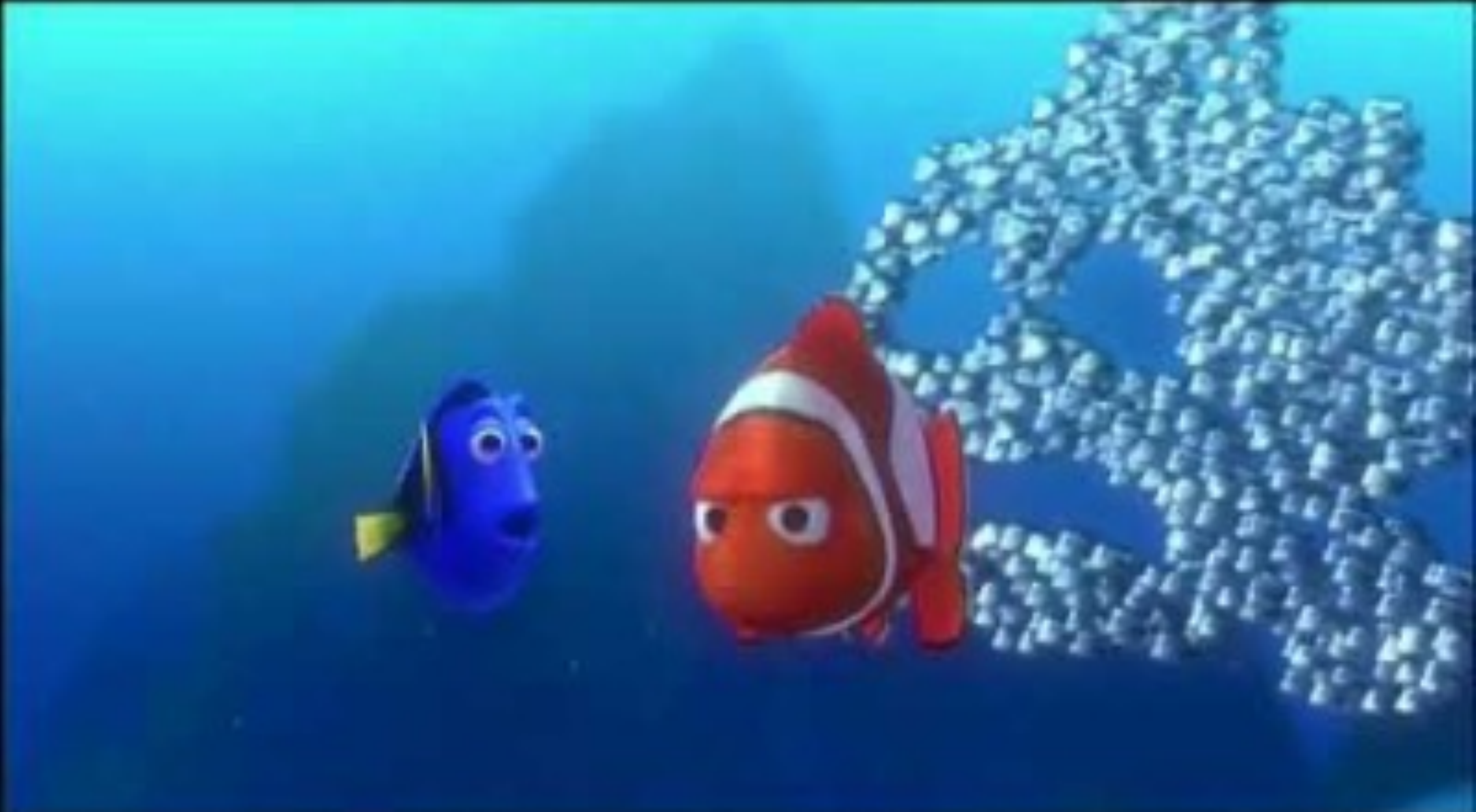
CS31: Introduction to Computer Systems

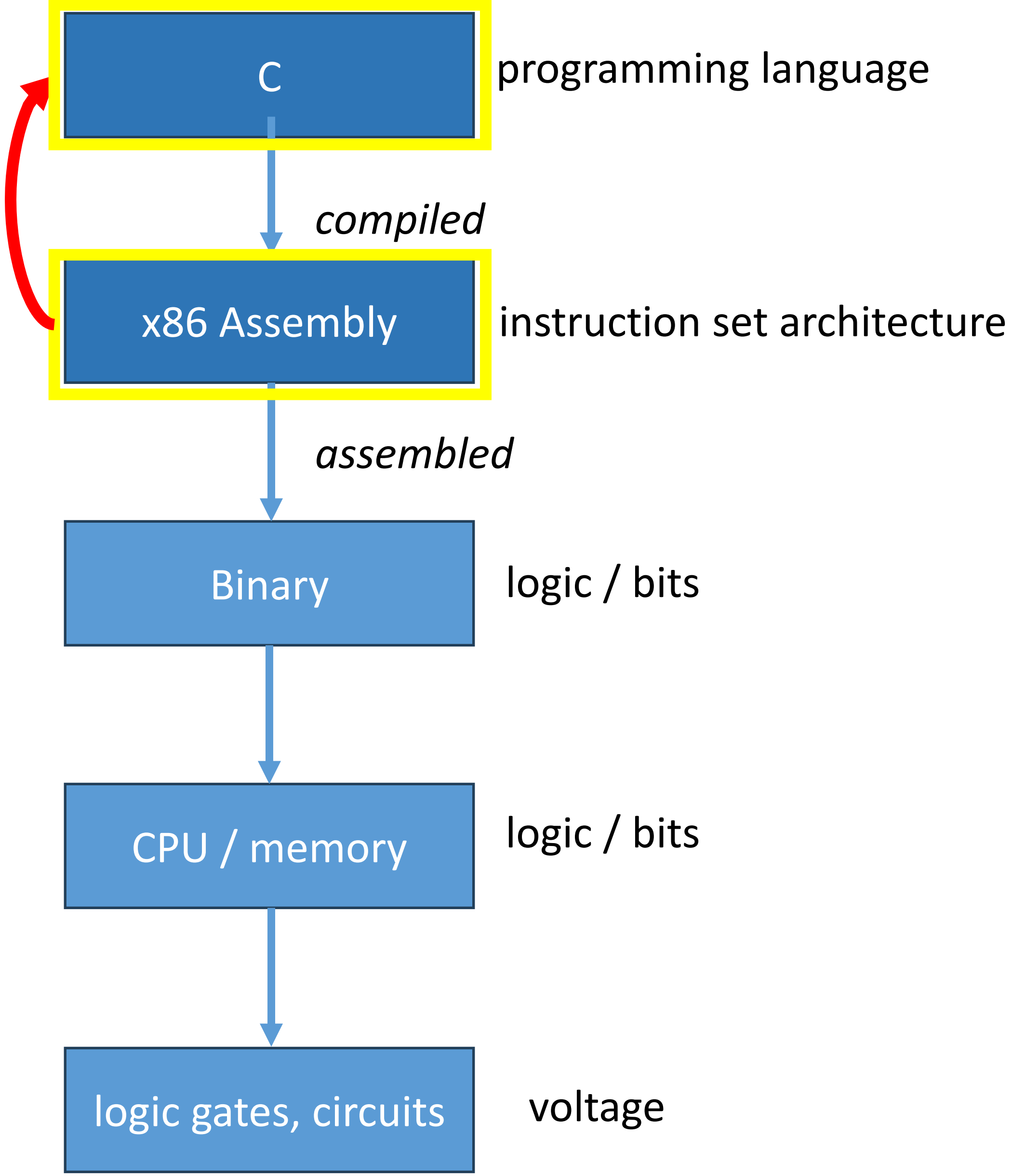
Week 5, Class 2
Pointers and Memory
02/21/24

Dr. Sukrit Venkatagiri
Swarthmore College



Where are we?

Wk	Lecture	Lab
1	Intro to C	C Arrays, Sorting
2	Binary Representation, Arithmetic	Data Rep. & Conversion
3	Digital Circuits	Circuit Design
4	ISAs & Assembly Language	”
5	Pointers and Memory	Pointers and Assembly
6	Functions and the Stack	Binary Maze
7	Arrays, Structures & Pointers	”
Spring Break		
8	Storage and Memory Hierarchy	Game of Life
9	Caching	“
10	Operating System, Processing	Strings
11	Virtual Memory	Unix Shell
12	Parallel Applications, Threading	“
13	Threading	pthreads Game of Life
14	Threading	“



C
programming language
compiled
x86 Assembly
instruction set architecture
assembled
Binary
logic / bits
CPU / memory
logic / bits
logic gates, circuits
voltage

Overview

- How to reference the location of a variable in memory

- How to make this information useful
  - Allocating memory
  - Calling functions with pointer arguments

- Where variables are placed in memory

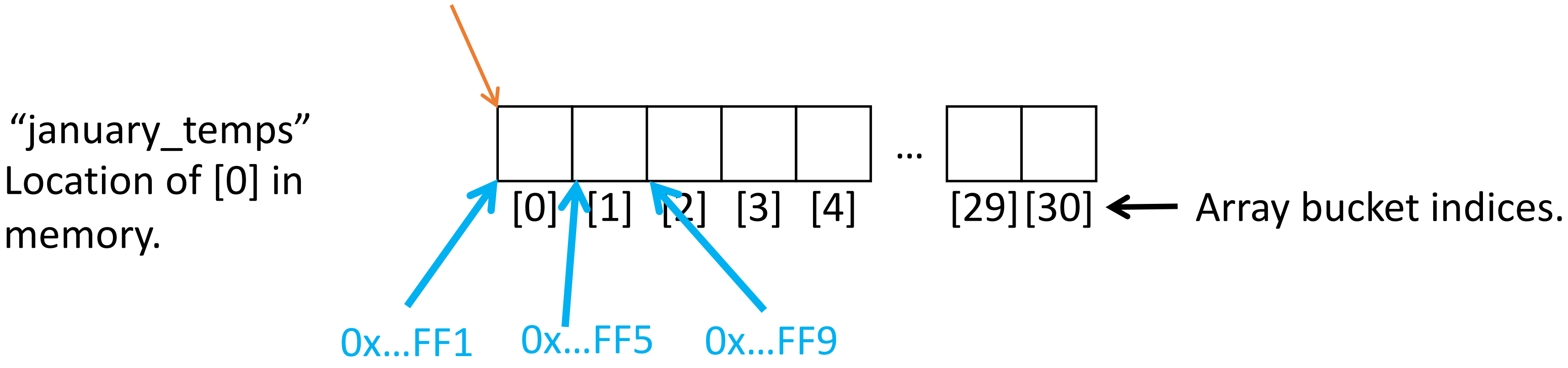
Pointers

- Pointer: A variable that stores a reference to (the address of) a memory location
- Pointer: sequence of bits that should be *interpreted* as an index into memory
- Where have we seen this before?

- A pointer is like a mailing address, it tells you where a variable is **located in memory**

Recall: Arrays

`int january_temps[31];  // Daily high temps`



- Array variable name means, to the compiler, the beginning of the memory chunk (address)

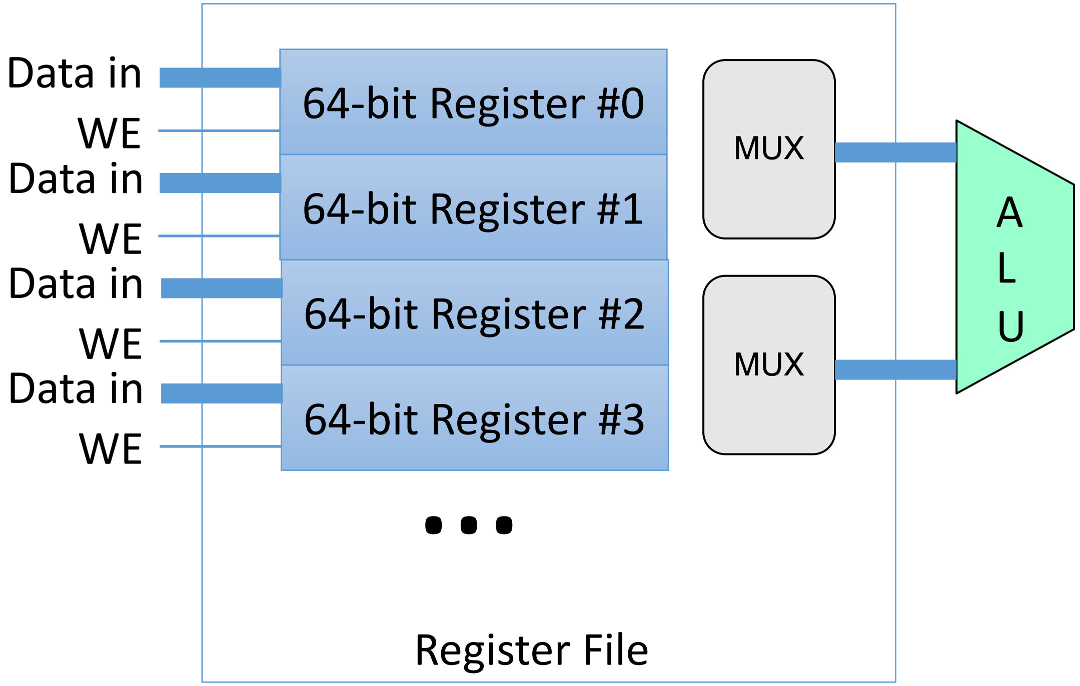
Recall: Program Counter

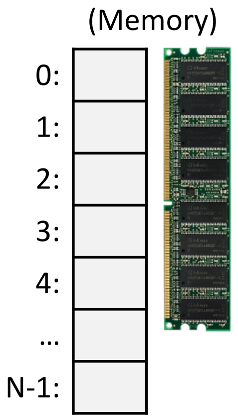
X86_64 refers to the PC as %rip

Instruction
Pointer

Program Counter (PC): **Memory address of next instr**

Instruction Register (IR): **Instruction contents (bits)**

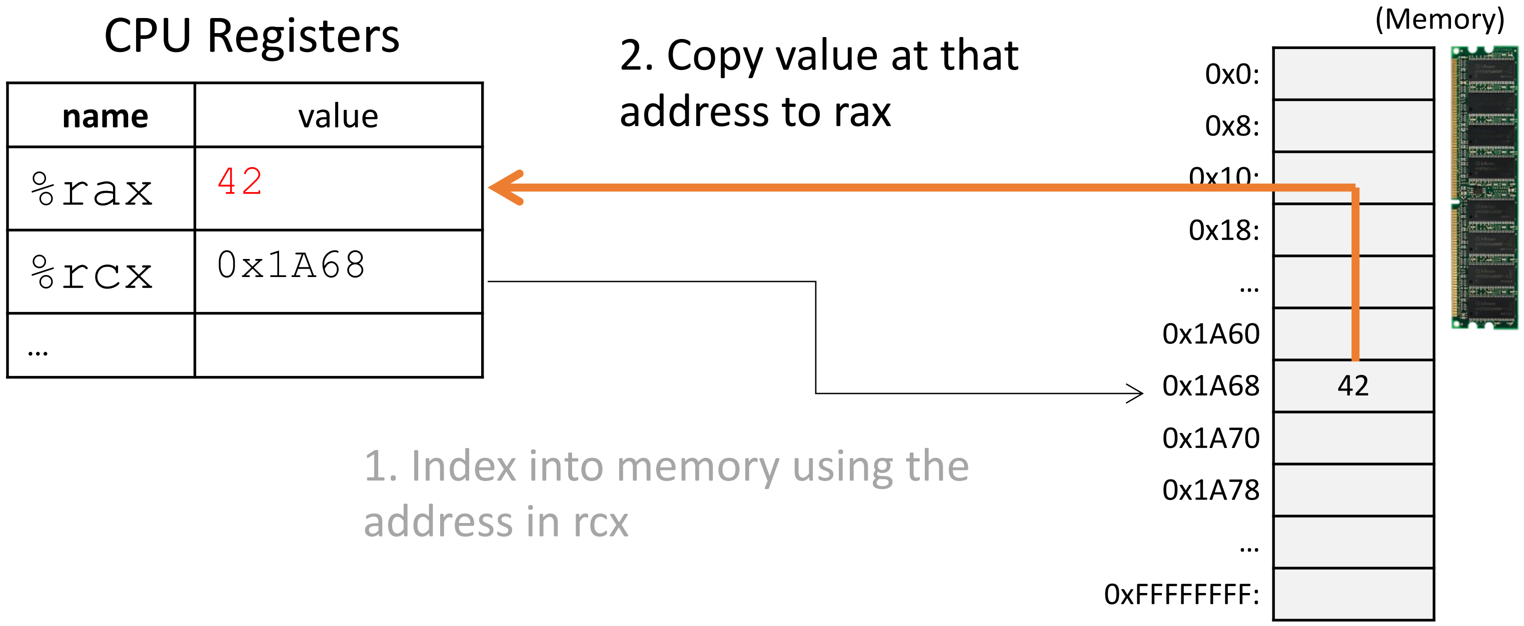




Recall: Addressing Mode: Memory

`movl (%rcx), %rax`

- Use the address in register %rcx to access memory, store result in register %rax



CPU Registers

name	value
`%rax`	`42`
`%rcx`	`0x1A68`
…	

2. Copy value at that address to rax

(Memory)

0x0:	
0x8:	
0x10:	
0x18:	
…	
0x1A60	
0x1A68	42
0x1A70	
0x1A78	
…	
0xFFFFFFFF:	

1. Index into memory using the address in rcx

Pointers in C

- Like any other variable, must be declared: **`type *name;`**
- Example:
    - `int *myptr;`
    - This is a ***promise*** to the compiler:
      "This variable holds a memory address and if you follow what it points to in memory (dereference it), you'll find an integer"
- A note on syntax:
    - `int* myptr;`   `int * myptr;`   `int *myptr;`
    - These all do the same thing (note the * position)

Dereferencing a Pointer

- To follow the pointer, we ***dereference*** it
- Dereferencing re-uses the * symbol
- If **`iptr`** is declared as an integer pointer,
  `*iptr` will follow the address it stores to find an integer in memory

Putting a * in front of a variable…

- When you ***declare*** the variable: `int* a;`
  - Declares the variable to be a pointer
  - Variable stores a memory address
- When you ***use*** the variable (“dereference”): `printf(“%p”, *p);`
  - Like putting () around a register name
  - Follows the pointer out to memory
  - Acts like the specified type (e.g., int, float, etc.)

Why Pointers?

- Using pointers seems like a lot of work, and if used incorrectly, things can go wrong
- Pointers also add a level of "indirection" to retrieve / store a value

- Two main benefits:
  1. **"Pass by pointer" function parameters**
     - **By passing a pointer into a function, the function can dereference it so that the changes persist to the caller**
  2. Dynamic memory allocation
     - A program can allocate memory on demand, as it needs it during execution

Why Pointers?

A)

Iris Washington
365 York Ave.
League City, TX 77539

Jaimie Vega
UL #WC230
4200 Martin Luther King Boulevard
Houston, TX 77204-7004

B)

Why Pointers?

- Using pointers seems like a lot of work, and if used incorrectly, things can go wrong.
- Pointers also add a level of “indirection” to retrieve / store a value

- Two main benefits:
  1. “Pass by pointer” function parameters
     - By passing a pointer into a function, the function can dereference it so that the changes persist to the caller.
  2. **Dynamic memory allocation**
     - **A program can allocate memory on demand, as it needs it during execution**

Why Pointers?

Static vs. Dynamic

Static	**Dynamic**
• The compiler can know in advance	• The compiler cannot know -- must be determined at run time
• The size of a C variable (based on its type)	• User input (or things that depend on it)
• E.g., hard-coded constants	• E.g., create an array where the size is typed in by user (or file)

So we declared a pointer … `int * a;`

- How do we make it point to something?
  1. **Assign it the address of an existing variable**
  2. Copy some other pointer
  3. Allocate some memory dynamically and point to it

The Address Of (&)

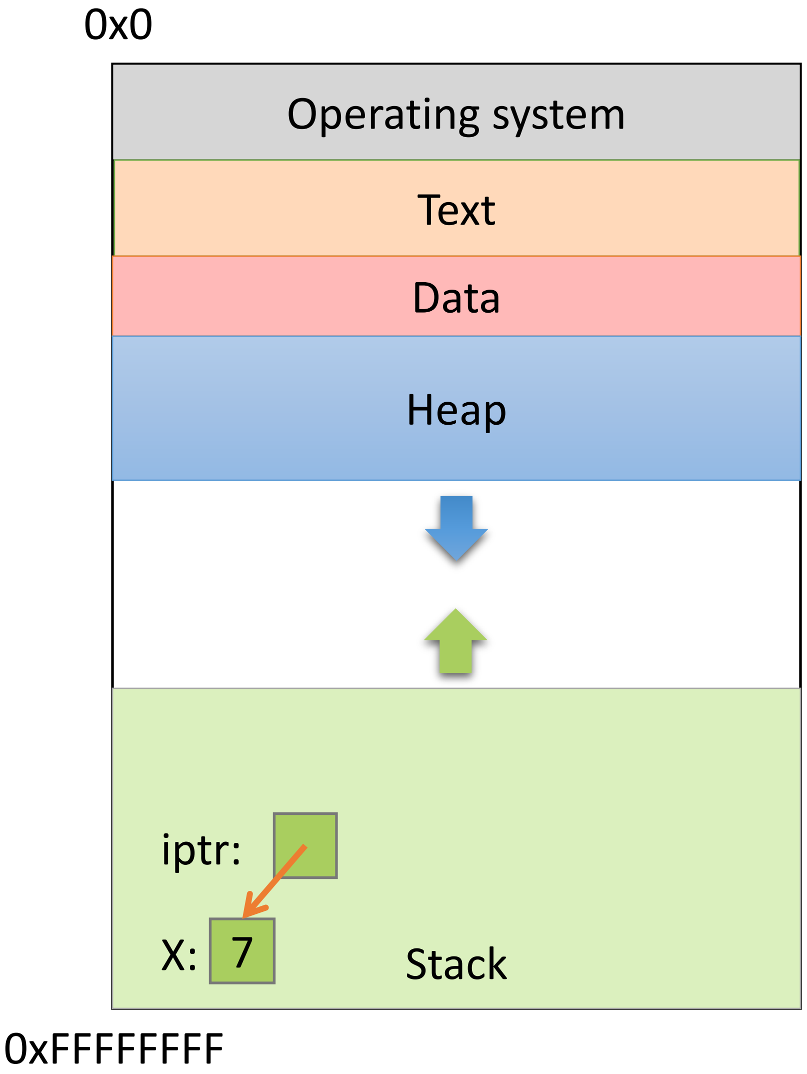
- You can create a pointer to anything by taking its address with the *address of* operator (**&**)

Iris Washington
365 York Ave.
League City, TX 77539

Jaimie Vega
UL #WC230
4200 Martin Luther King Boulevard
Houston, TX 77204-7004

The Address Of (&)

```
int main(void) {
   int x = 7;
   int *iptr = &x;




   return 0;
}
```



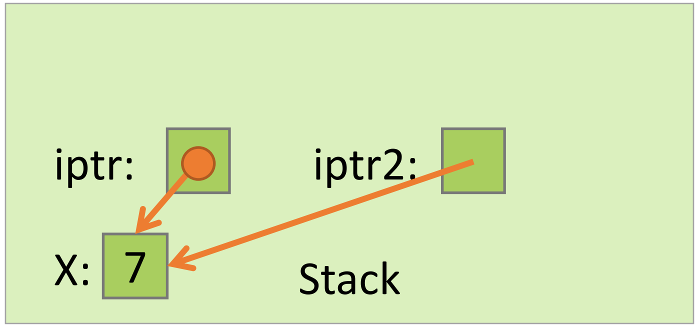
So we declared a pointer … **int * a;**

- How do we make it point to something?
  1. Assign it the address of an existing variable
  2. **Copy some other pointer**
  3. Allocate some memory dynamically and point to it

Copying a Pointer

- We can perform assignment on pointers to copy the stored address.

```
int x = 7;
int *iptr, *iptr2;
iptr = &x;
iptr2 = iptr;
```



Pointer Types

- By default, we can only assign a pointer if the type matches what C expects

✓

```
int x = 7;
int *iptr = &x;
```

```
int x = 7;
float *fptr = &x;
```

✖

- “Warning: initialization from incompatible pointer type” (Don’t ignore this message!)

Recall: Dereferencing a Pointer

- To follow the pointer, we *dereference* it
- Dereferencing re-uses the * symbol
- If `iptr` is declared as an **integer pointer**,
  `*iptr` will follow the address it stores to find an **integer** in memory

void *

- There exists a special type, void *, which represents a “generic pointer” type
  - Can be assigned to any pointer variable
  - `int *iptr = (void *) &x;    // Doesn’t matter what x is`

- This is useful for cases when:
  1. You want to create a generic “safe value” that you can assign to any pointer variable
  2. You want to pass a pointer to / return a pointer from a function, but you don’t know its type
  3. You know better than the compiler that what you’re doing is safe, and you want to eliminate the warning

NULL: A special pointer value

- You can assign NULL to any pointer, regardless of what type it points to (it's a void *)
    - `int *iptr = NULL;`
    - `float *fptr = NULL;`

- NULL is equivalent to pointing at memory address 0x0. This address is NEVER in a valid segment of your program's memory.
    - This guarantees a segfault if you try to dereference it
    - Generally a good ideal to initialize pointers to NULL

So, we declared a pointer… **int * a;**

- How do we make it point to something?
    1. Assign it the address of an existing variable (&)
    2. Copy some other pointer (=)
    3. **Allocate some memory dynamically and point to it (malloc)**

Allocating (Heap) Memory

- The standard C library (`#include <stdlib.h>`) includes functions for allocating memory:

```
void *malloc(size_t size)
```

  - Allocate `size` bytes on the heap and return a pointer to the beginning of the memory block

```
void free(void *ptr)
```

  - Release the `malloc()-ed` block of memory starting at `ptr` back to the system

Recall: void *

- void * is a special type that represents “generic pointer”
  - Can be assigned to any pointer variable

- This is useful for cases when:
  1. You want to create a generic “safe value” that you can assign to any pointer variable
  2. You want to pass a pointer to / return a pointer from a function, but you don’t know its type
  3. You know better than the compiler that what you’re doing is safe, and you want to eliminate the warning

- When malloc() gives you bytes, it doesn’t know or care what you use them for…

Allocation Size

`void *malloc(size_t size)`

- Allocate `size` bytes on the heap and return a pointer to the beginning of the memory block

- How much memory should we ask for?

- Use C's **`sizeof()`** operator:

```
int *iptr = NULL;
iptr = malloc(sizeof(int));
```

`sizeof()`

- Despite the ()’s, it’s an **operator**, not a function
  - Other operators:
    - addition / subtraction (+ / -)
    - address of (&)
    - indirection (*) (dereference a pointer)
- Works on any type to tell you how much memory it needs
- Size value is determined at compile time (static)

Why `sizeof()` is important

```
struct student {
  char name[40];
  int age;
  double gpa;
}
```

How many bytes is this?
Who cares…
Let the compiler figure that out.

```
struct student *bob = NULL;
bob = malloc(sizeof(struct student));
```

I don't ever want to see a number hard-coded in here!

Running out of Memory

- If you're ever unsure of malloc / free's behavior:

```
$ man malloc
```

- According to the C standard:

"The `malloc` function returns a pointer to the allocated memory that is suitably aligned for any kind of variable. **On error, this function returns NULL.**"

- Further down in the "Notes" section of the manual:

"[On Linux], when `malloc` returns non-NULL there is no guarantee that memory is really available. **If the system is out of memory, one or more processes will be killed by the OOM killer.**"

Running out of Memory

- If you're ever unsure of malloc / free's behavior:

```
$ man malloc
```

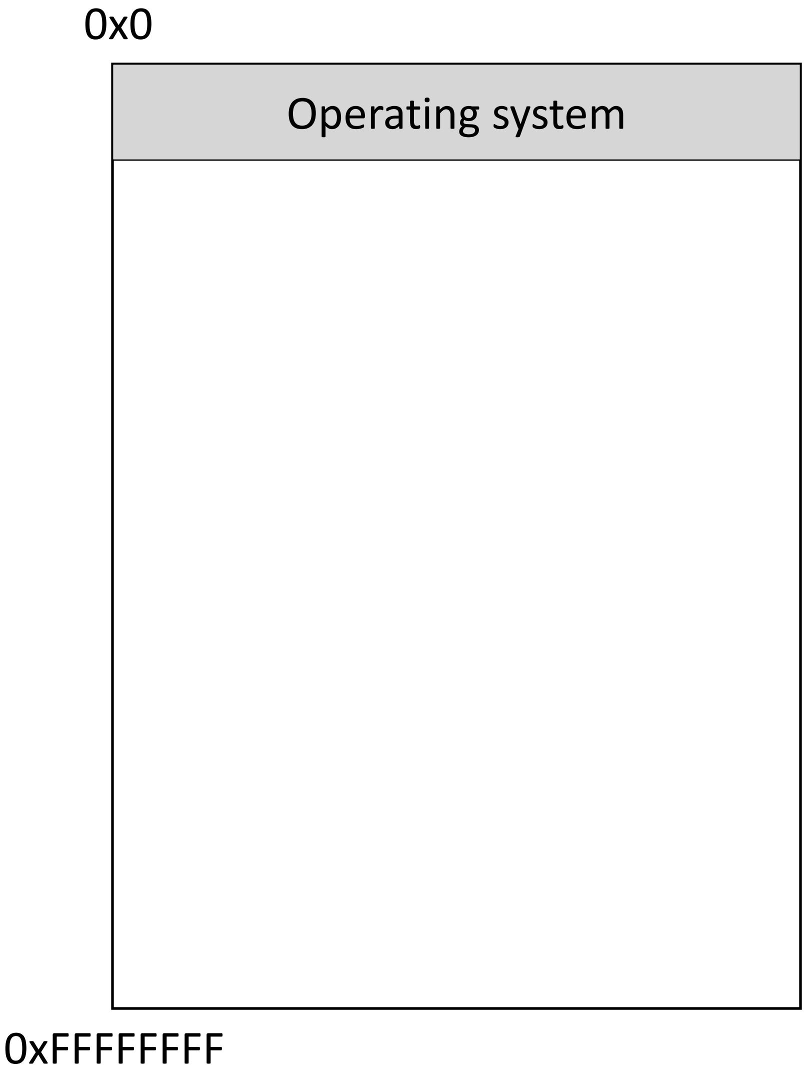
- According to the C standard:

"The `malloc` function returns a pointer to the allocated memory that is suitably aligned for any kind of variable. **On error, this function returns NULL.**"

- You should check for NULL after every malloc:

```
struct student *bob = NULL;
bob = malloc(sizeof(struct student));

if (bob == NULL) {
    /* Handle this. Often, print and exit. */
}
```

How is dynamically allocated memory stored?

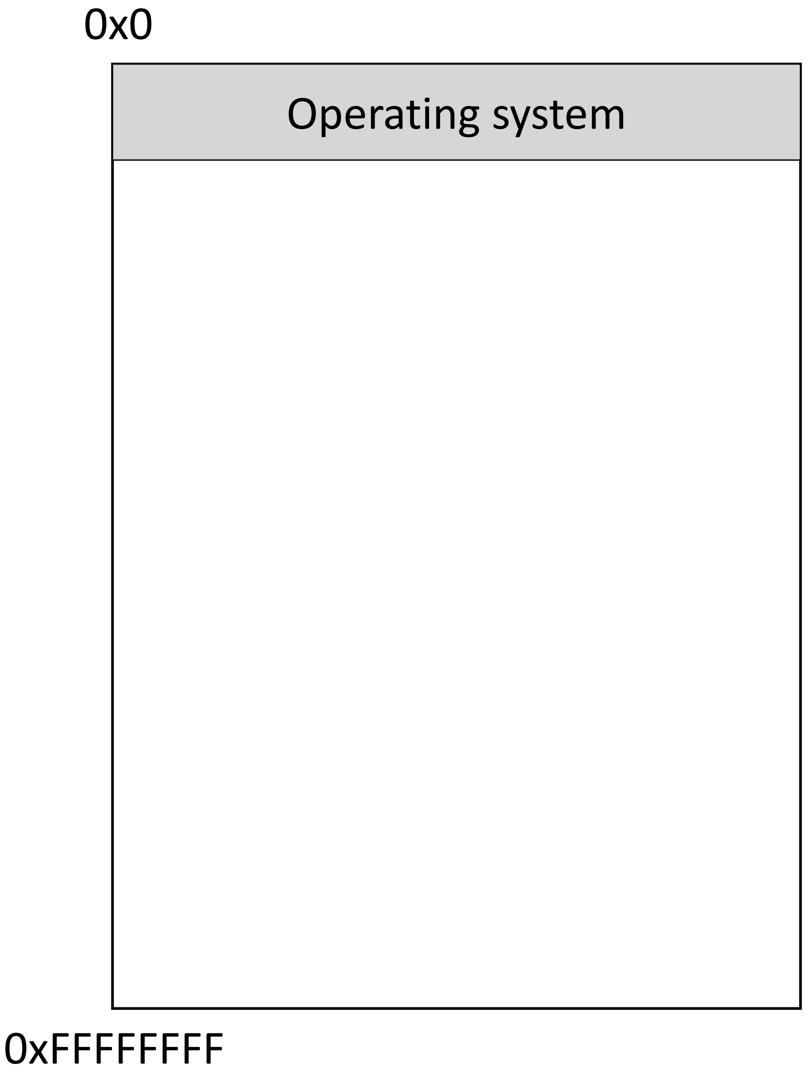


Memory

- Behaves like a big array of bytes, each with an address (bucket #)

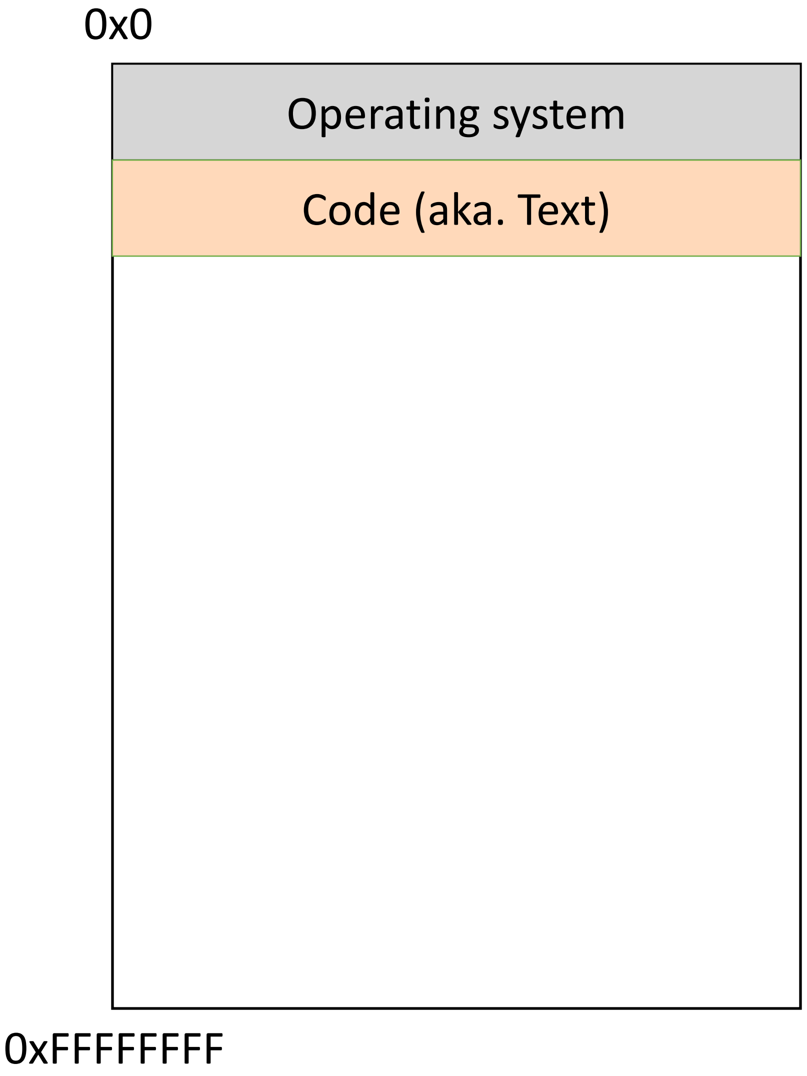
- By convention, we divide it into regions

- The region at the lowest addresses is usually reserved for the OS



Memory - Text

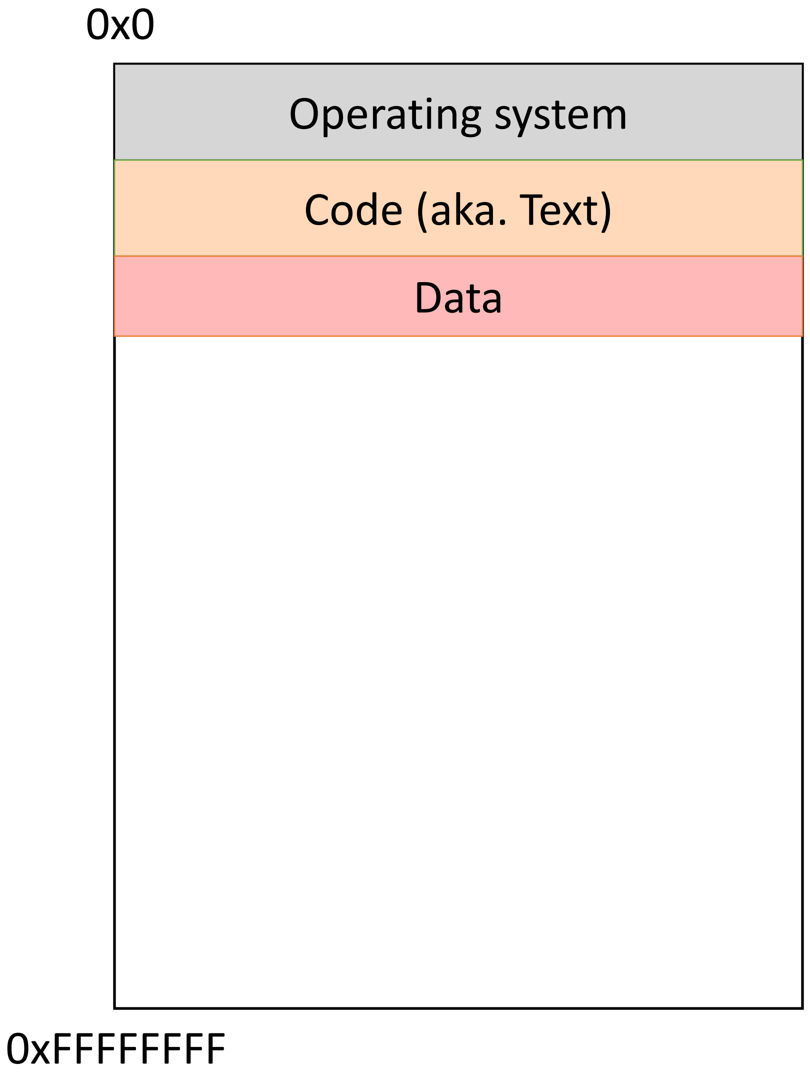
- After the OS, we store the program's code
- Instructions generated by the compiler



Memory – (Static) Data

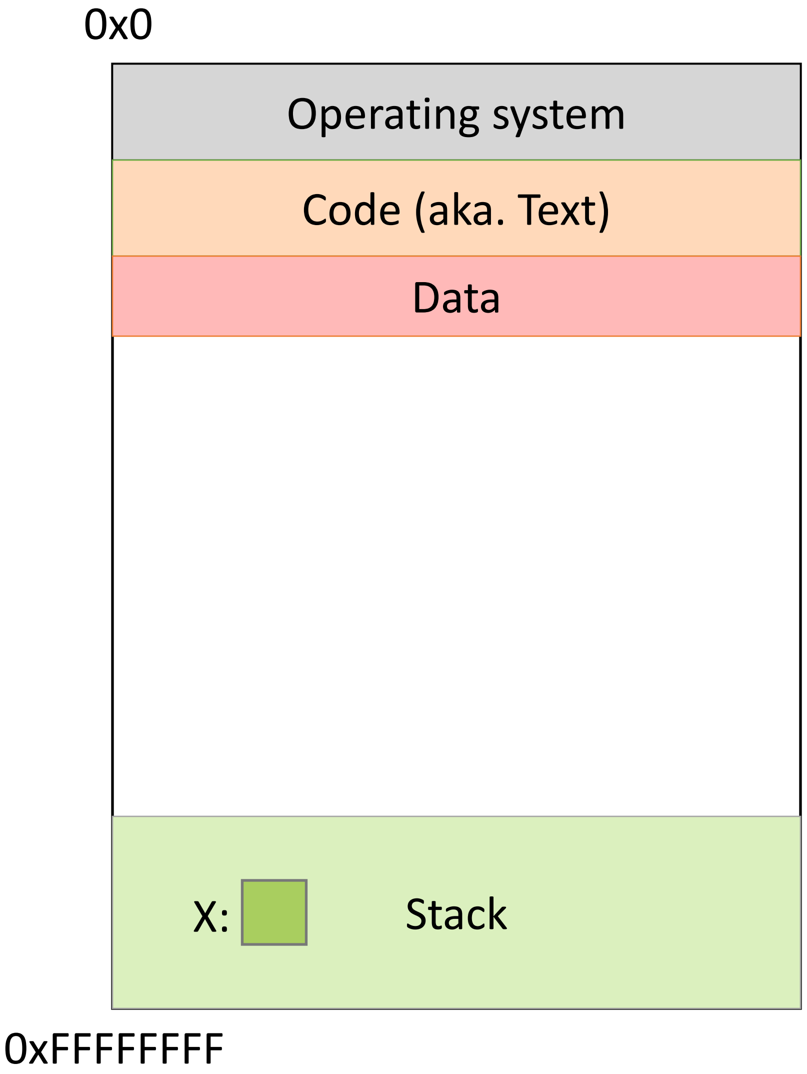
- Next, there's a fixed-size region for static data

- This stores static variables that are known at compile time
  - Global variables
  - Static (hard-coded) strings



Memory - Stack

- At high addresses, we keep the stack
- This stores local (automatic) variables
  - The kind we've been using in C so far
  - e.g., **`int x;`**



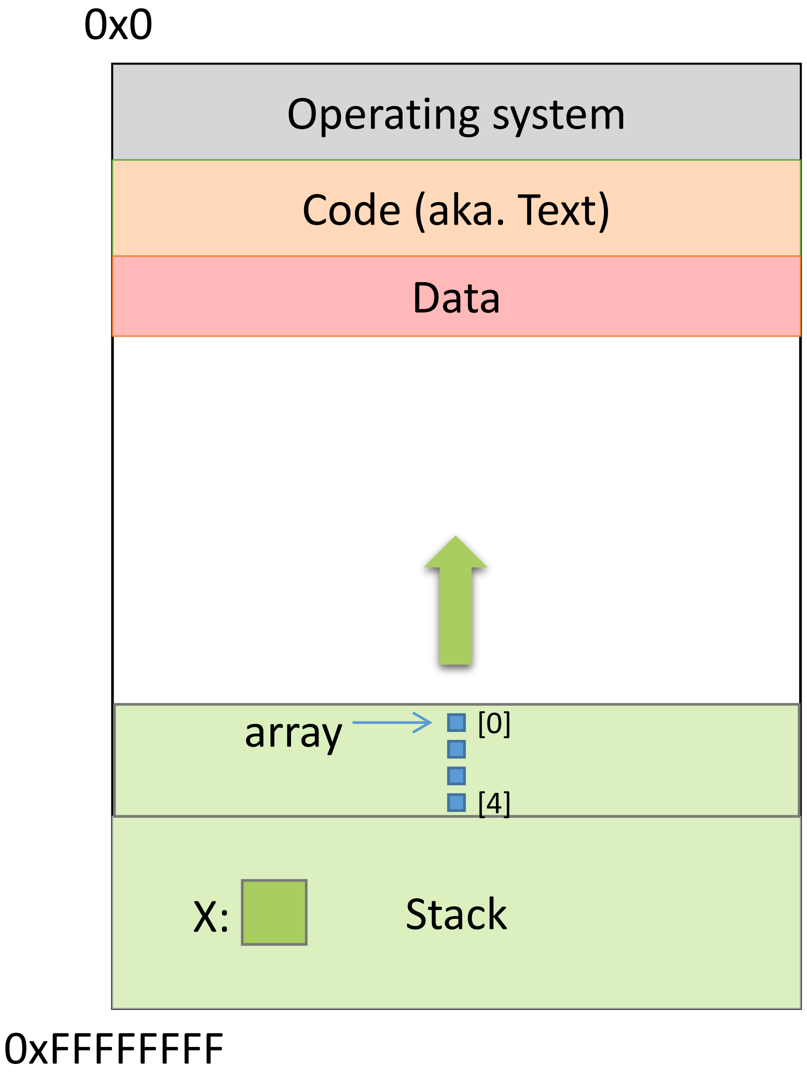
Memory - Stack

- The stack grows upwards towards lower addresses (negative direction)

- Example: Allocating array

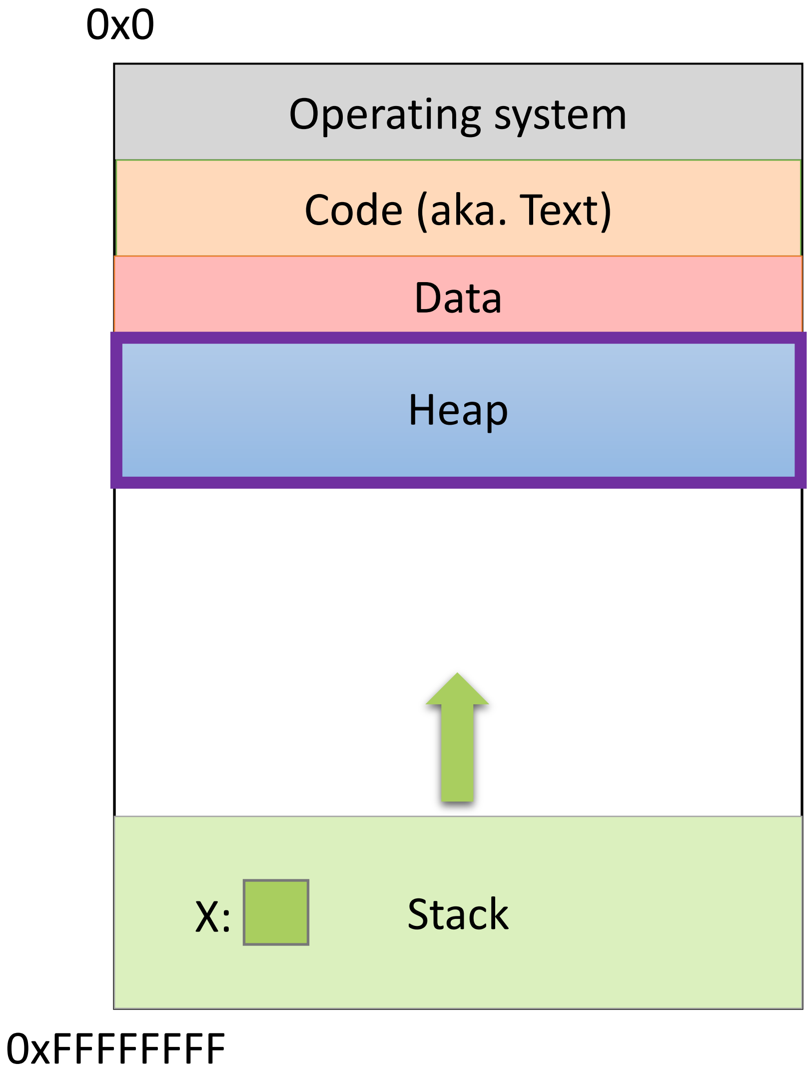
  `int array[3];`

- (Note: this differs from Python)



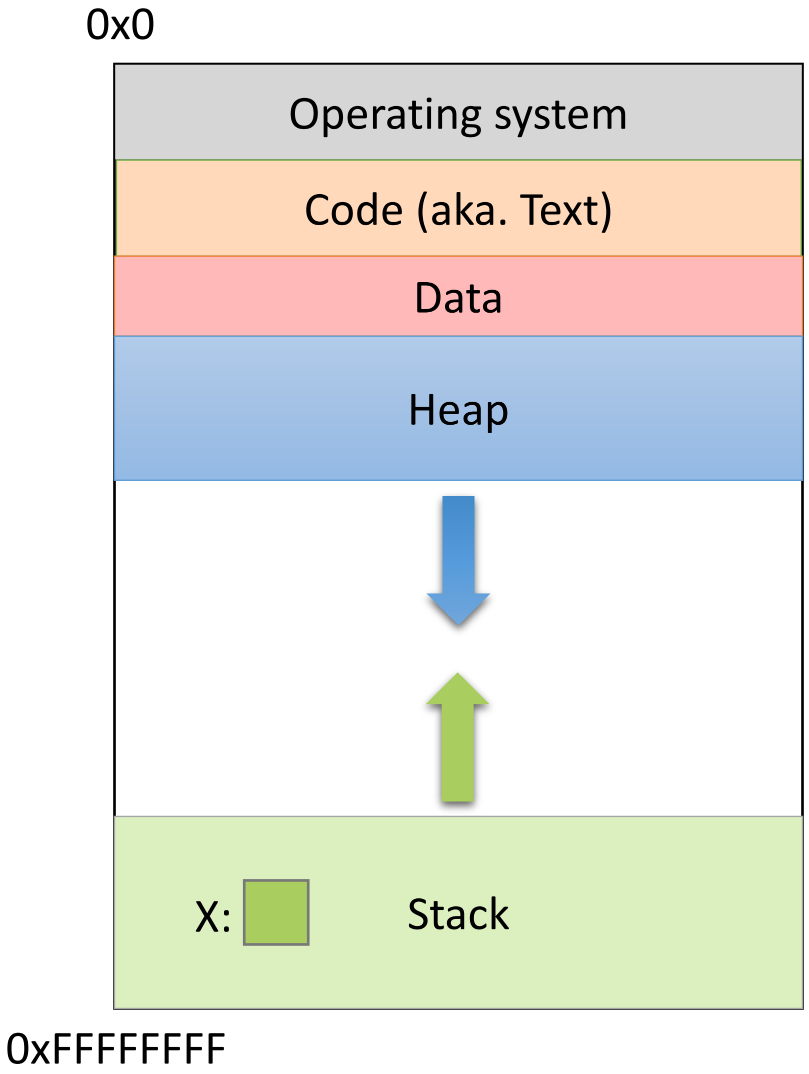
Memory - Heap

- The heap stores dynamically allocated variables
- When programs explicitly ask the OS for memory, it comes from the heap
  - malloc() function



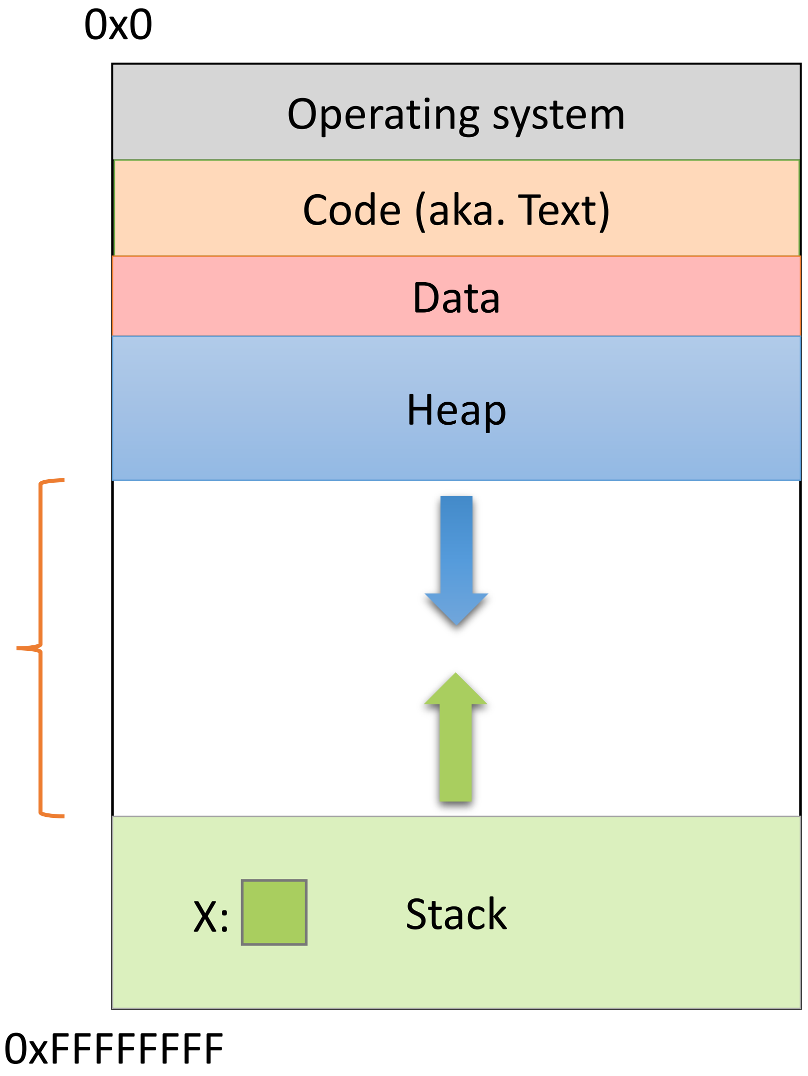
Memory - Heap

- The heap grows downwards, towards higher addresses.
- I know you want to ask a question…

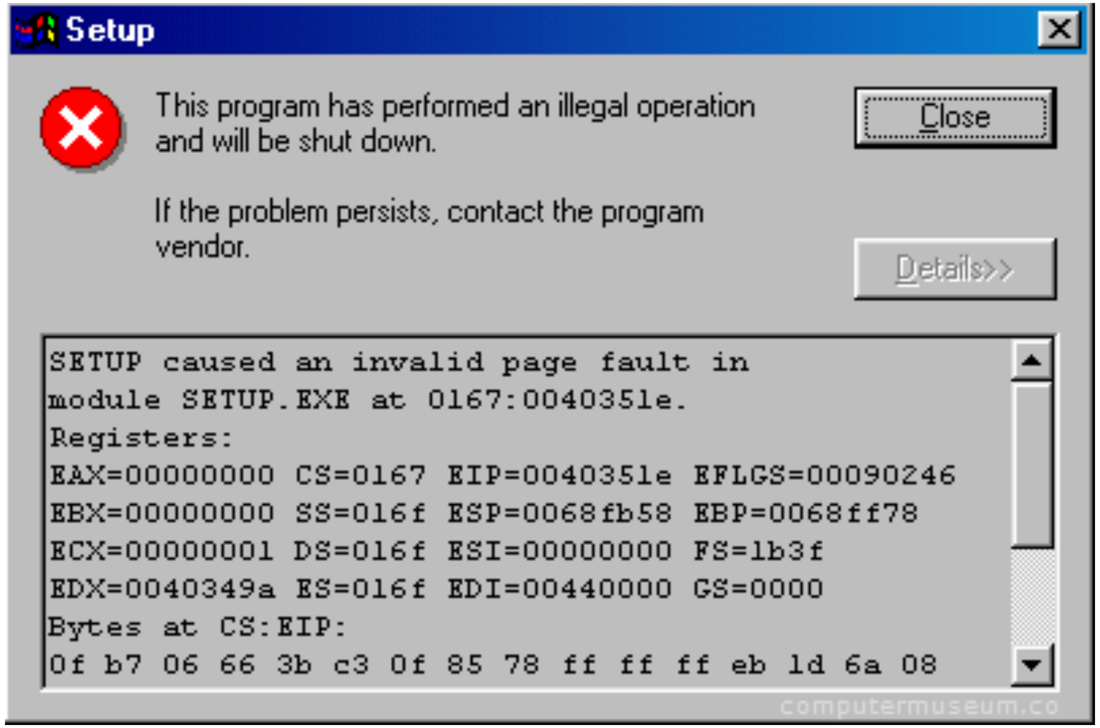


Memory - Heap

- “What happens if the heap and stack collide?”
- This picture is not to scale – the gap is huge
- The OS works really hard to prevent this.
  - Would likely kill your program before it could happen.



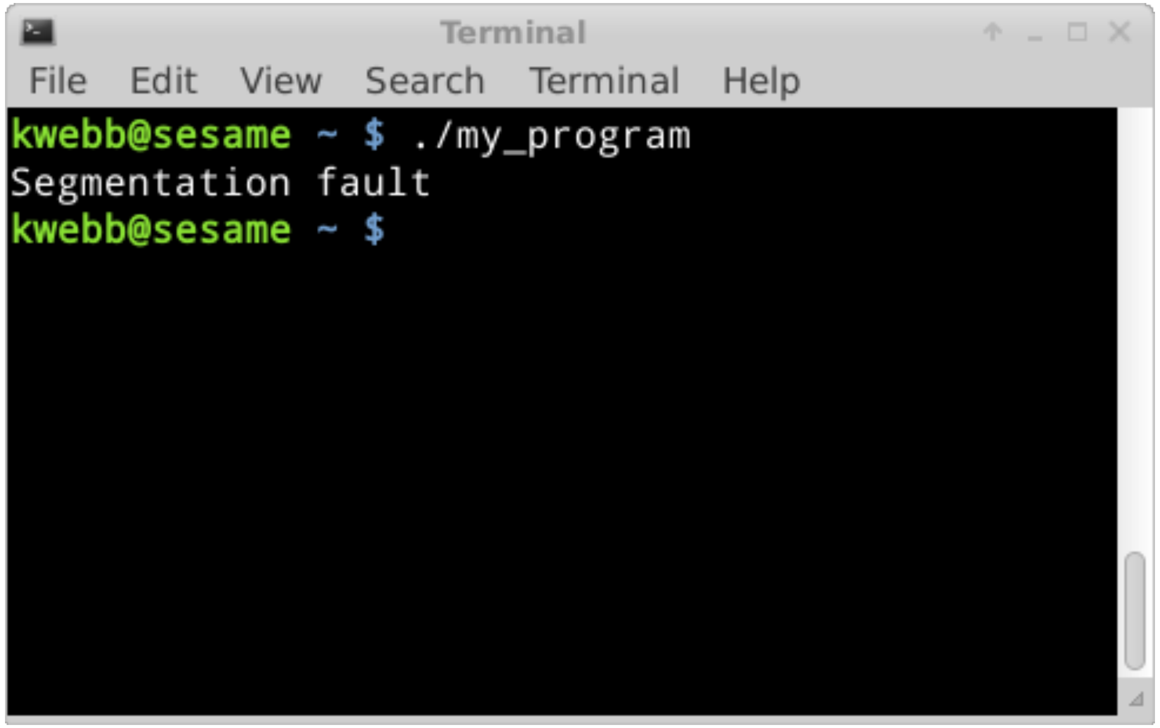
Segmentation Violation



This program has performed an illegal operation and will be shut down.

If the problem persists, contact the program vendor.

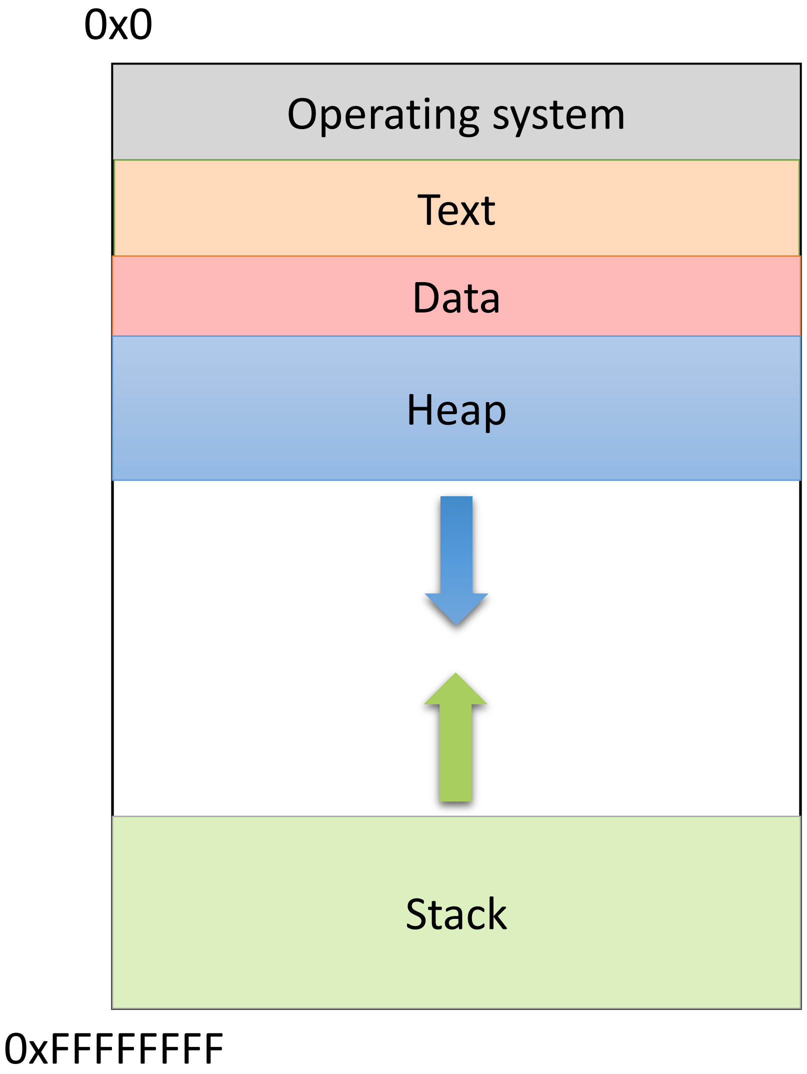
```
SETUP caused an invalid page fault in
module SETUP.EXE at 0167:0040351e.
Registers:
EAX=00000000 CS=0167 EIP=0040351e EFLGS=00090246
EBX=00000000 SS=016f ESP=0068fb58 EBP=0068ff78
ECX=00000001 DS=016f ESI=00000000 FS=1b3f
EDX=0040349a ES=016f EDI=00440000 GS=0000
Bytes at CS:EIP:
0f b7 06 66 3b c3 0f 85 78 ff ff ff eb 1d 6a 08
```



```
kwebb@sesame ~ $ ./my_program
Segmentation fault
kwebb@sesame ~ $
```

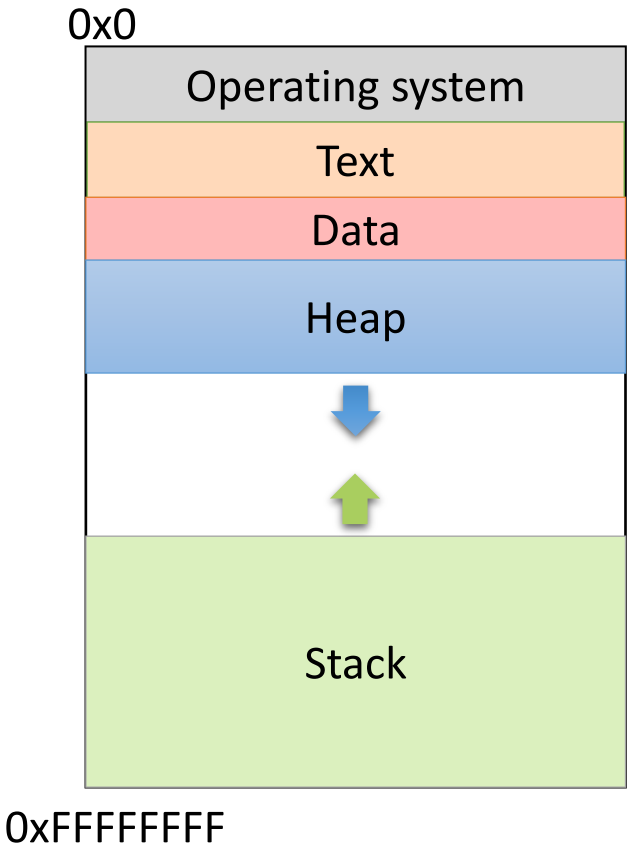
Segmentation Violation

- Each region also known as a memory segment
- Accessing memory outside a segment is not allowed
- Can also happen if you try to access a segment in an invalid way
  - OS not accessible to users
  - Text and Data are usually read-only



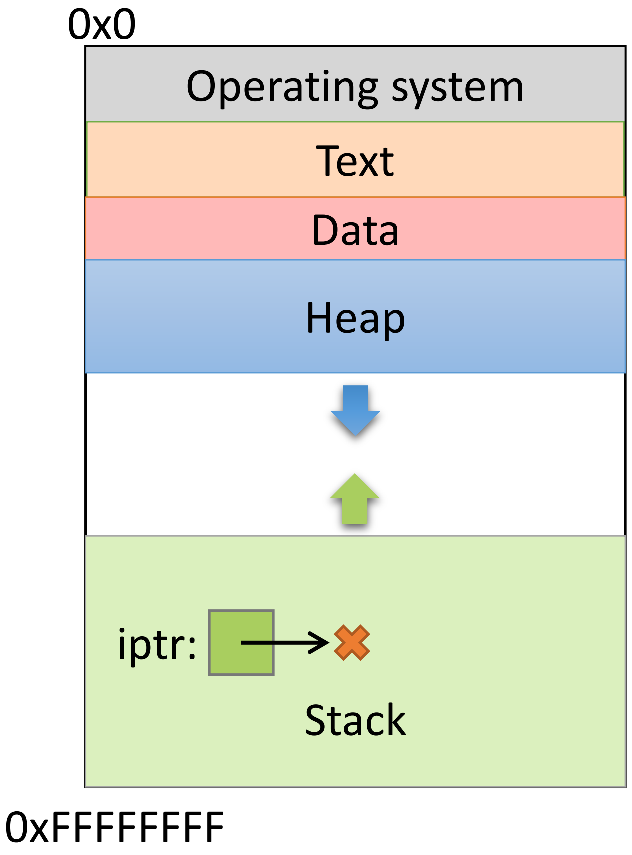
Malloc and the Heap

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```



Malloc and the Heap

```
➡ int *iptr = NULL;

  iptr = malloc(sizeof(int));

  *iptr = 5;
```



Create an integer pointer, named iptr, on the stack.

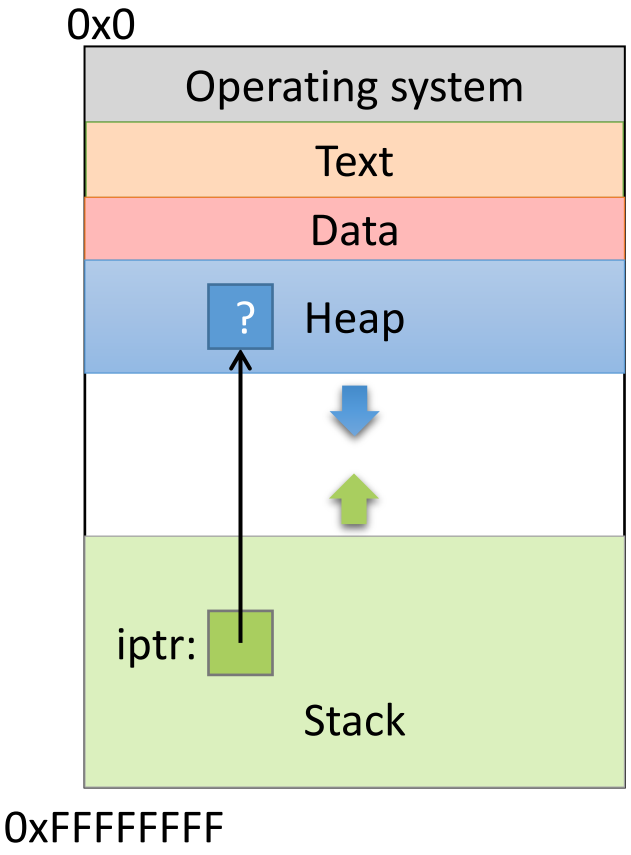
Assign it NULL.

Malloc and the Heap

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```

Allocate space for an integer on the heap (4 bytes), and return a pointer to that space.

Assign that pointer to iptr.



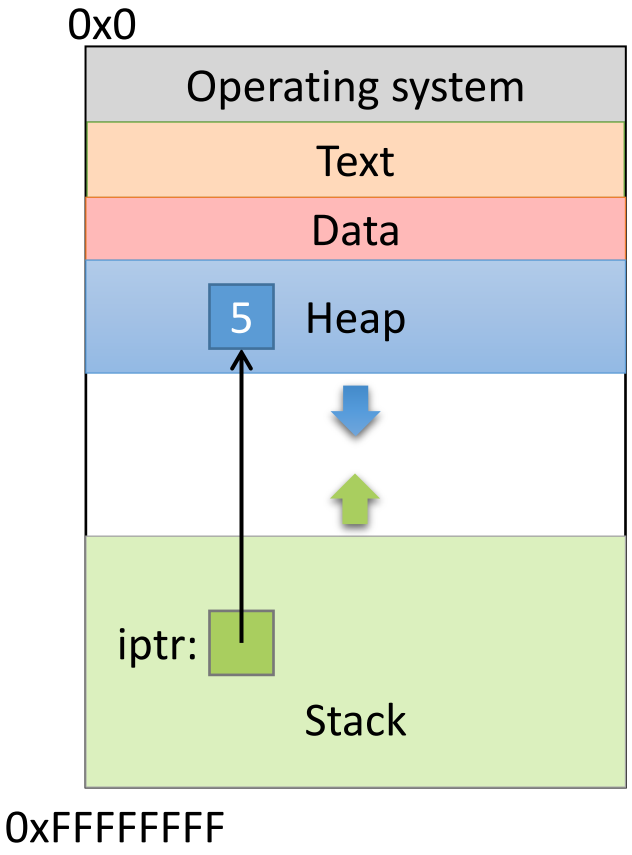
What value is stored in that area right now?

Who knows… Garbage.

Malloc and the Heap

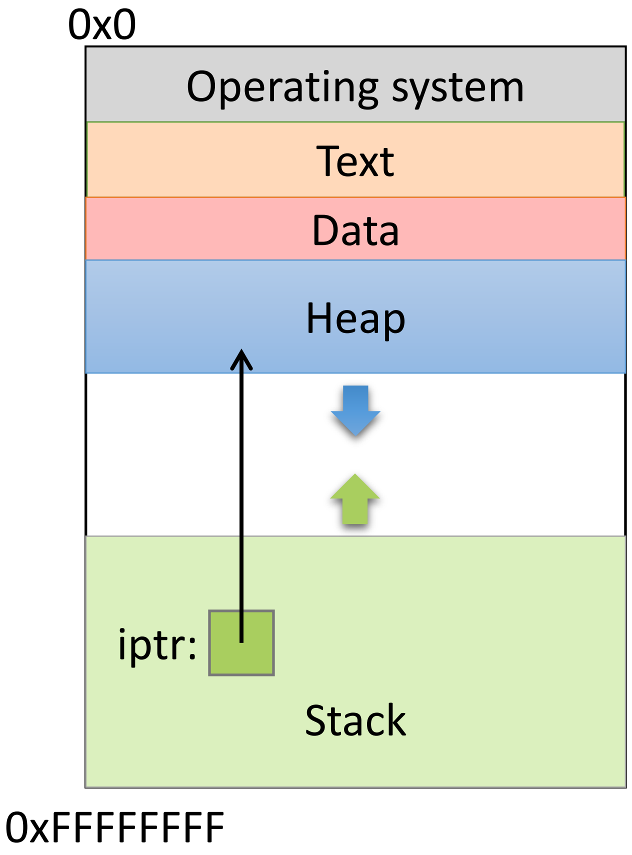
```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```

Use the allocated heap space by dereferencing the pointer.



Malloc and the Heap

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

free(iptr);
```

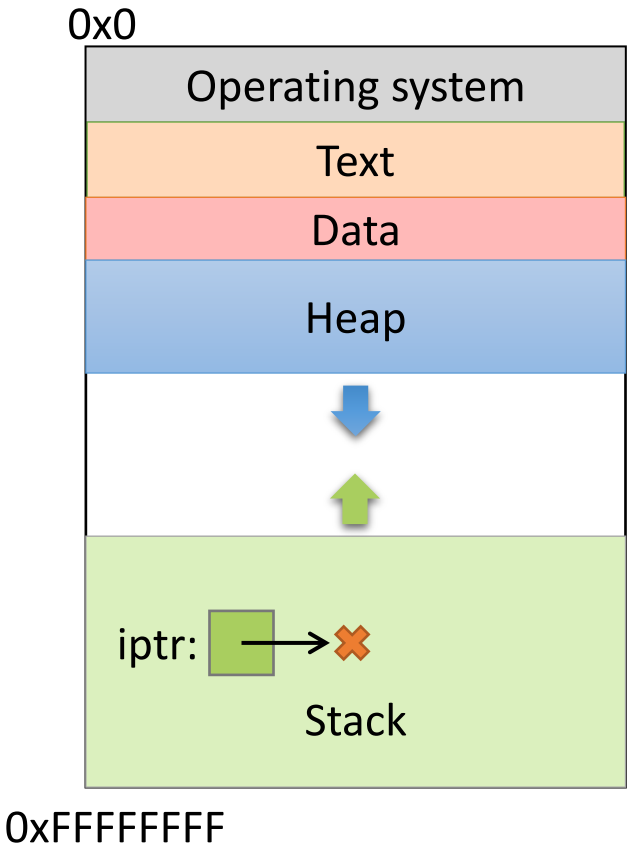


Free up the heap memory we used.

Malloc and the Heap

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

free(iptr);
iptr = NULL;
```

Clean up this pointer, since it’s no longer valid



“Memory Leak”

- Memory that is allocated, and not freed, for which there is no longer a pointer

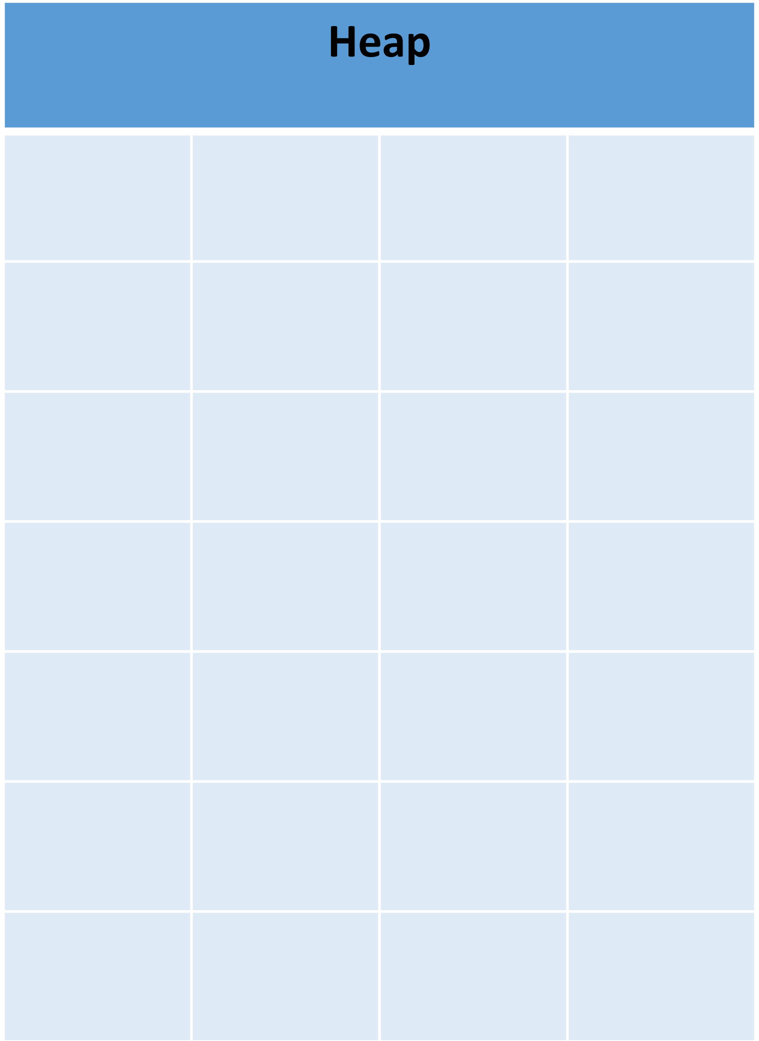
- In many languages (Java, Python, …), this memory will be cleaned up for you
  - “Garbage collector” finds unreachable memory blocks, frees them
  - (This can be a time consuming feature)
  - C does **NOT** do this for you!

Memory Bookkeeping

- To free a chunk, you MUST call `free` with the same pointer that `malloc` gave you. (or a copy)
- The standard C library keeps track of the chunks that have been allocated to your program.
  - This is called "metadata" – data about your data.
- Wait, where does it store that information?
  - It's not like it can use `malloc` to get memory…

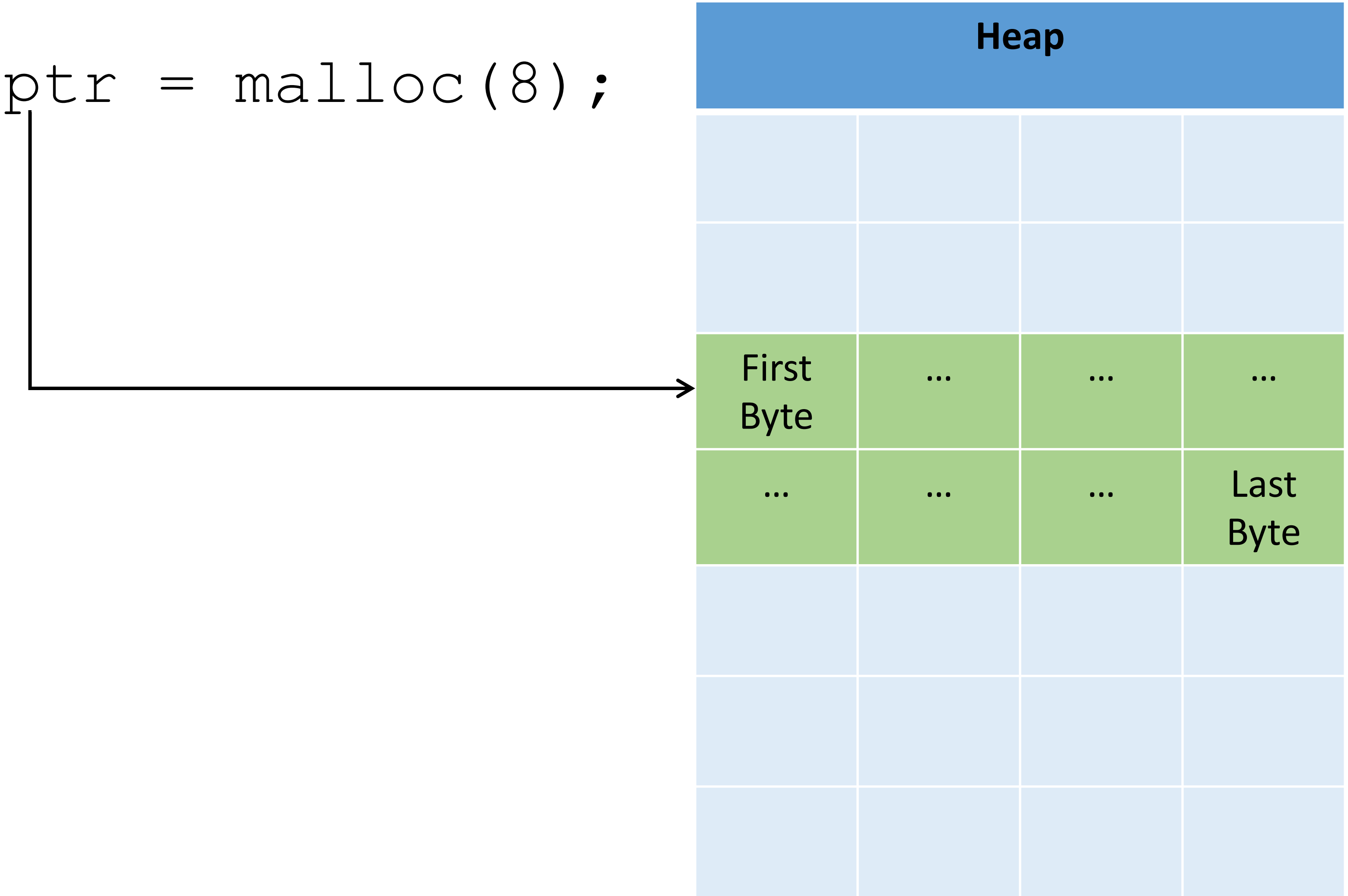
Metadata

```
int *iptr = malloc(8);
```



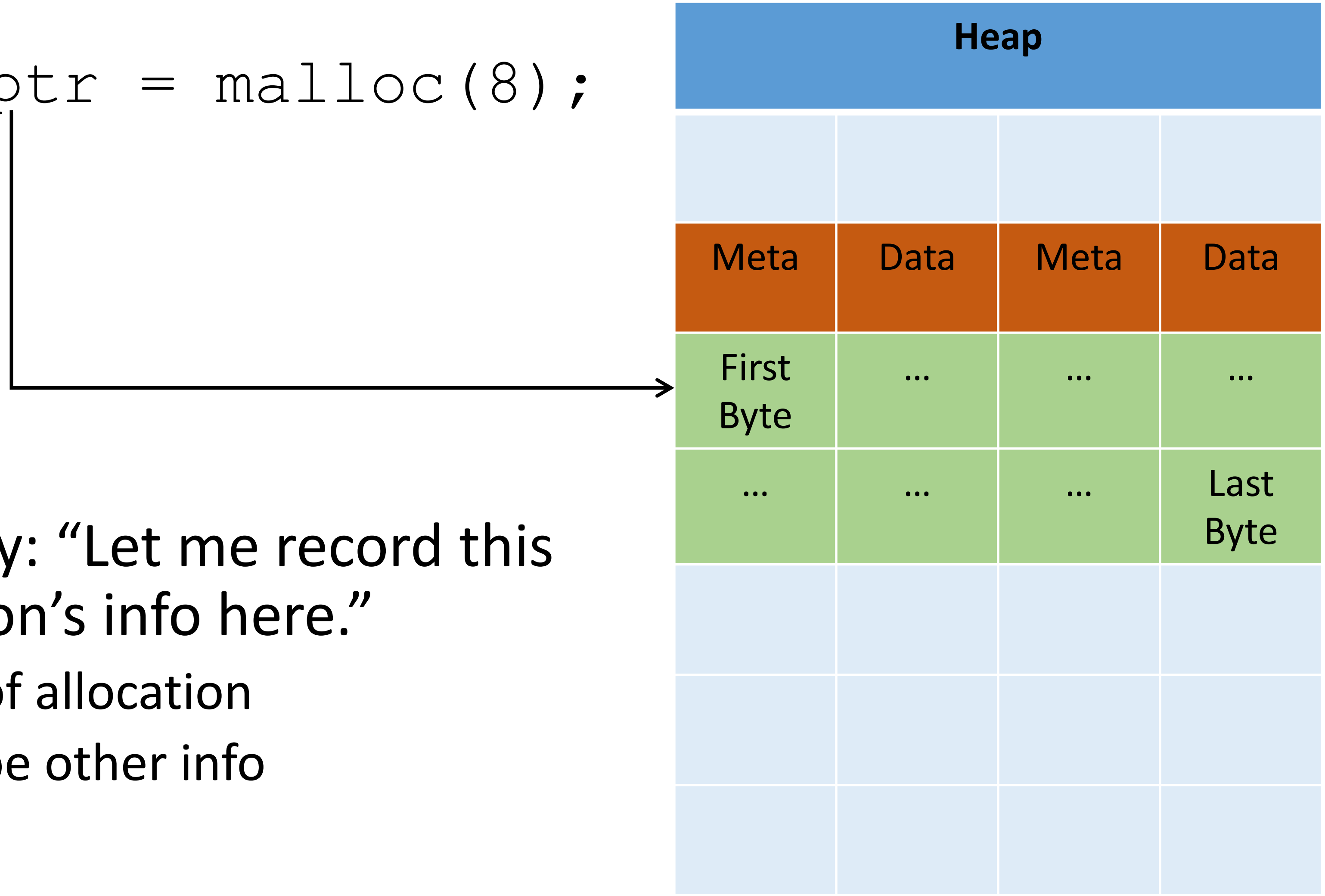
Metadata

```
int *iptr = malloc(8);
```



Metadata

`int *iptr = malloc(8);`

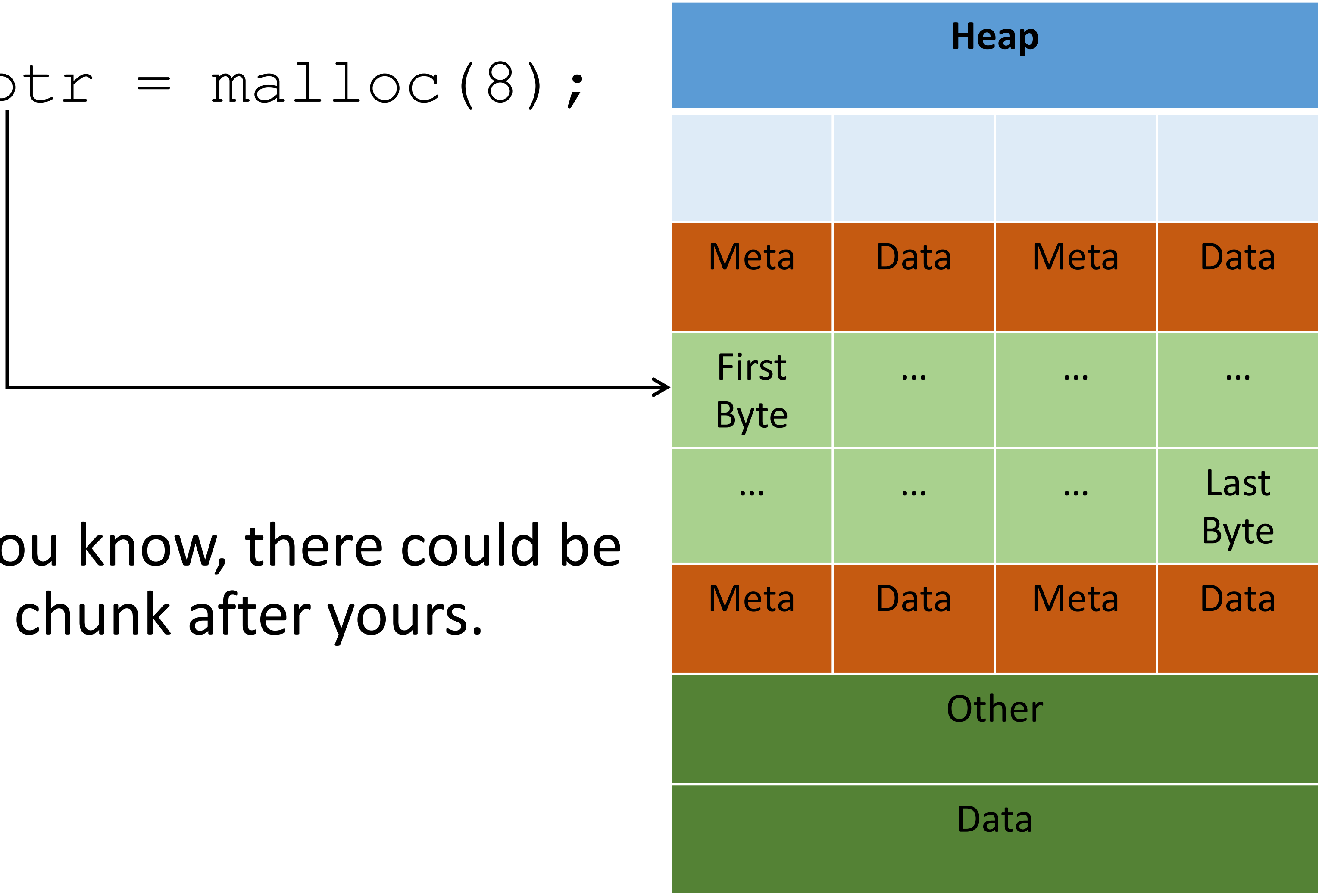


Heap			
Meta	Data	Meta	Data
First Byte	…	…	…
…	…	…	Last Byte

- C Library: “Let me record this allocation’s info here.”
  - Size of allocation
  - Maybe other info

Metadata

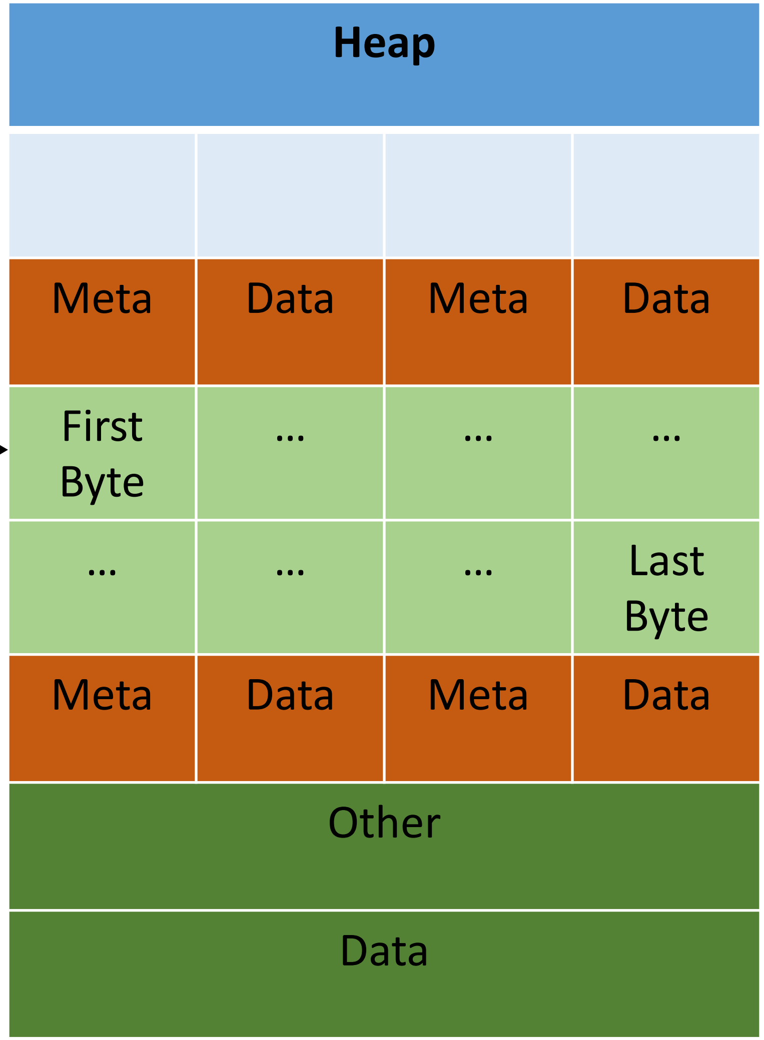
`int *iptr = malloc(8);`



- For all you know, there could be another chunk after yours.

Metadata

```
int *iptr = malloc(8);
```



Heap			
Meta	Data	Meta	Data
First Byte	…	…	…
…	…	…	Last Byte
Meta	Data	Meta	Data
Other			
Data			

- Takeaway: very important that you stay within the memory chunks you allocate.
- If you corrupt the metadata, you will get weird behavior.

Valgrind is your new best friend.

Pointers as Arrays

- “Why did you allocate 8 bytes for an int pointer? Isn’t an int only 4 bytes?”
    - `int *iptr = malloc(8);`

- Recall: an array variable acts like a pointer to a block of memory. The number in **[]** is an offset from bucket 0, the first bucket.

- We can treat pointers in the same way!

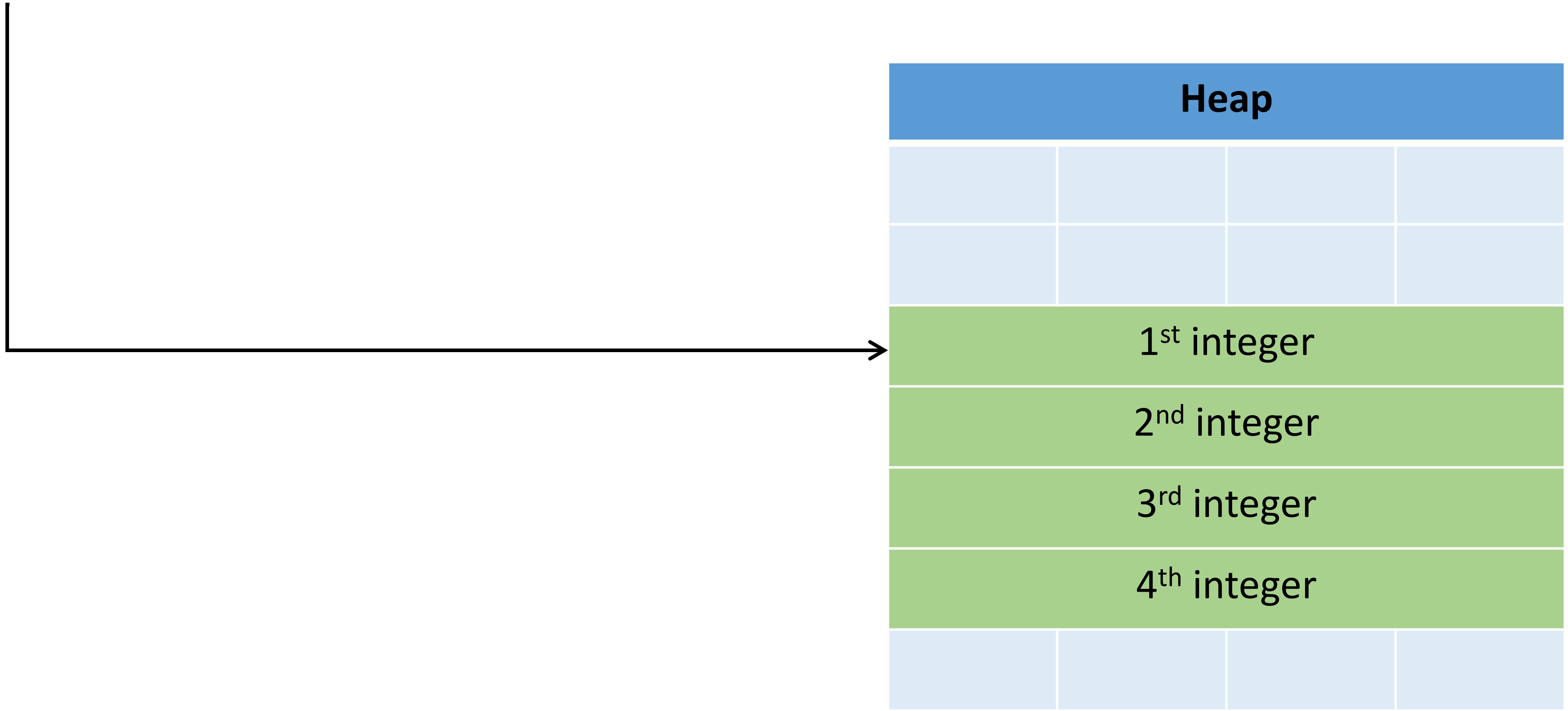
Pointers as Arrays

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```

Heap			

Pointers as Arrays

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```



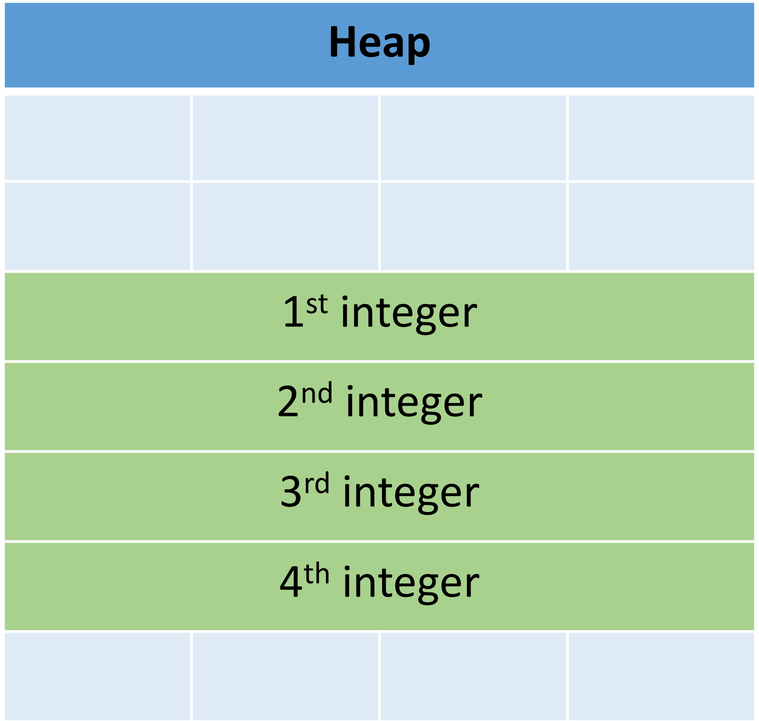
Pointers as Arrays

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```

The C compiler knows how big an integer is.

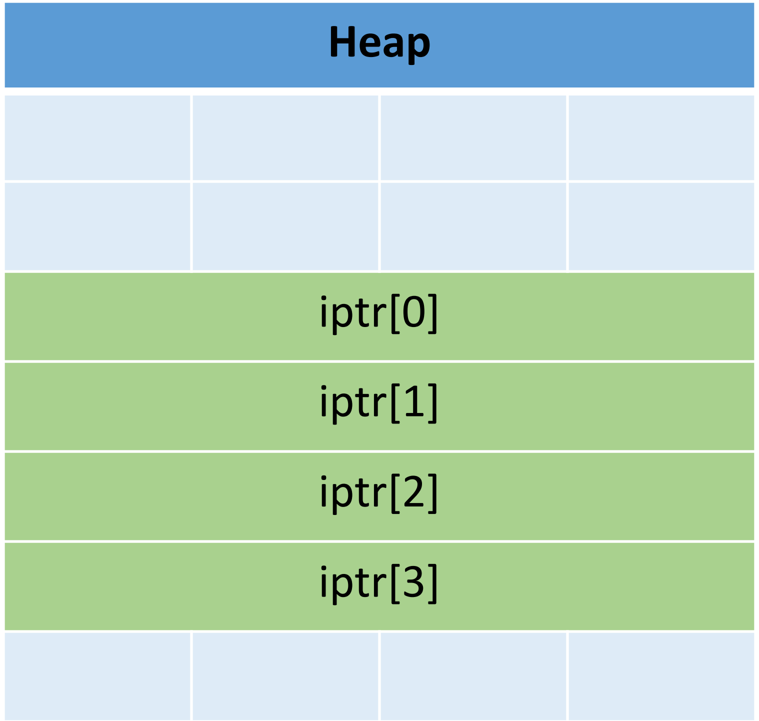
As an alternative way of dereferencing, you can use **[]**’s like an array.

The C compiler will jump ahead the right number of bytes, based on the type.



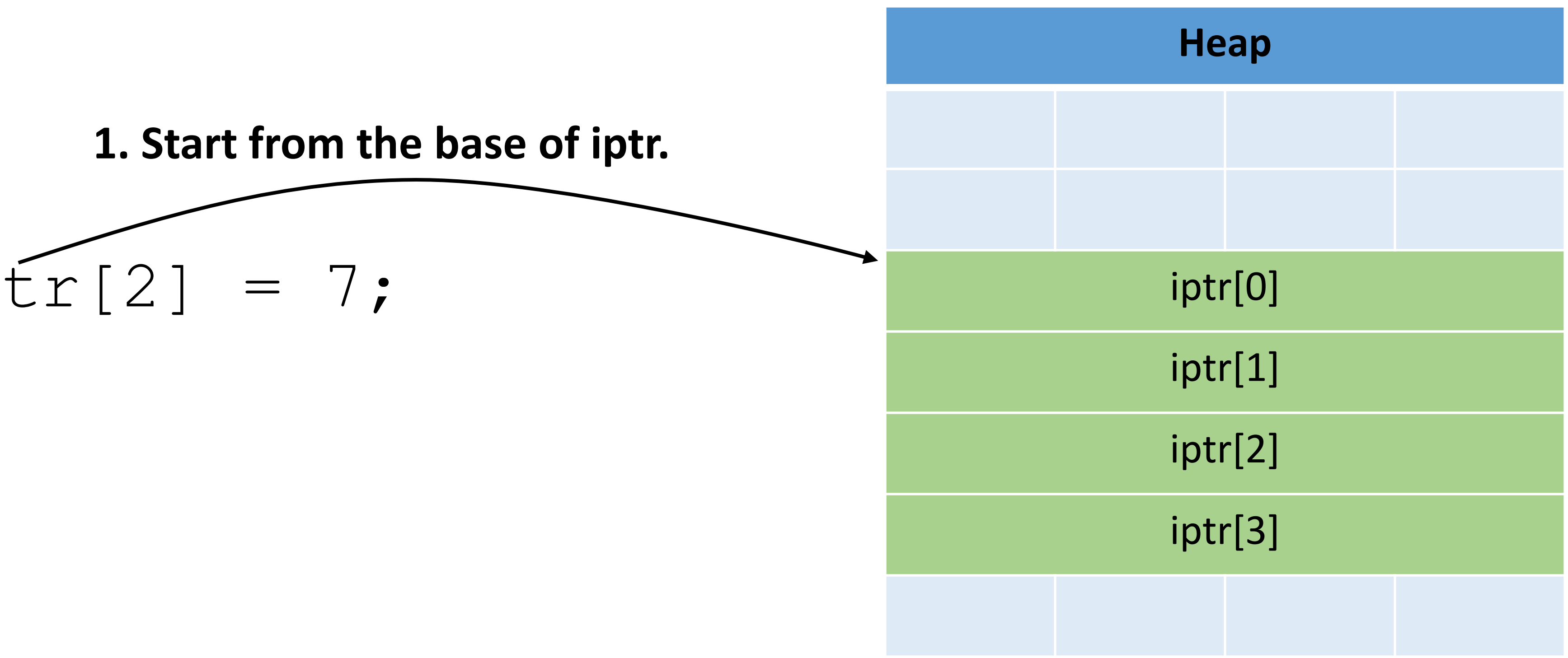
Pointers as Arrays

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```



Pointers as Arrays

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```

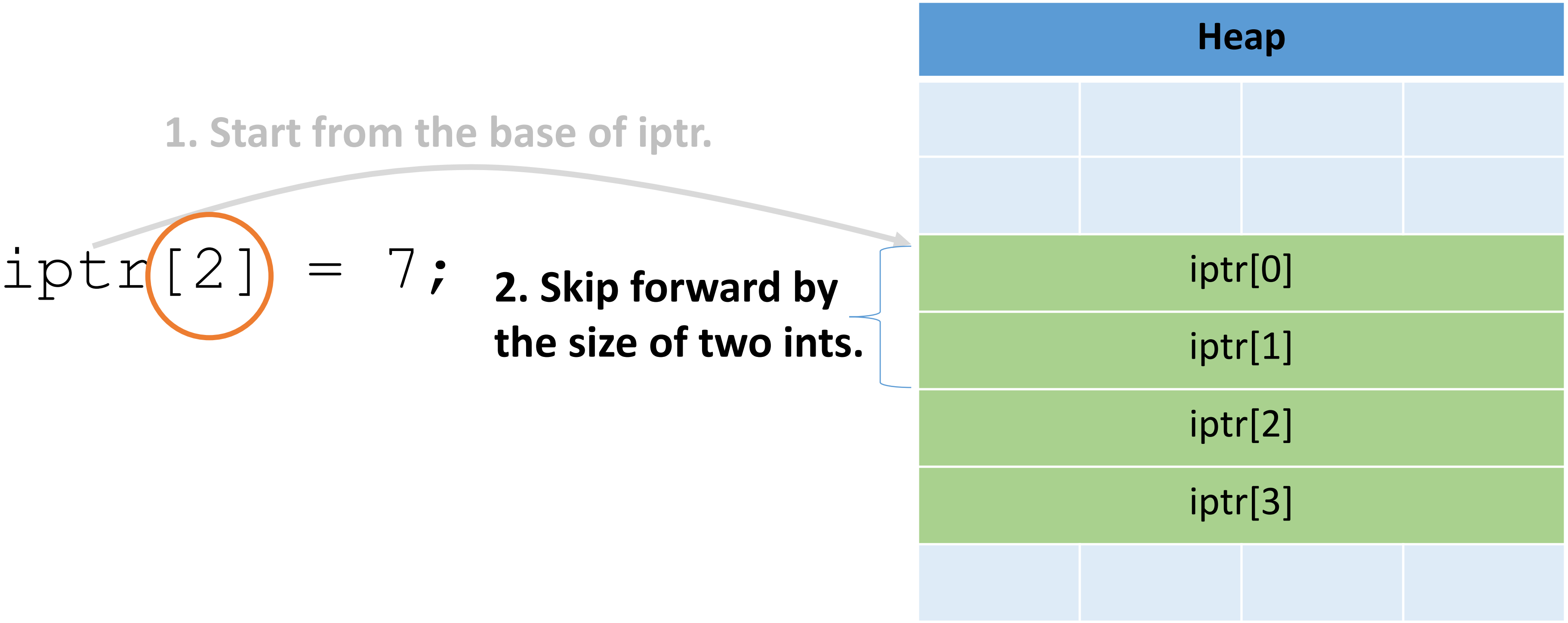


1. Start from the base of iptr.

```
iptr[2] = 7;
```

Pointers as Arrays

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```



1. Start from the base of iptr.

```
iptr[2] = 7;
```

2. Skip forward by the size of two ints.

Pointers as Arrays

- This is one of the most common ways you’ll use pointers:
  - You need to dynamically allocate space for a collection of things (ints, structs, whatever)
  - You don’t know how many at compile time

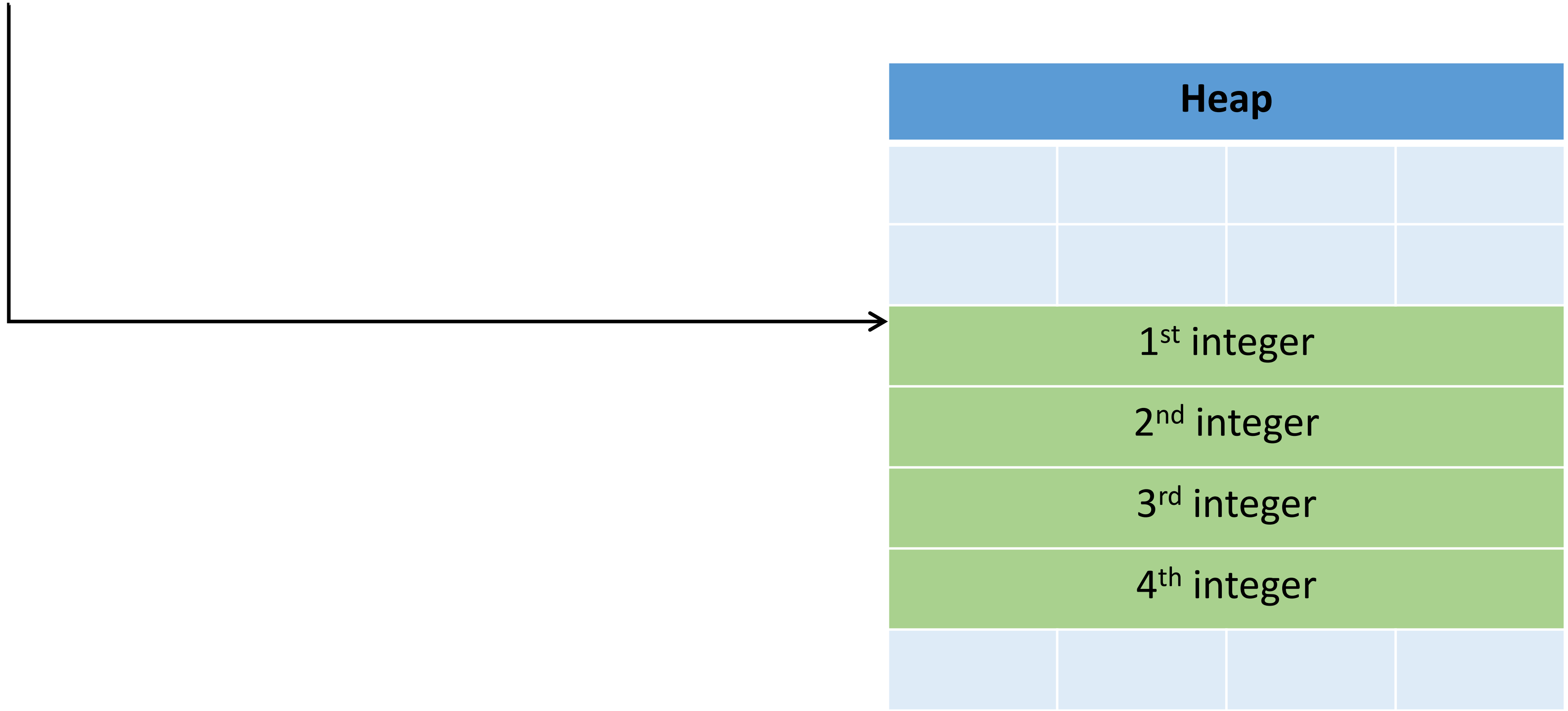
```
float *student_gpas = NULL;
student_gpas = malloc(n_students * sizeof(int));
…
student_gpas[0] = …;
student_gpas[1] = …;
```

Pointer Arithmetic

- Addition and subtraction work on pointers
- C automatically increments by the size of the type that’s pointed to

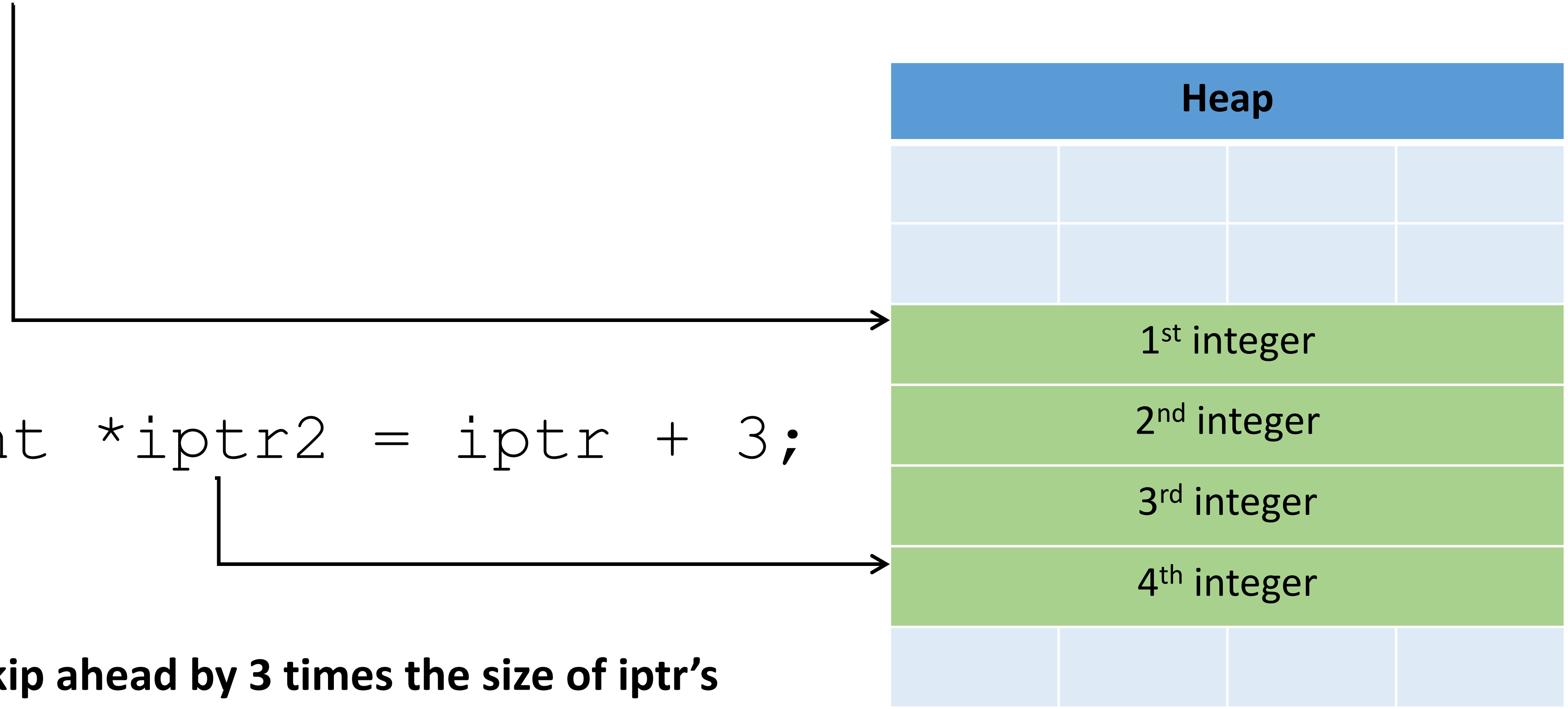
Pointer Arithmetic

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```



Pointer Arithmetic

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```



```
int *iptr2 = iptr + 3;
```

Skip ahead by 3 times the size of iptr's type (integer, size: 4 bytes).

Why Pointers?

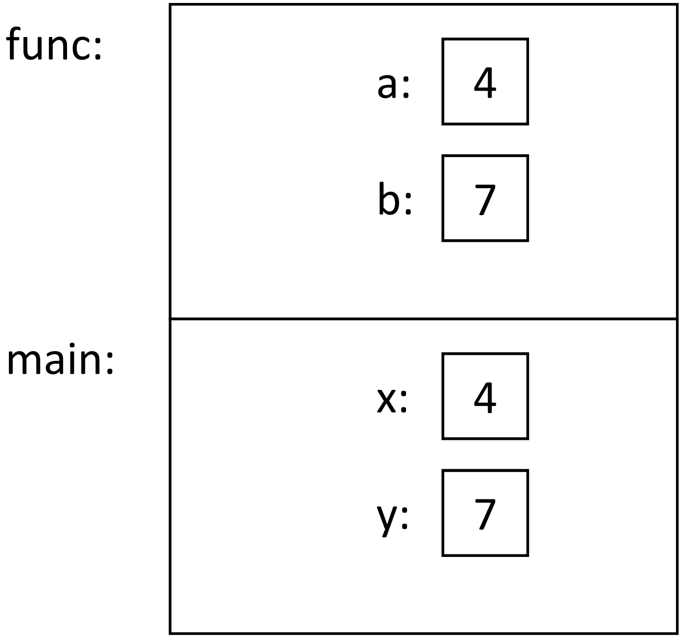
- Using pointers seems like a lot of work, and if used incorrectly, things can go wrong
- Pointers also add a level of "indirection" to retrieve / store a value

- Two main benefits:
  1. "Pass by pointer" function parameters
     - By passing a pointer into a function, the function can dereference it so that the changes persist to the caller.
  2. Dynamic memory allocation
     - A program can allocate memory on demand, as it needs it during execution

Function Arguments

- Arguments are **passed by value**
  - The function gets a separate copy of the passed variable

```
int func(int a, int b) {
       a = a + 5;
       return a - b;
}

int main(void) {
    →  int x, y;  // declare two integers
       x = 4;
       y = 7;
       y = func(x, y);
       printf("%d, %d", x, y);
}
```



func:

a: 4

b: 7

main:

x: 4

y: 7

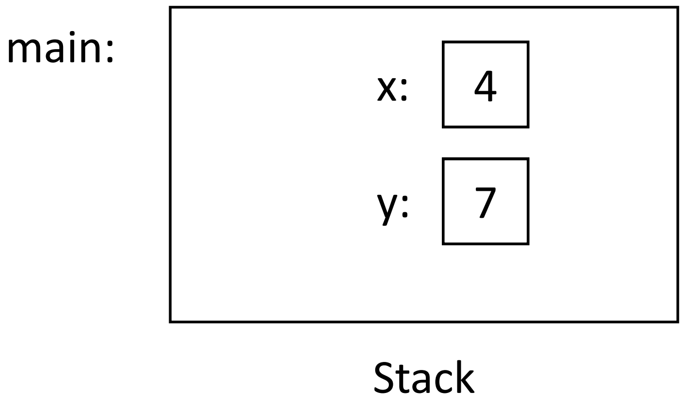
Stack

Function Arguments

- Arguments are **passed by value**
    - The function gets a separate copy of the passed variable

```
int func(int a, int b) {
        a = a + 5;
        return a - b;
}

int main(void) {
        int x, y;  // declare two integers
        x = 4;
        y = 7;
        y = func(x, y);
        printf(“%d, %d”, x, y);
}
```

It doesn’t matter what func does with a and b. The value of x in main doesn’t change.



Pass by Pointer

- Want a function to modify a value on the caller’s stack? Pass a pointer!

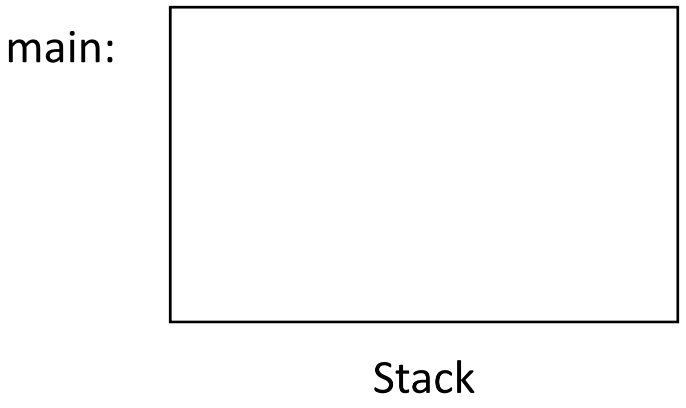
- The called function can modify the memory location it points to.
  - passing the address of an argument to function:
  - pointer parameter *holds the address of* its argument
  - *dereference* parameter to modify argument’s value

- You’ve already used functions like this:
  - `readfile` library functions and `scanf`
  - pass address of (&) argument to these functions

Function Arguments

- Arguments can be pointers!
  - The function gets the address of the passed variable!

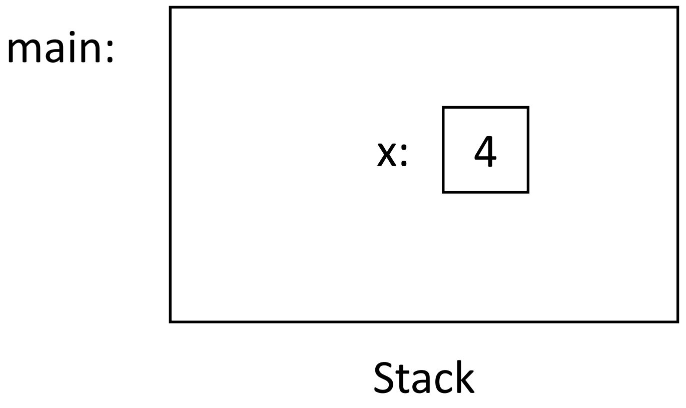
```
void func(int *a) {
       *a = *a + 5;
}

int main(void) {
       int x = 4;

       func(&x);
       printf(“%d”, x);
}
```



Pointer Arguments

- Arguments can be pointers!
  - The function gets the address of the passed variable!

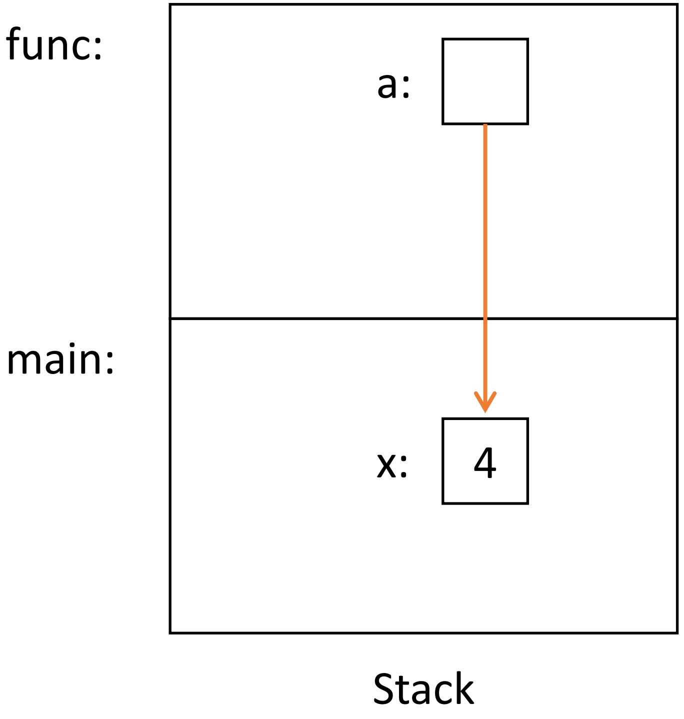
```
void func(int *a) {
      *a = *a + 5;
}

int main(void) {
   ⇨  int x = 4;

      func(&x);
      printf(“%d”, x);
}
```



Pointer Arguments

- Arguments can be pointers!
  - The function gets the address of the passed variable!

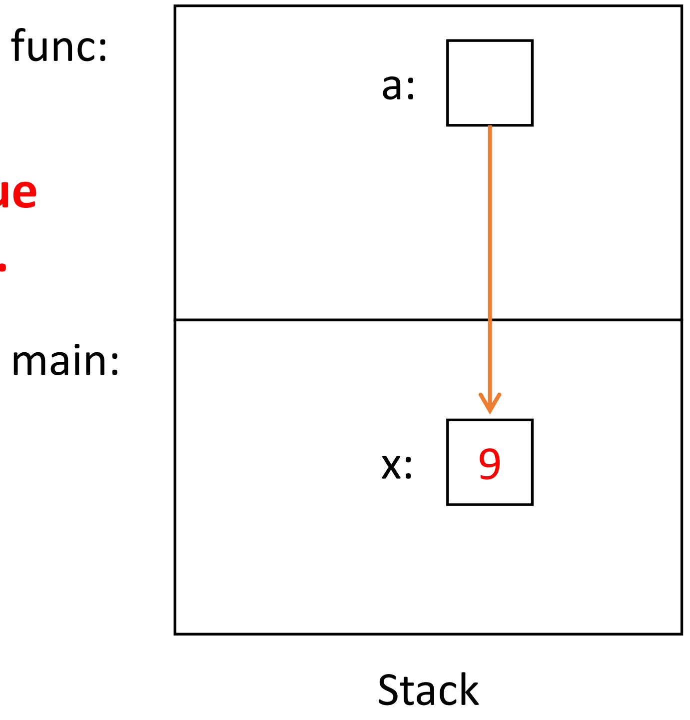
```
void func(int *a) {
      *a = *a + 5;
}

int main(void) {
      int x = 4;

   ⇨ func(&x);
      printf(“%d”, x);
}
```



Pointer Arguments

- Arguments can be pointers!
  - The function gets the address of the passed variable!

```
void func(int *a) {
   ➡ *a = *a + 5;
}

int main(void) {
      int x = 4;

      func(&x);
      printf(“%d”, x);
}
```



Dereference pointer, set value that a points to.

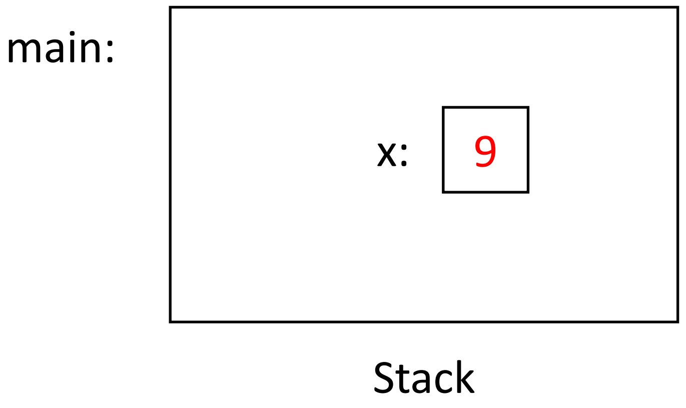
Pointer Arguments

- Arguments can be pointers!
    - The function gets the address of the passed variable!

```
void func(int *a) {
      *a = *a + 5;
}

int main(void) {
      int x = 4;

      func(&x);
    ➡ printf(“%d”, x);
}
```

Prints: 9

Haven’t we seen this somewhere before?



main:

x: 9

Stack

Readfile Library

- We saw this in lab 1 with read_int, read_float.
  - This is why you needed an &.
  - e.g.,

```
int value;
status_code = read_int(&value);
```

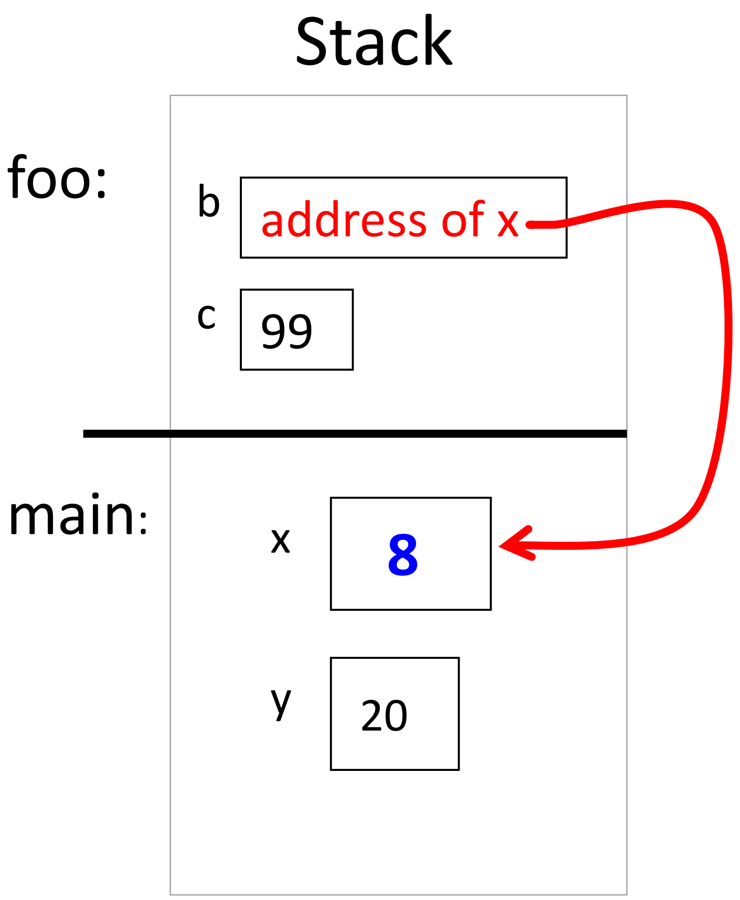
- You're asking read_int to modify a parameter, so you give it a pointer to that parameter.
  - read_int will dereference it and set it.

Pass by Pointer - Example

```
int main(void){
   int x, y;
   x = 10; y = 20;
   foo(&x, y);
   …
}

void foo(int *b, int c){
   c = 99
  *b = 8;     // Stack drawn here
}
```

pass the value of &x

dereference parameter b to set argument x’s value



Passing Arrays

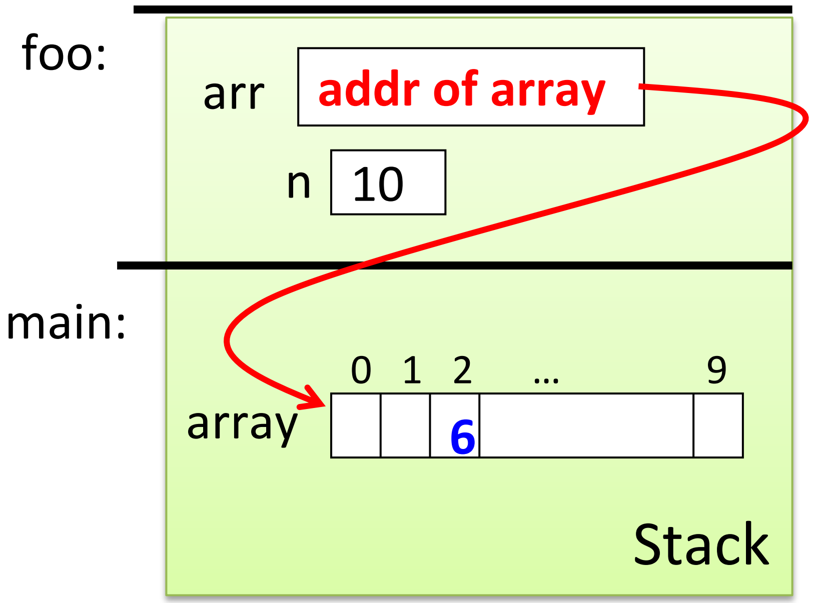
- An array argument’s value is its base address
- Array parameter “points to” its array argument

Passing Arrays

- An array argument's value is its base address
- Array parameter "points to" its array argument

```
int main(void){
   int array[10];
   foo(array, 10);
}
void foo(int arr[], int n){
   arr[2] = 6;
}
```

array base address

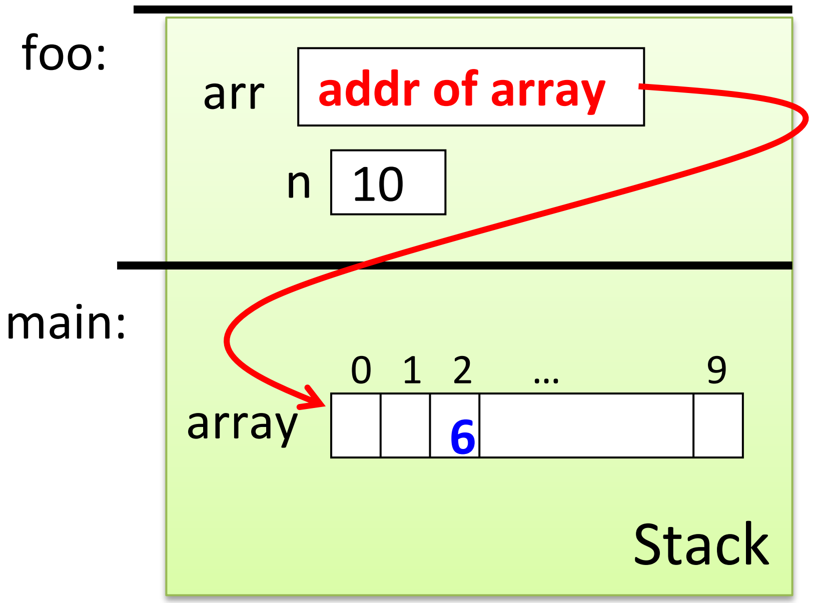


Passing Arrays

- An array argument's value is its base address
- Array parameter "points to" its array argument

```
int main(void){
   int array[10];
   foo(array, 10);
}
void foo( ________ , int n){
   arr[2] = 6;
}
```

alternative declaration?

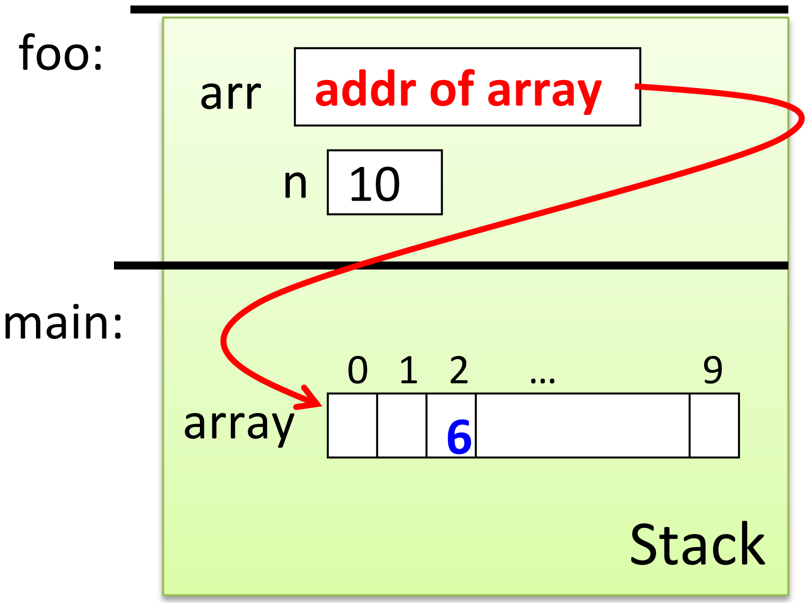


Passing Arrays

- An array argument's value is its base address
- Array parameter "points to" its array argument

```
int main(void){
   int array[10];
   foo(array, 10);
}
void foo(int *arr, int n){
   arr[2] = 6;
}
```

pass a pointer instead



Can you return an array?

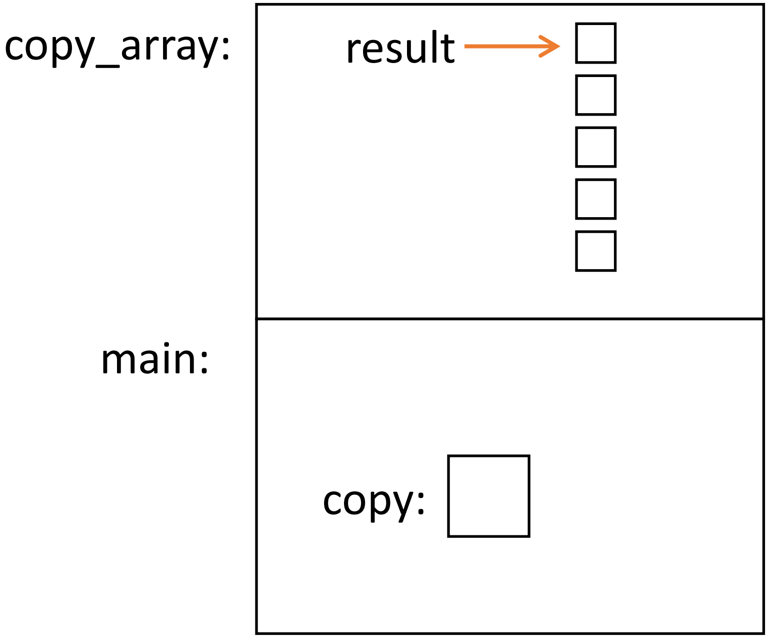
- Suppose you wanted to write a function that copies an array (of 5 integers).
  - Given: array to copy

```
copy_array(int array[]) {
  int result[5];
  result[0] = array[0];
  …
  result[4] = array[4];
  return result;
}
```

As written above, this would be a terrible way of implementing this.
(Don’t worry, compiler won’t let you do this anyway.)

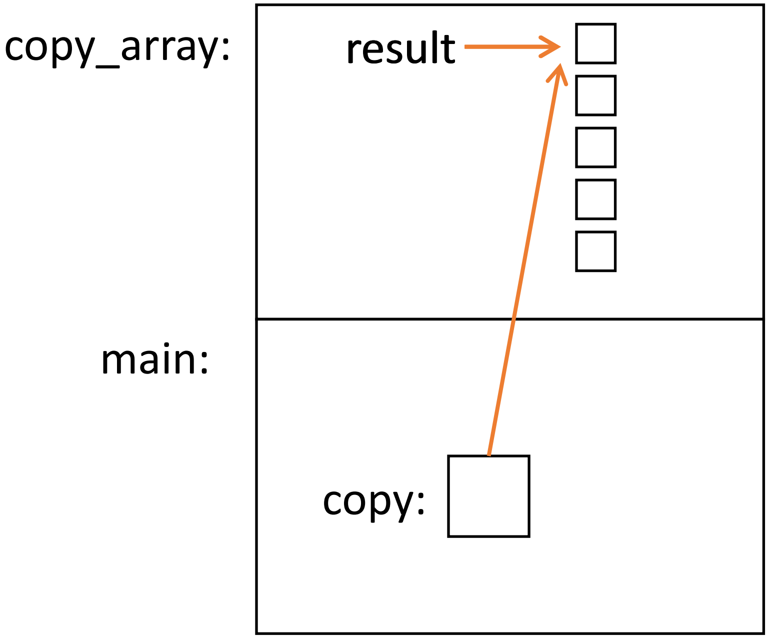
Consider the memory…

```
copy_array(int array[]) {
  int result[5];
  result[0] = array[0];
  …
  result[4] = array[4];
  return result;
}

(In main):
copy = copy_array(…)
```



Consider the memory…

```
copy_array(int array[]) {
  int result[5];
  result[0] = array[0];
  …
  result[4] = array[4];
➡ return result;
}

(In main):
copy = copy_array(…)
```

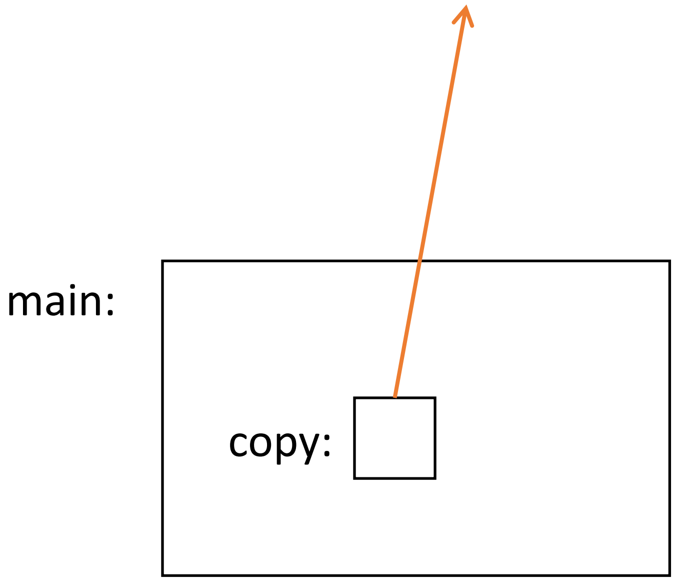


Consider the memory…

When we return from copy_array, its stack frame is gone!

```
(In main):
copy = copy_array(…)
```

Left with a pointer to nowhere.

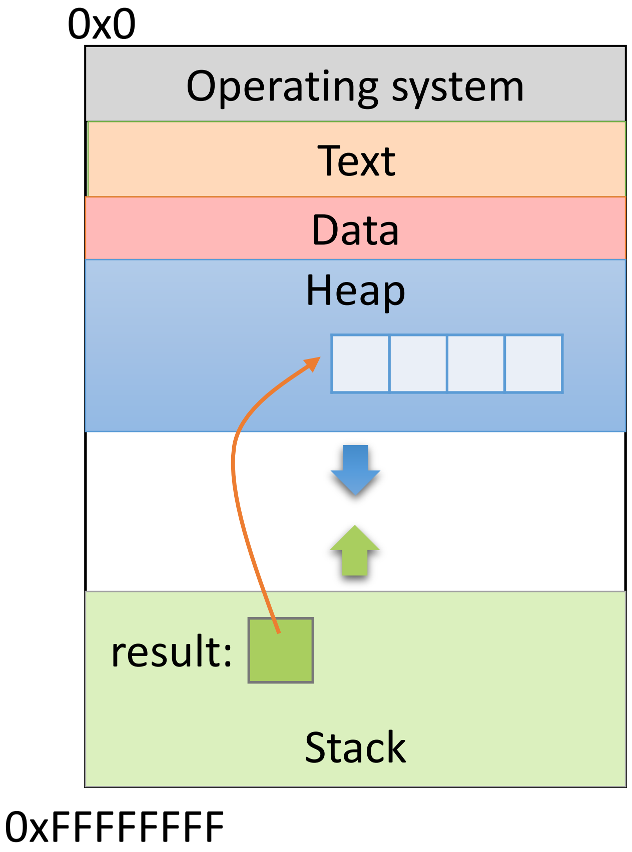


Using the Heap

```
int *copy_array(int num, int array[]) {
  int *result = malloc(num * sizeof(int));

  result[0] = array[0];
  …

  return result;
}
```

malloc memory is on the heap.

Doesn't matter what happens on the stack (function calls, returns, etc.)



Pointers to Pointers

- Why stop at just one pointer?

```
int **double_iptr;
```

- “A pointer to a pointer to an int.”
  - Dereference once: pointer to an int
  - Dereference twice: int

- Commonly used to:
  - Allow a function to modify a pointer (data structures)
  - Dynamically create an array of pointers.
  - (Program command line arguments use this.)

Up Next:

- Function calls and stack management