo_ptr = &foo;`
- Follow ("*dereference*") a pointer using the unary `*` operator
  - Access the memory referred to by a pointer
  - Example: `int bar = 5 + *foo_ptr;`

Pointer Example

pointy.c

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

int main(int argc, char** argv) {
  int x = 351;
  int* 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 value of x
  printf(" x is %d\n",  x);
  // prints the same value
  printf(" *p is %d\n",  *p);

  return 0;
}
```

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

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

It's going to be a long one! let's take another five minute break to get up and stretch (and drink water)

(Local) Arrays

- Definition: `type name[num_elems];`
  - Allocates `num_elems*sizeof(type)` bytes of *contiguous* memory on the *stack*
  - Initially, array values are "garbage" (i.e., uninitialized, unknown)

- Size of an array
  - Not stored anywhere at runtime – array does not know its own size!
    - `sizeof(array)` only works in variable scope of array definition
  - Normal usage is a compile-time constant for `size` (*e.g.* `int scores[175];`)
  - Recent versions of C (but *not* C++) allowed variable-length arrays

```
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

```
int fibs[] = {1, 1, 2, 3, 5, 8}; // this is okay
```

- 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 n… start of the arra…

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

Multi-dimensional Arrays

- Generic 2D format:

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

  - Still allocates a single, contiguous chunk of memory
  - C stores arrays in *row-major* order

```
// 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 statically in advance. Otherwise use dynamically-allocated data and pointers (later)

Box-and-Arrow Diagrams

boxarrow.c

```
int main(int argc, char** argv) {
  int x = 1;
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return EXIT_SUCCESS;
}
```

address	**name**	value

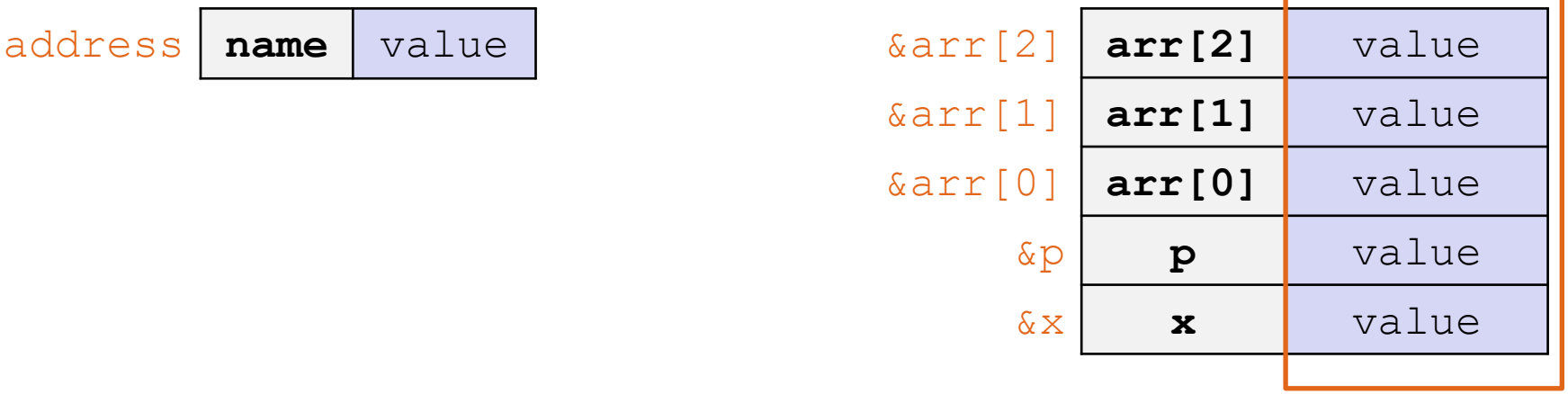
Box-and-Arrow Diagrams

boxarrow.c

```
int main(int argc, char** argv) {
  int x = 1;
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return EXIT_SUCCESS;
}
```



Box-and-Arrow Diagrams

boxarrow.c

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  int x = 1;
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
  printf("&arr[0]: %p;  arr[0]: %d\n", &arr[0], arr[0]);
  printf("&arr[2]: %p;  arr[2]: %d\n", &arr[2], arr[2]);
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return EXIT_SUCCESS;
}
```

address	name	value

&arr[2]	**arr[2]**	4
&arr[1]	**arr[1]**	3
&arr[0]	**arr[0]**	2
&p	**p**	&arr[1]
&x	**x**	1

Box-and-Arrow Diagrams

boxarrow.c

```
int main(int argc, char** argv) {
  int x = 1;
  int arr[3] = {2, 3, 4};
  int* p = &arr[1];

  printf("&x: %p;  x: %d\n", &x, x);
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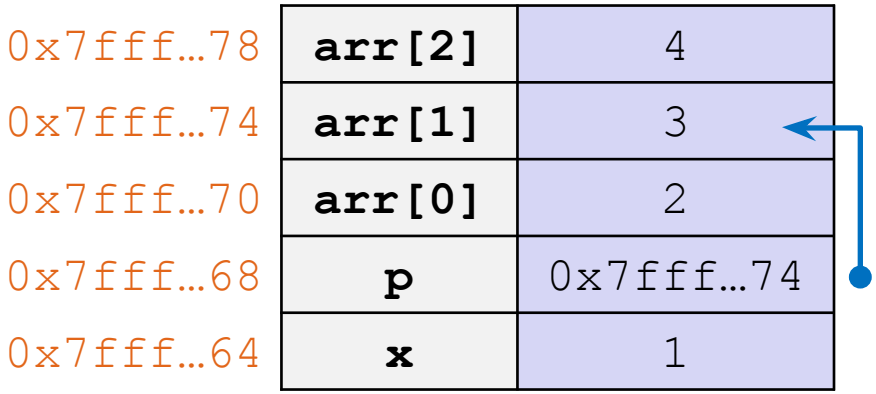
  printf("&p: %p; p: %p; *p: %d\n", &p, p, *p);

  return EXIT_SUCCESS;
}
```

address	name	value



Arrays as Parameters

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

```
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

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?

```
int* copyArray(int src[], int size
  int i, dst[size];   // allowed i

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

  return dst;
}
```

No compiler error, but wrong! Returns a pointer to abandoned memory

buggy_copyarray.c

Solution: Output Parameter

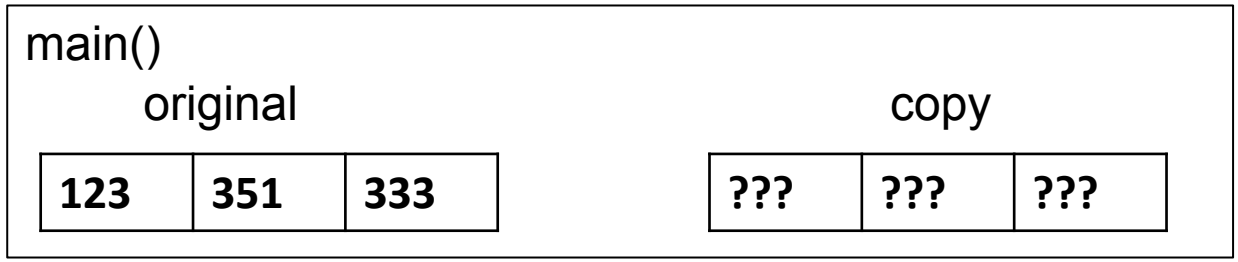
- Create the "returned" array in the caller
  - Pass it as an output parameter to `copyarray()`
  - "output parameter": A pointer parameter that allows the called function to store values that the caller can use
  - Works because arrays are "passed" as pointers

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

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

copyarray.c

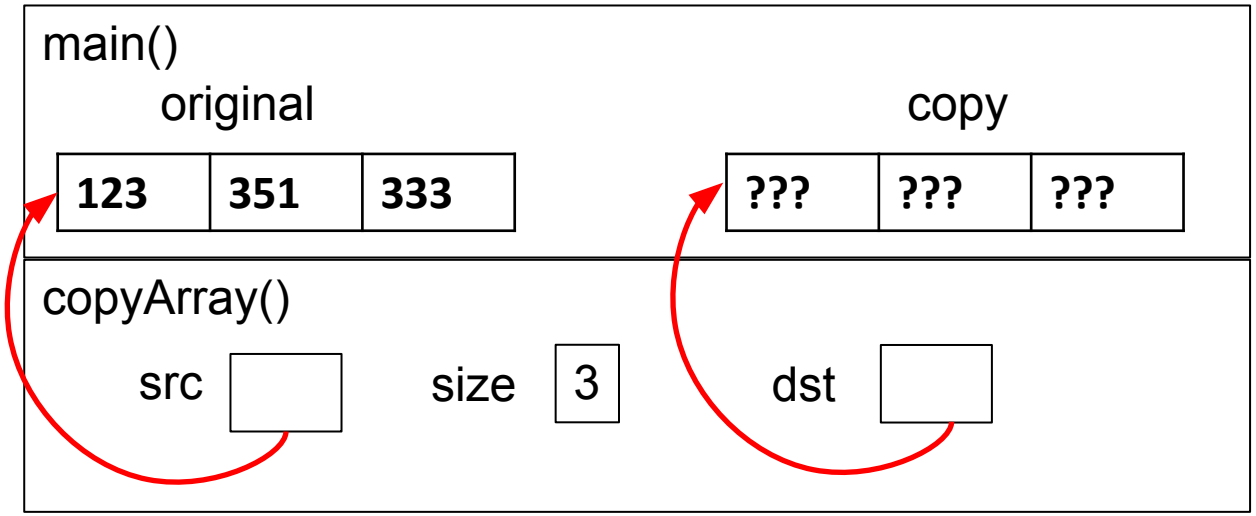
Array Memory Diagram




```
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

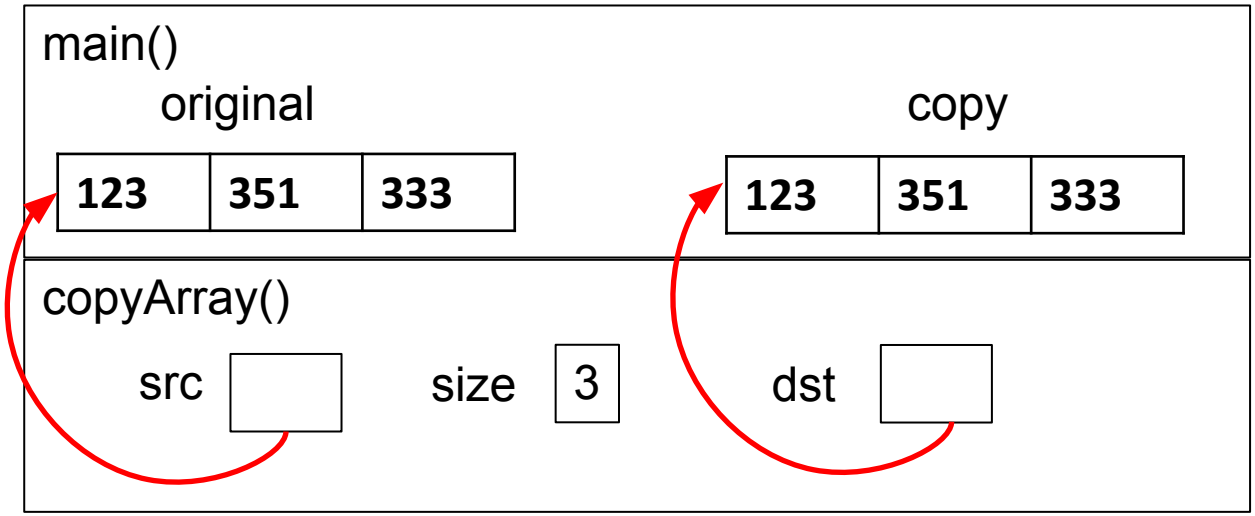



```
int main(){
  int original[] = {123, 351, 333};
  int copy[3];
  copyArray(original, copy, 3);
}

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

We aren't changing the pointer `dst`, just the values where it points to

Array Memory Diagram




```
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  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];
  }
}
```

Output Parameters

- Output parameters aren't just for arrays
- They're a common paradigm in C
  - `long int strtol(char* str, char** endptr, int base);`
  - `int sscanf(char* str, char* format, ...);`

```
int   num, i;
char* pEnd;
char* str1 = "333 rocks";  // ptr to read-only const data
char  str2[10];

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

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

outparam.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 these later)

So what's the story for arrays?

- Is it call-by-value or call-by-reference?
- 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 (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(!))

Array Parameters – [ ] or * ?

- Array parameters are *actually* pointers to the beginning of the array
  - 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];
  ...
  a[3] = 5;
  f(a);
  return EXIT_SUCCESS;
}
void f(int a[]) {...}
```

Equivalent to:

```
void f(int* a);

int main( ... ) {
  int a[5];
  ...
  *(a + 3) = 5;
  f(&(a[0]));
  return EXIT_SUCCESS;
}
void f(int* a) {...}
```

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
  - (probably need to wait until we look at malloc/free later)