CS 31: Introduction to Computer Systems

09-10: Pointers, Memory

February 20, 22

SWARTHMORE COLLEGE

Reading Quiz

Last class

- Assembly Programming

Today

- How to reference the location of a variable in memory
- Where variables are placed in memory
- How to make this information useful
  - Allocating memory
  - Calling functions with pointer arguments

Pointers

What is a pointer?

Pointers

What is a pointer?

A pointer is like a mailing address,
it tells you where something is **located**.

A **pointer** tells you where a variable is **located** in **memory**.

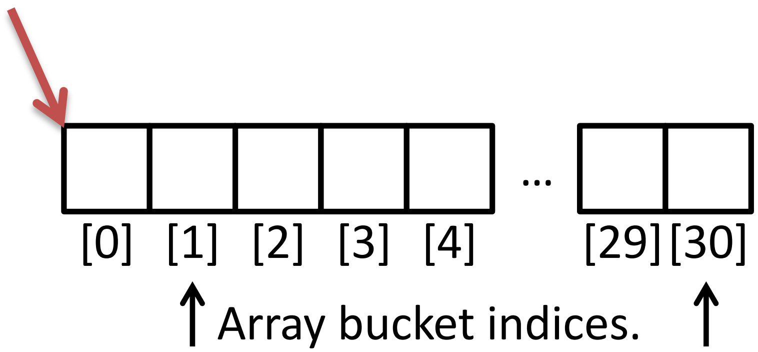
Pointers

- <u>Pointer: A variable that stores a reference to a memory location.</u>
- Pointer: sequence of bits that should be interpreted as an index into memory.
- Where have we seen this before?

Recall: Arrays

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

“january_temps” Location of [0] in memory.



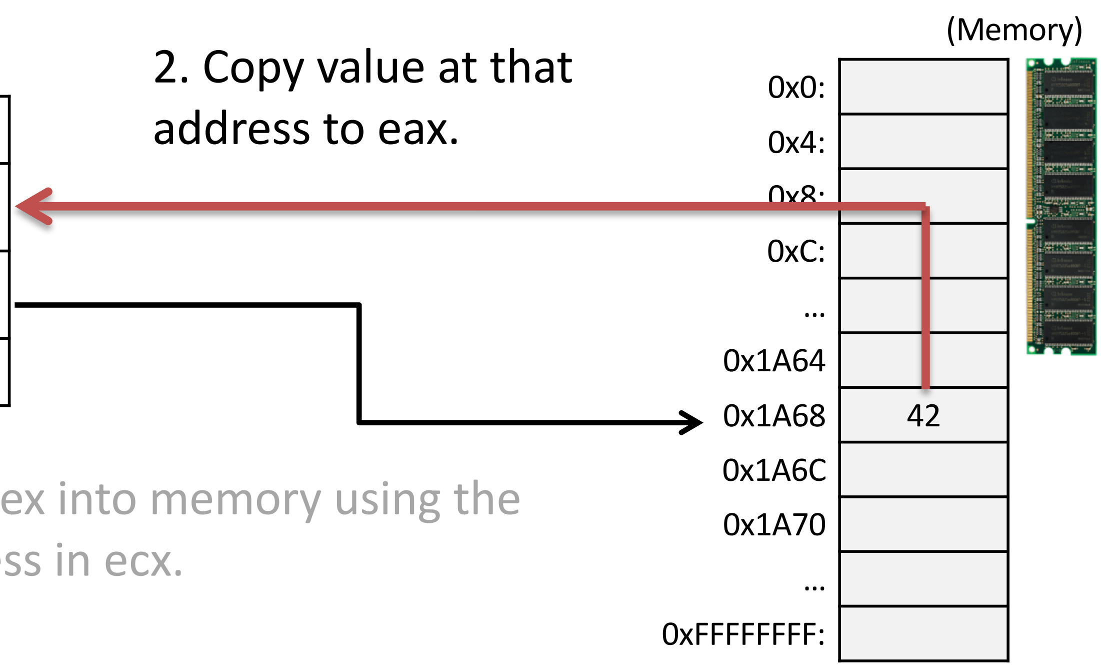
- Array variable name means, to the compiler, the beginning of the memory chunk. (address)

Recall: Addressing Modes

- `movl (%ecx), %eax`
  - Use the address in register ecx to access memory, store result in register eax

CPU Registers

name	value
`%eax`	42
`%ecx`	0x1A68
…	



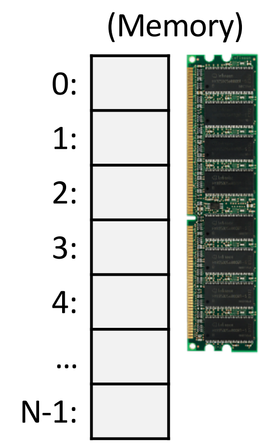
Recall: Program Counter

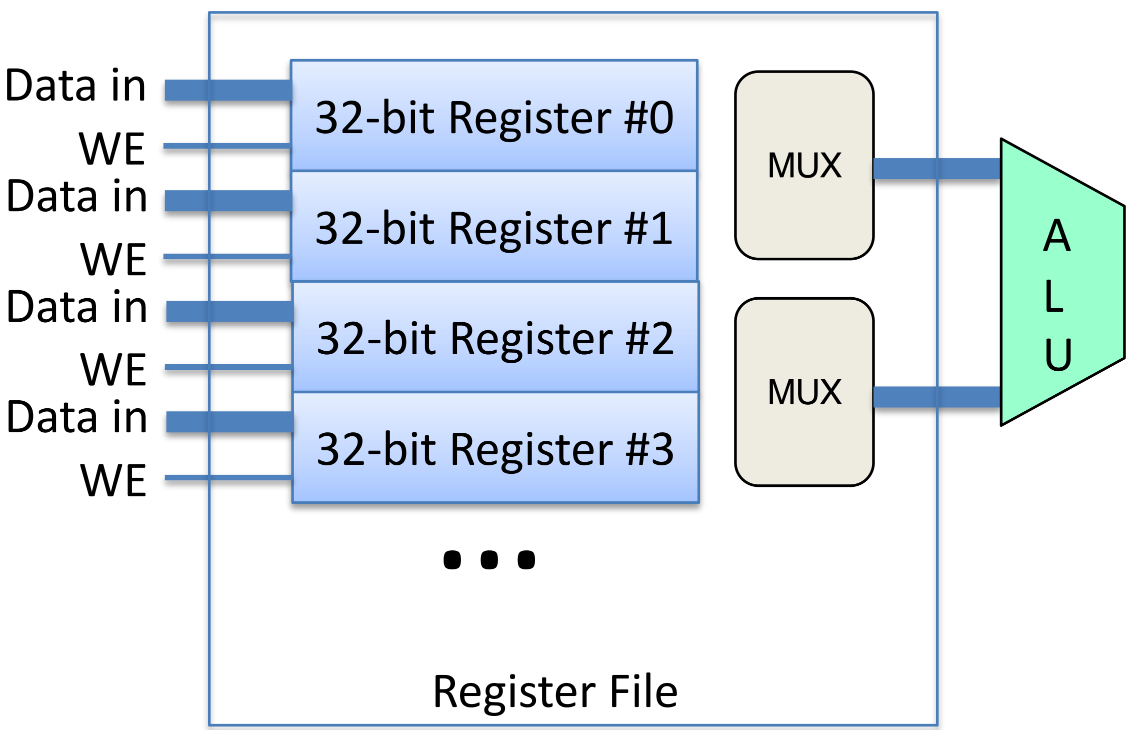
Program Counter (PC): **Memory address of next instr**

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

IA32 refers to the PC as %eip.

Instruction
Pointer





Pointers in C

- Like any other variable, must be declared:
  - Using the format: type *name;

- Example:
  - int *myptr;
  - This is a promise to the compiler:
  - myptr: holds a memory address. 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,
- then, `*iptr` will follow the address it stores to find an integer in memory.

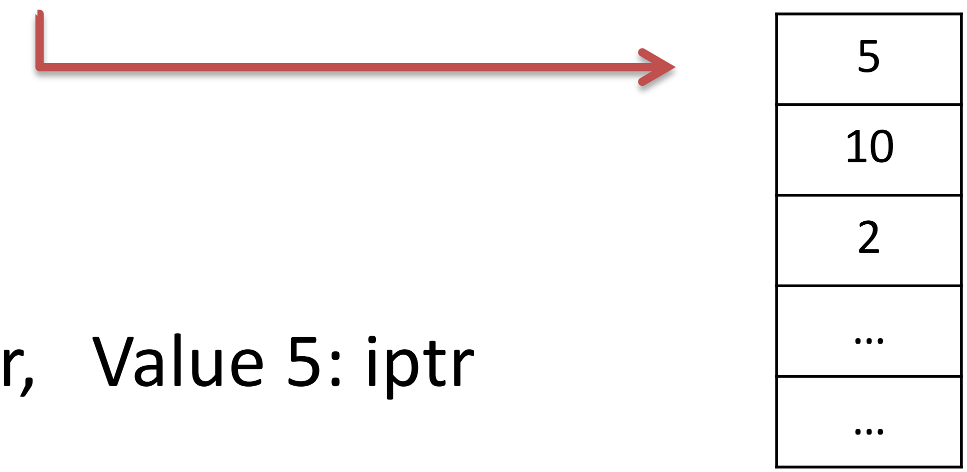
Putting a * in front of a variable…

- When you *declare* the variable:
  - Declares the variable to be a pointer
  - It stores a memory address

- When you *use* the variable (dereference):
  - Like putting () around a register name
  - Follows the pointer out to memory
  - Acts like the specified type (e.g., int, float, etc.)

Suppose we set up a pointer like the one below. Which expression gives us 5, and which gives us a memory address?

int *iptr = (the location of that memory);



A. Memory address: *iptr, Value 5: iptr

B. Memory address: iptr, Value 5: *iptr

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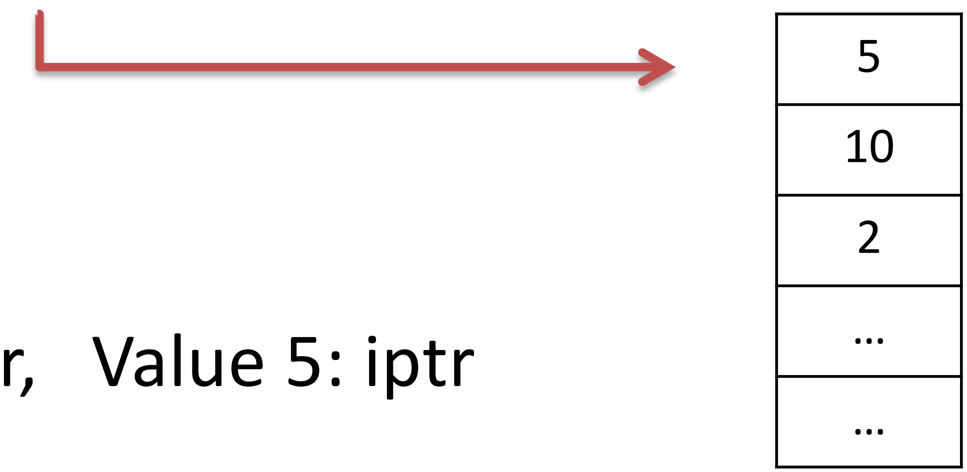


A. Memory address: *iptr,   Value 5: iptr

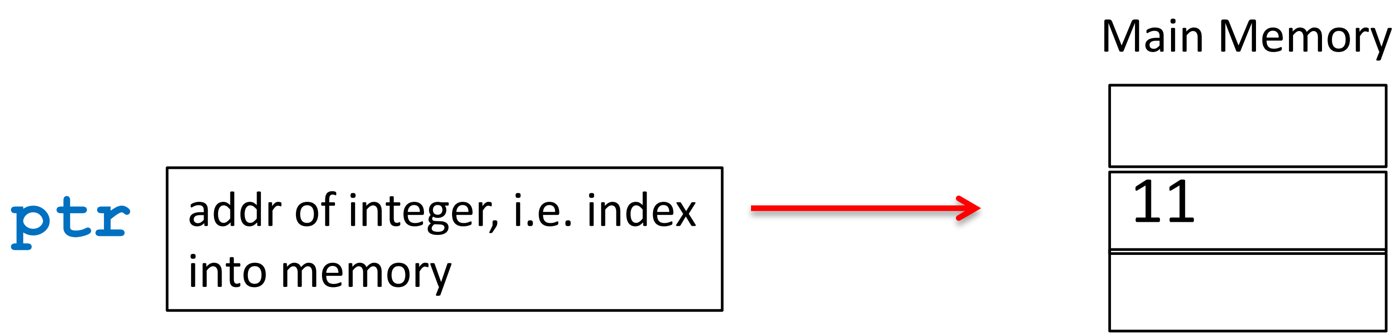
B. Memory address: iptr,   Value 5: *iptr

So we declared a pointer…

- 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 and point to it

Pointers

- Pointer: A variable that stores a memory address.



Pointers

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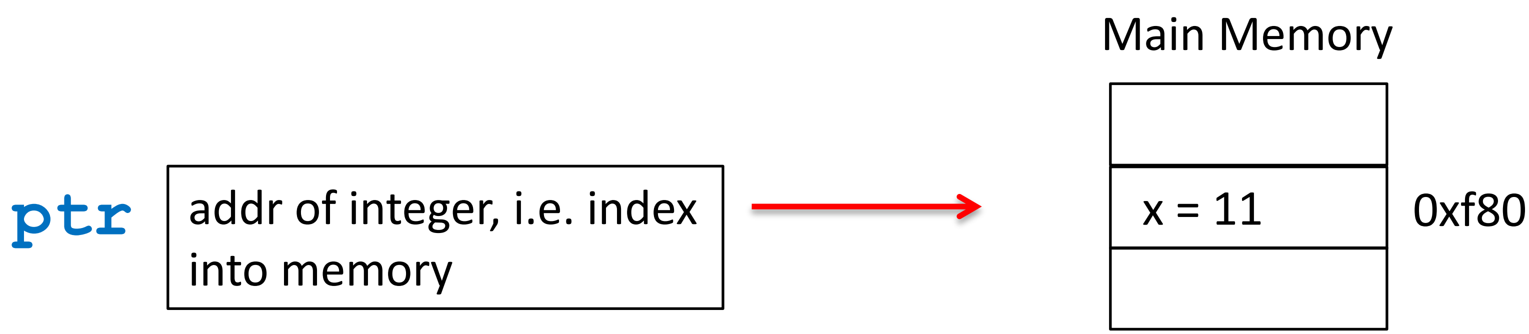
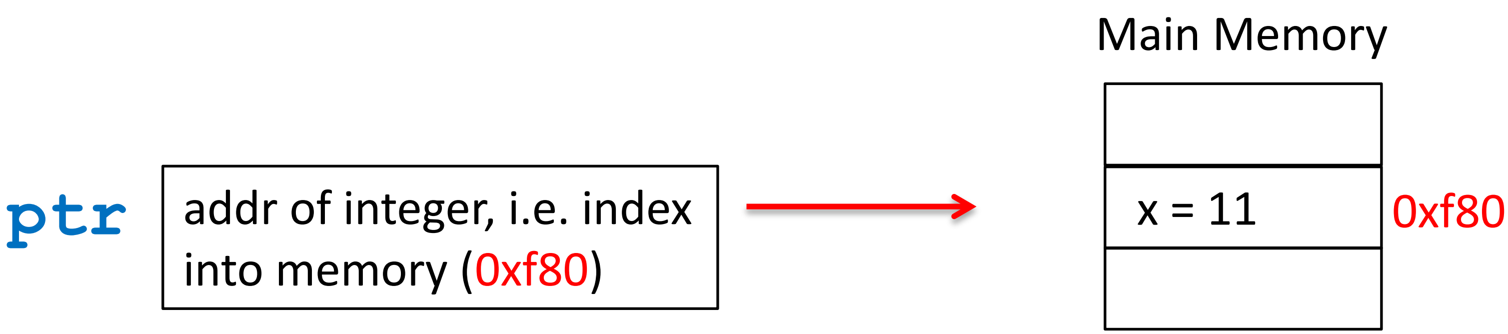


- Pointer declaration:
  int *ptr //ptr to an int

- Pointer assignment:
  int x;
  ptr = & x; // pointer stores address of x

Pointers

- **Pointer: A variable that stores a memory address.**



- Pointer declaration:
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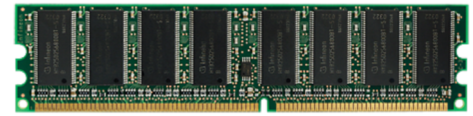
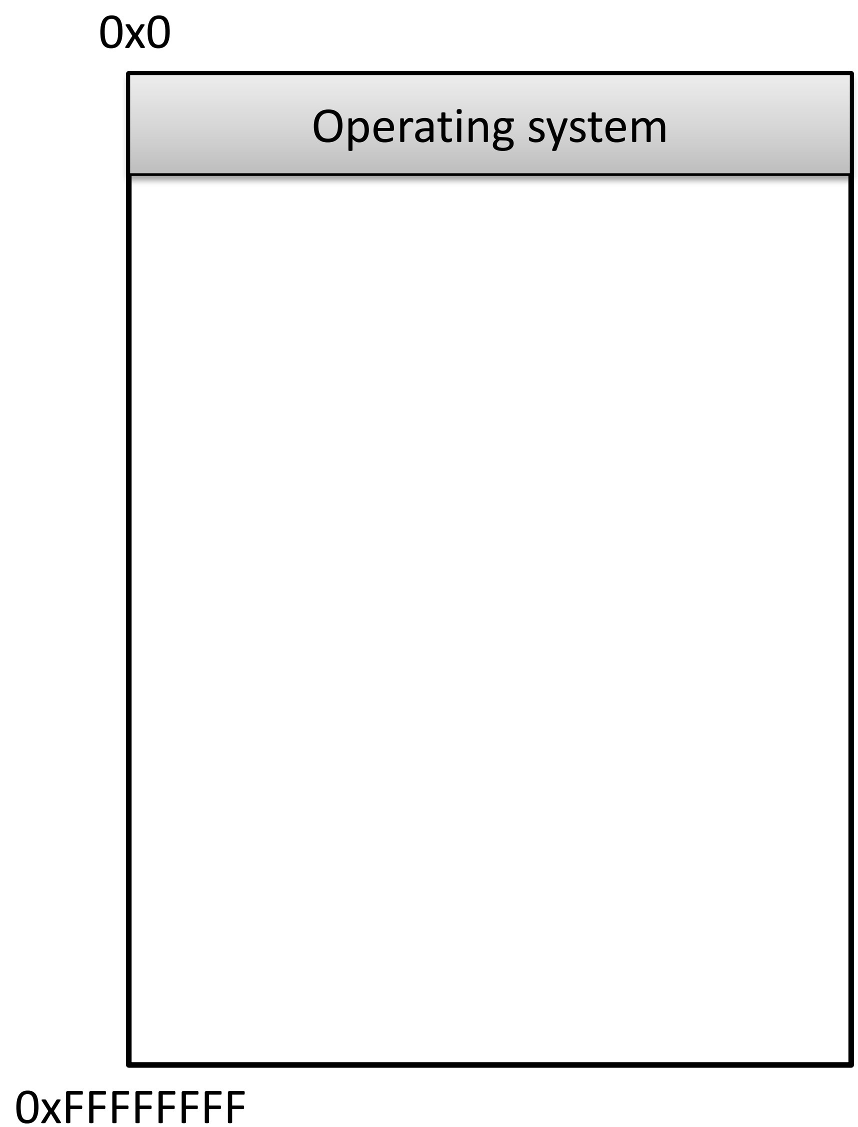
Memory



- 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.



So we declared a pointer…

- How do we make it point to something?
  1. Assign it the address of an existing variable (&)
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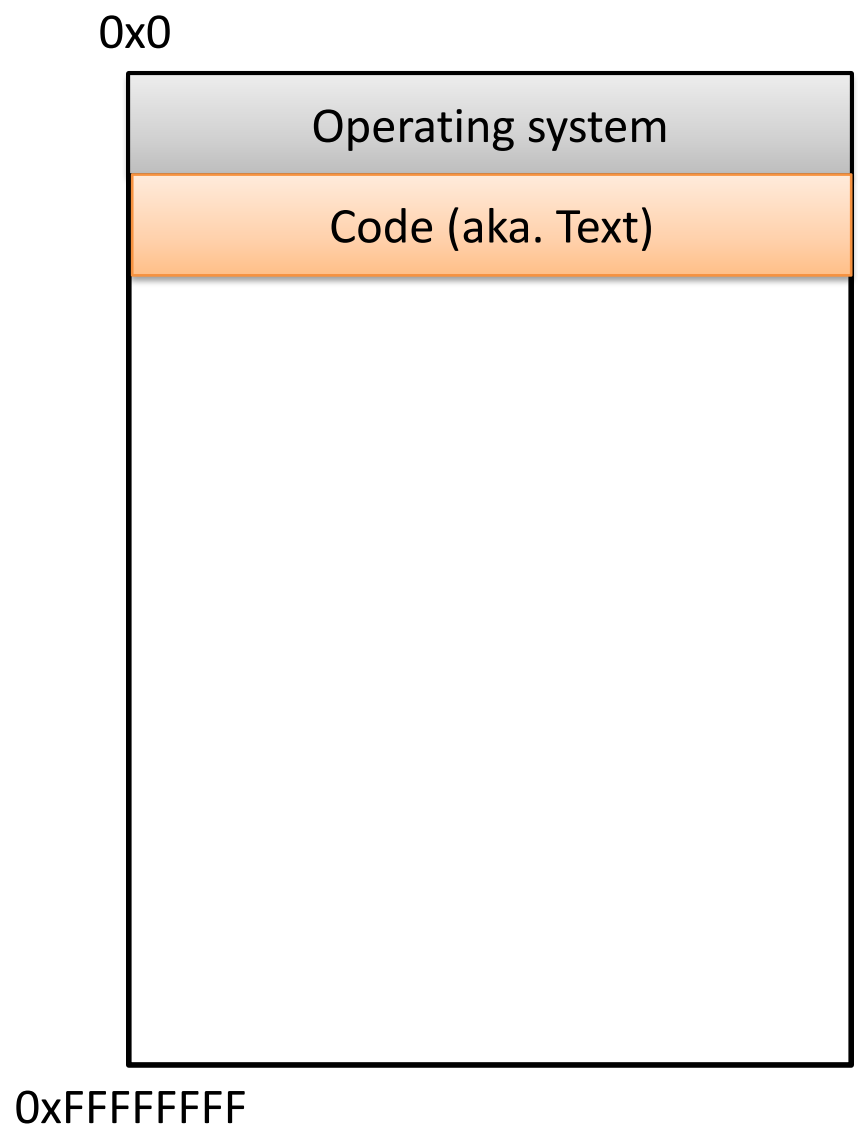
- First, let's look at how memory is organized.
  – From the perspective of one executing program.

Memory - Text

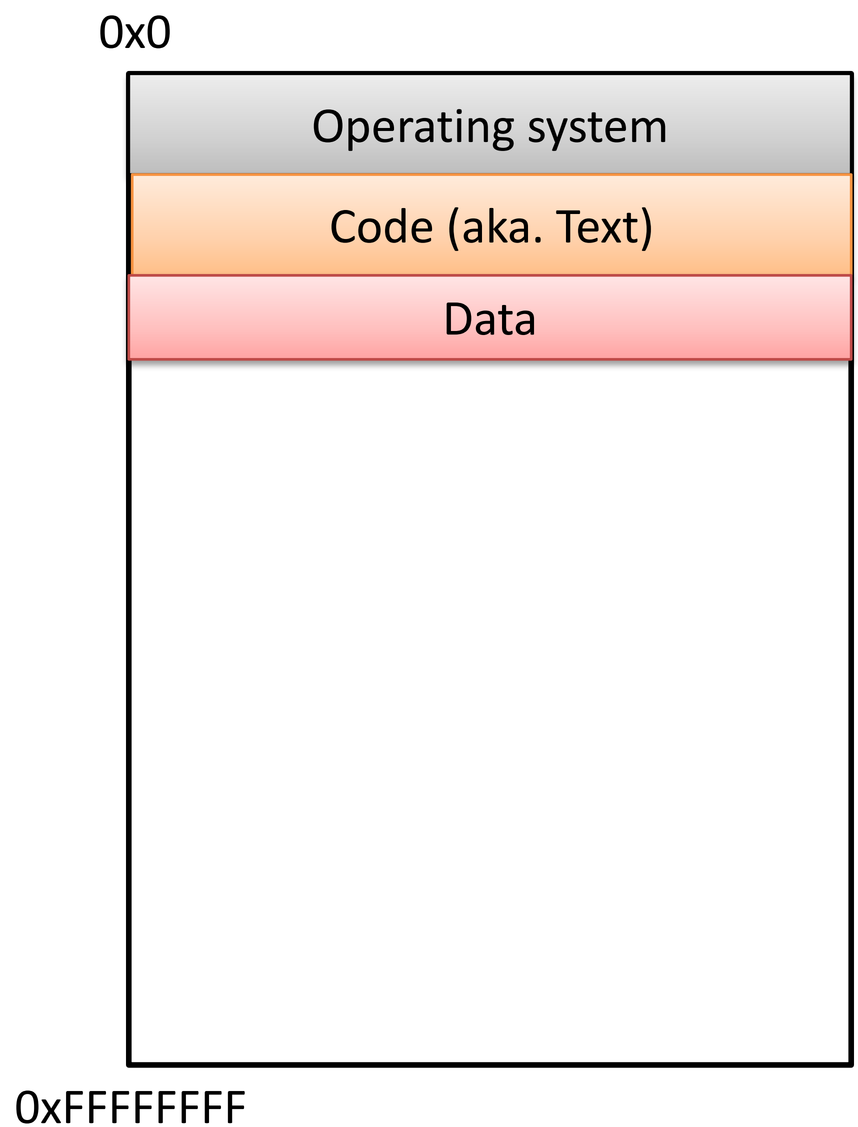
- After the OS, we store the program's code.

- Instructions generated by the compiler.



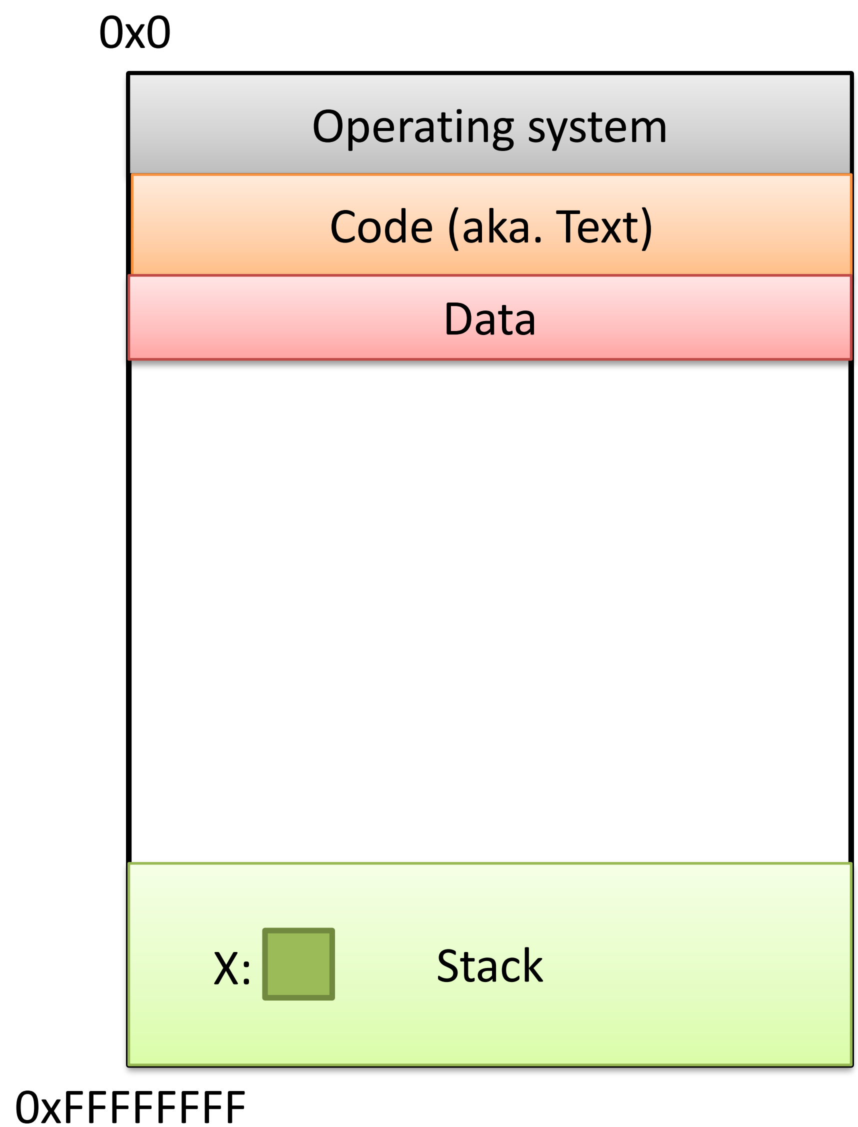
Memory – (Static) Data

- Next, there's a fixed-size region for static data.
- This stores static variables that are known at compile time.
  - Global variables



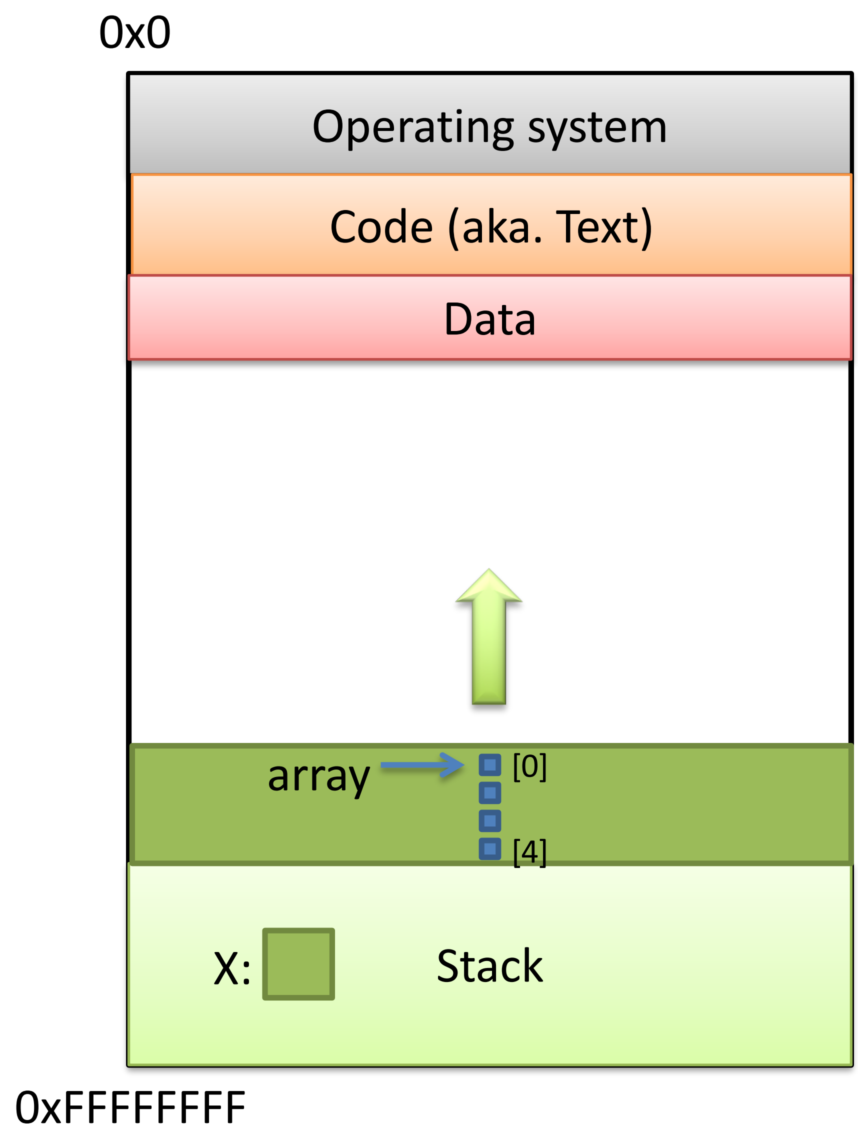
Memory - Stack

- 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

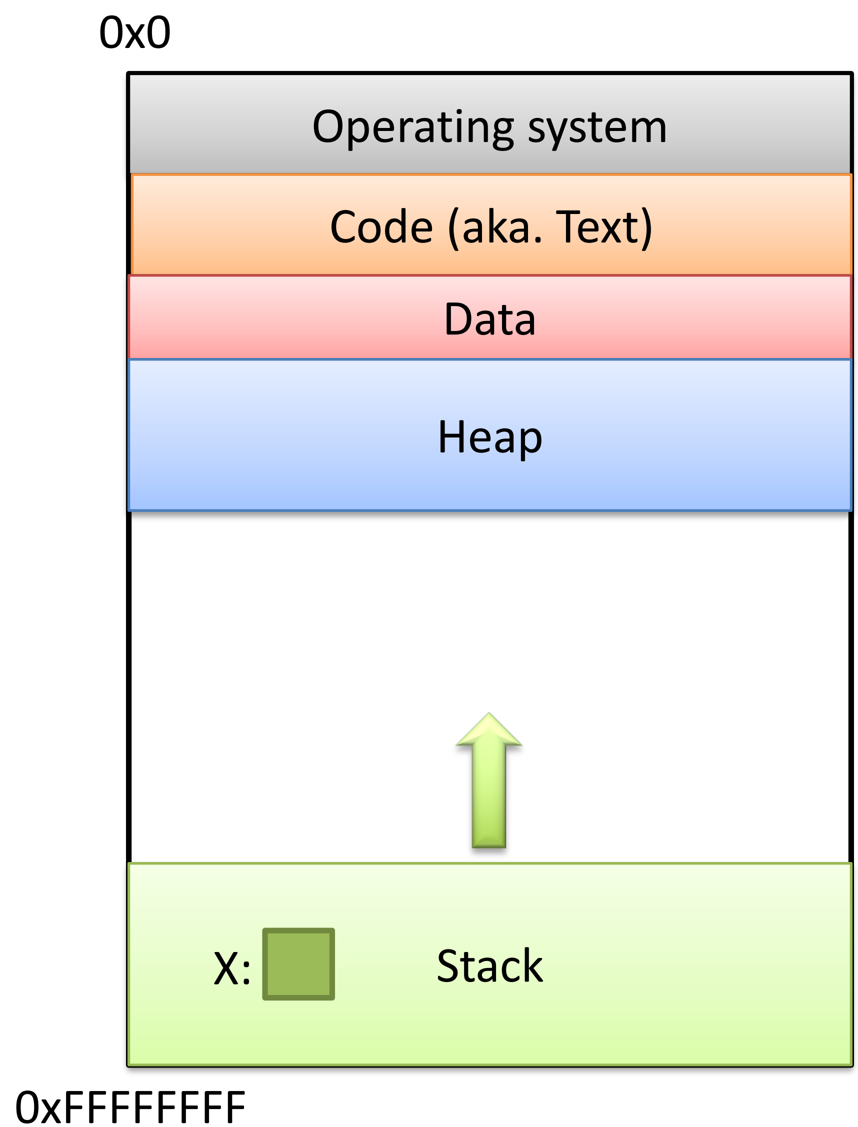
- The stack grows upwards towards lower addresses (negative direction).
- Example: Allocating array
  – int array[4];
- (Note: this differs from Python.)



Memory - Heap

- The heap stores dynamically allocated variables.

- When programs explicitly ask the OS for memory, it comes from the heap.
  - malloc() function



If we can declare variables on the stack, why do we need to dynamically allocate things on the heap?

A. There is more space available on the heap.

B. Heap memory is better. (Why?)

C. We may not know a variable's size in advance.

D. The stack grows and shrinks automatically.

E. Some other reason.

If we can declare variables on the stack, why do we need to dynamically allocate things on the heap?

A. There is more space available on the heap.

B. Heap memory is better. (Why?)

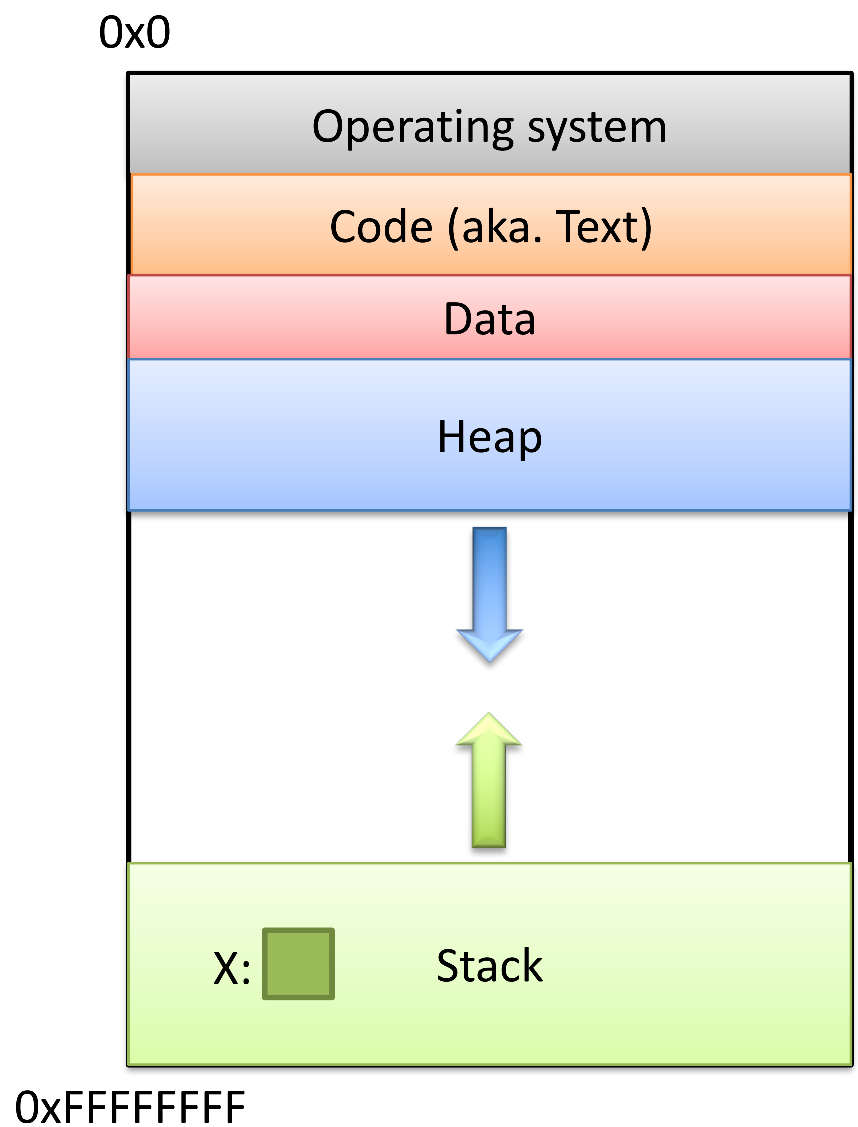
C. We may not know a variable's size in advance – prior to running - (primary reason).

D. The stack grows and shrinks automatically (return from function: can't return large chunk of memory safely) .

E. Some other reason.

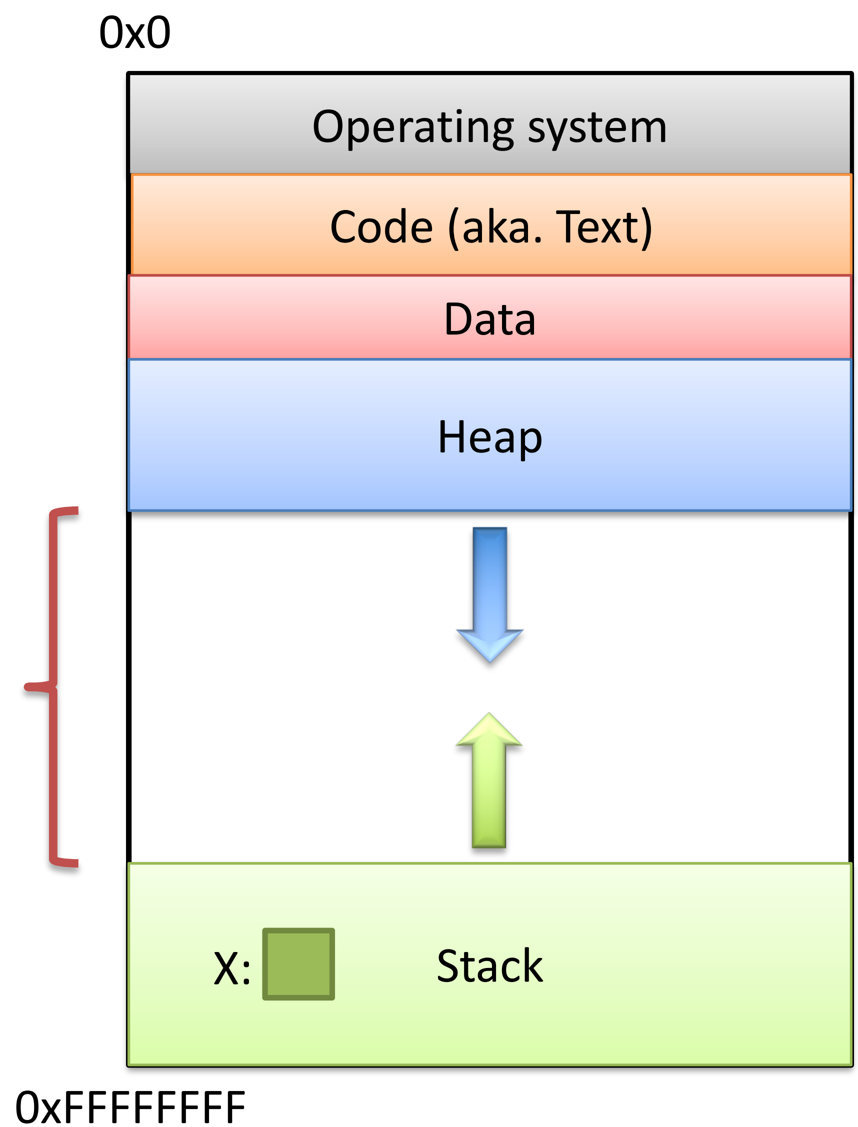
Memory - Heap

- 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.



Which region would we expect the PC register (program counter) to point to?

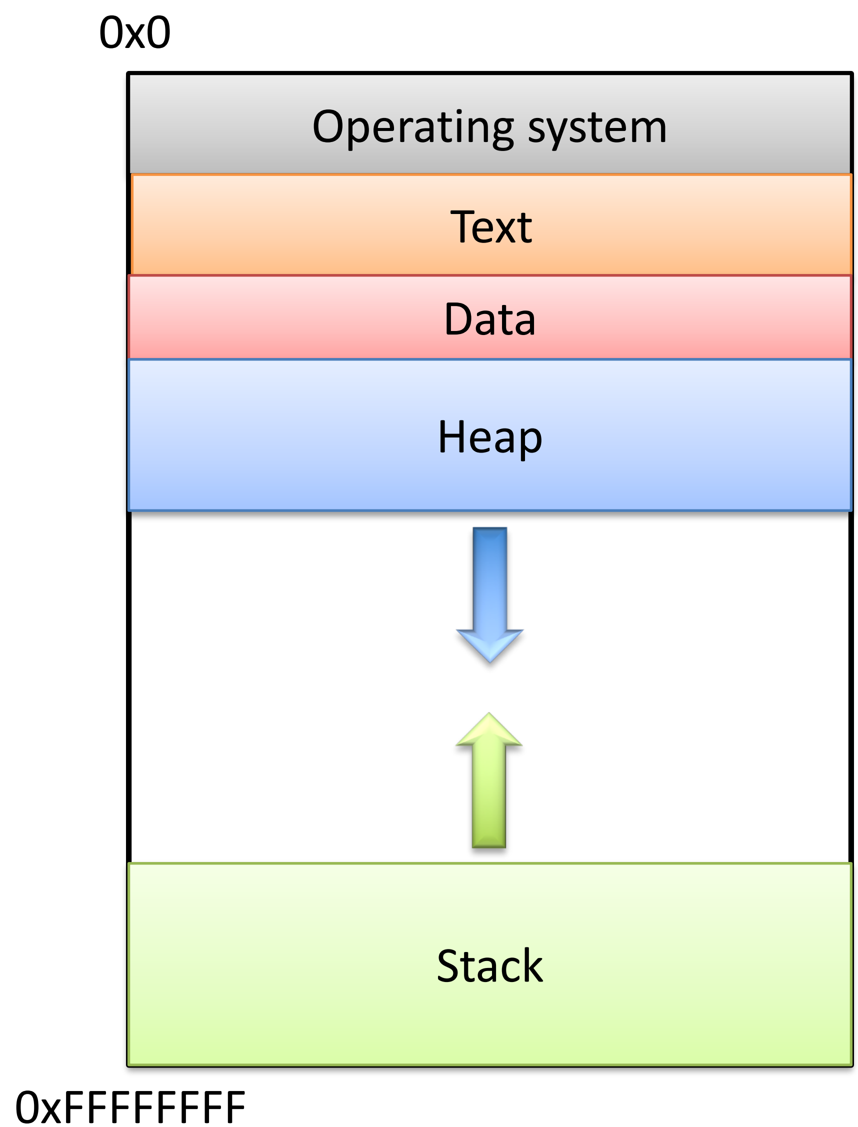
A. OS

B. Text

C. Data

D. Heap

E. Stack



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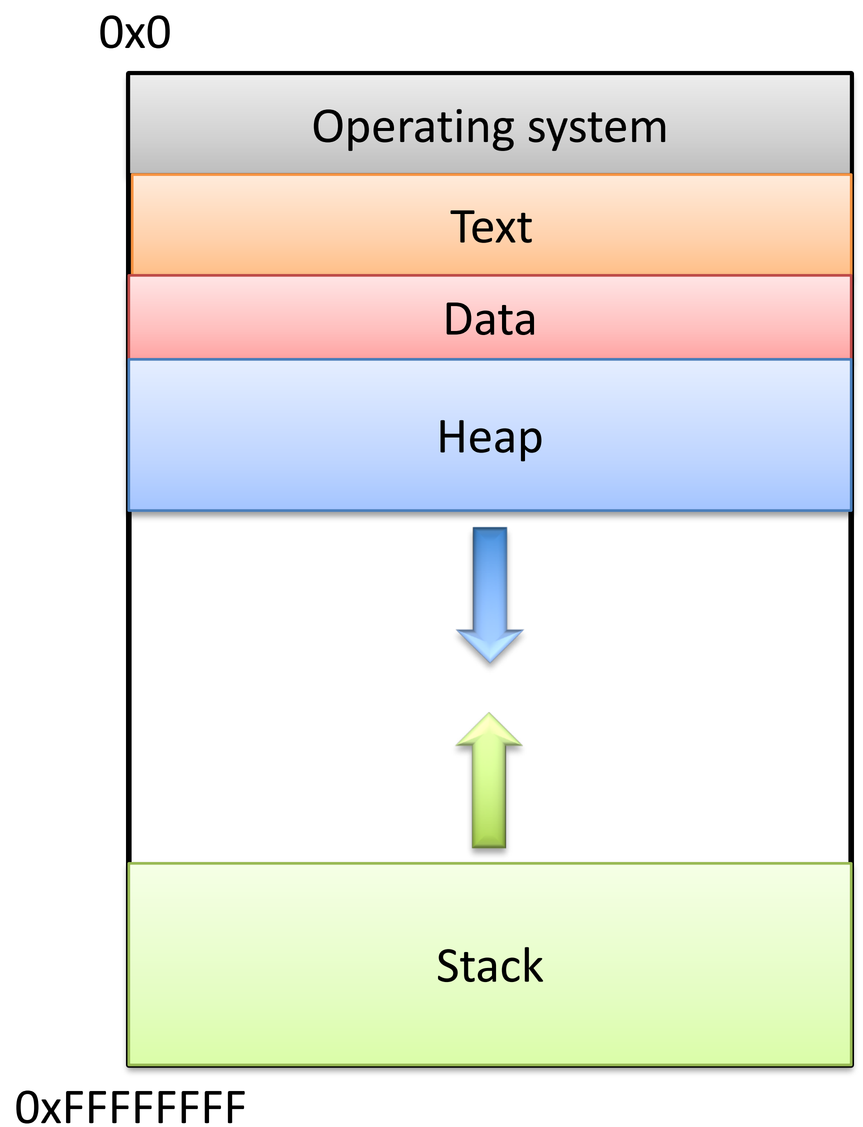


What should happen if we try to access an address that's NOT in one of these regions?

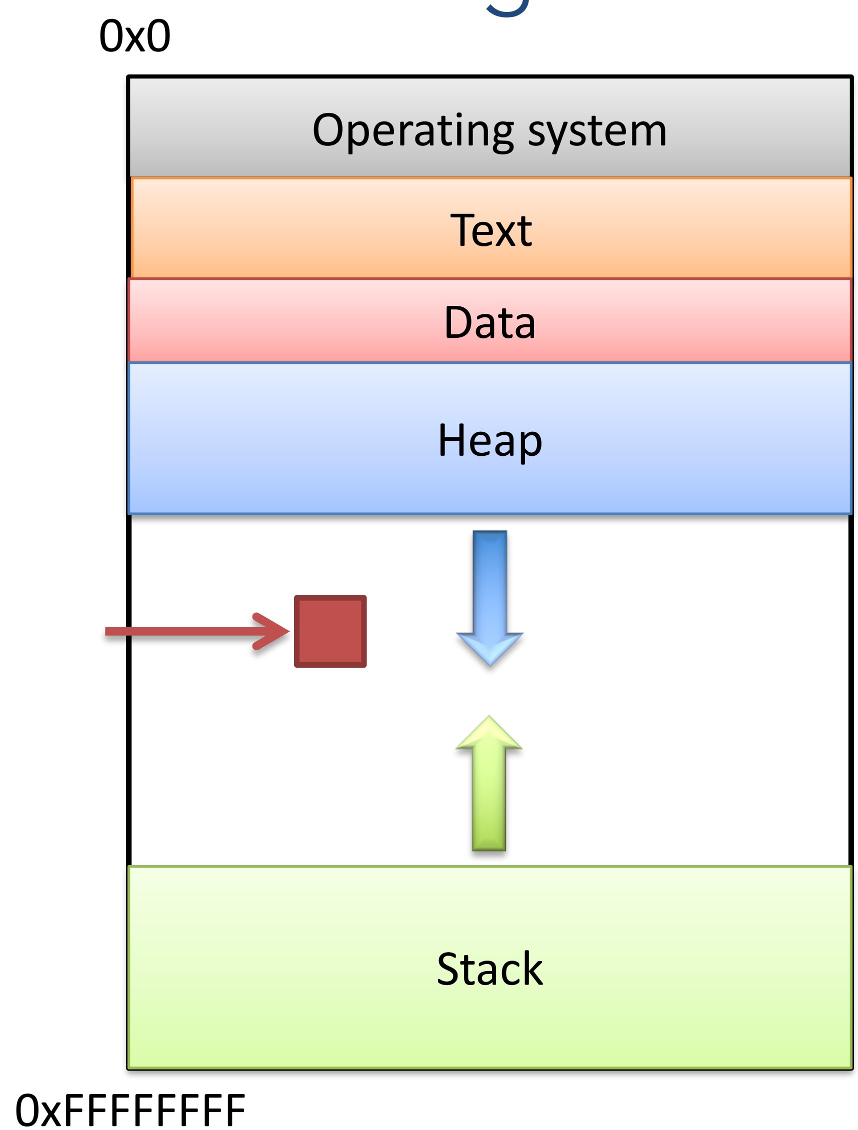
A. The address is allocated to your program.

B. The OS warns your program.

C. The OS kills your program.

D. The access fails, try the next instruction.

E. Something else



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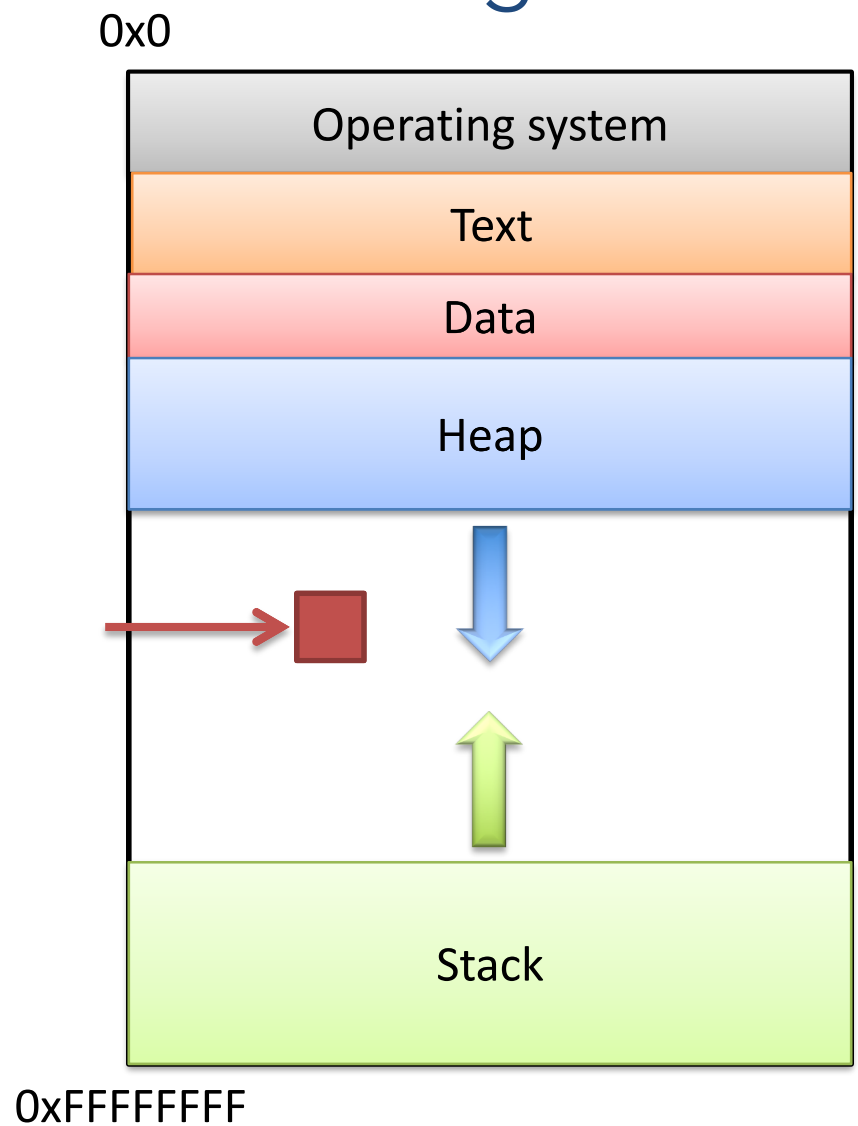
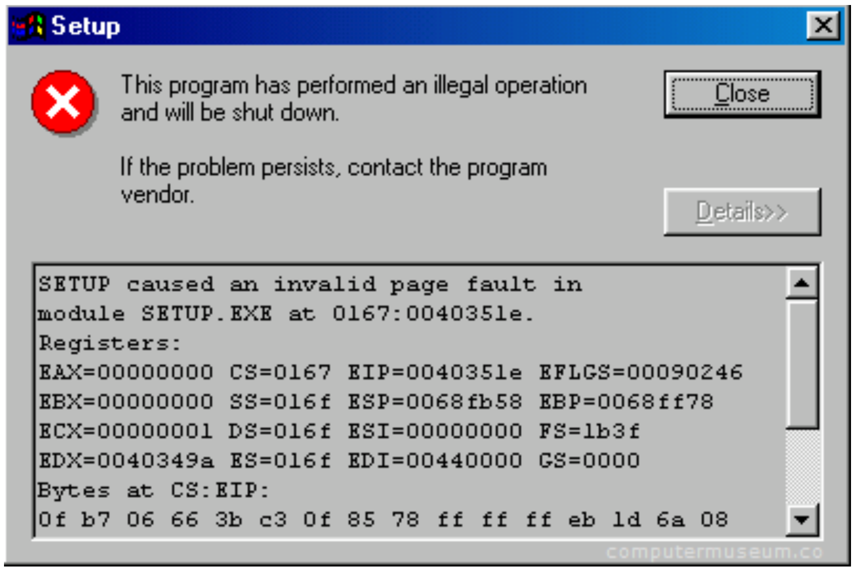
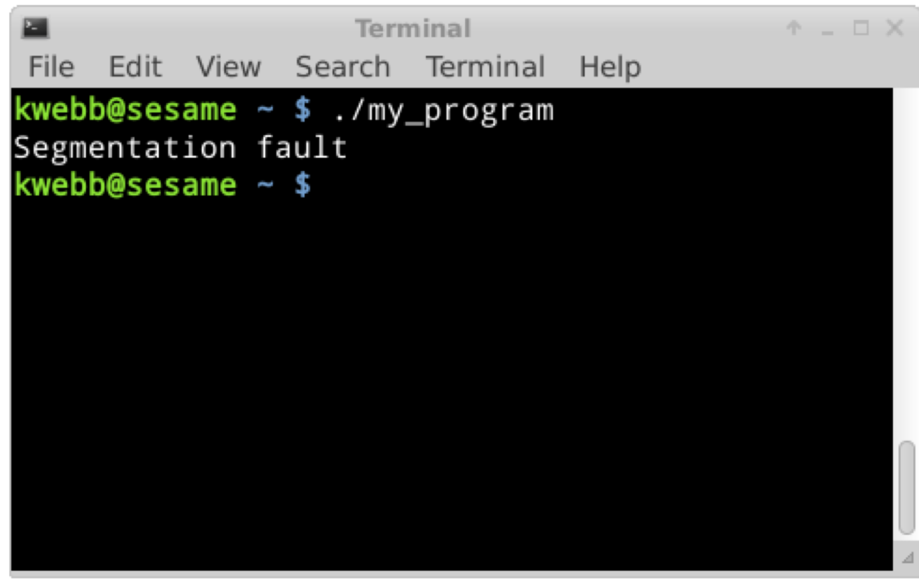


Segmentation Violation



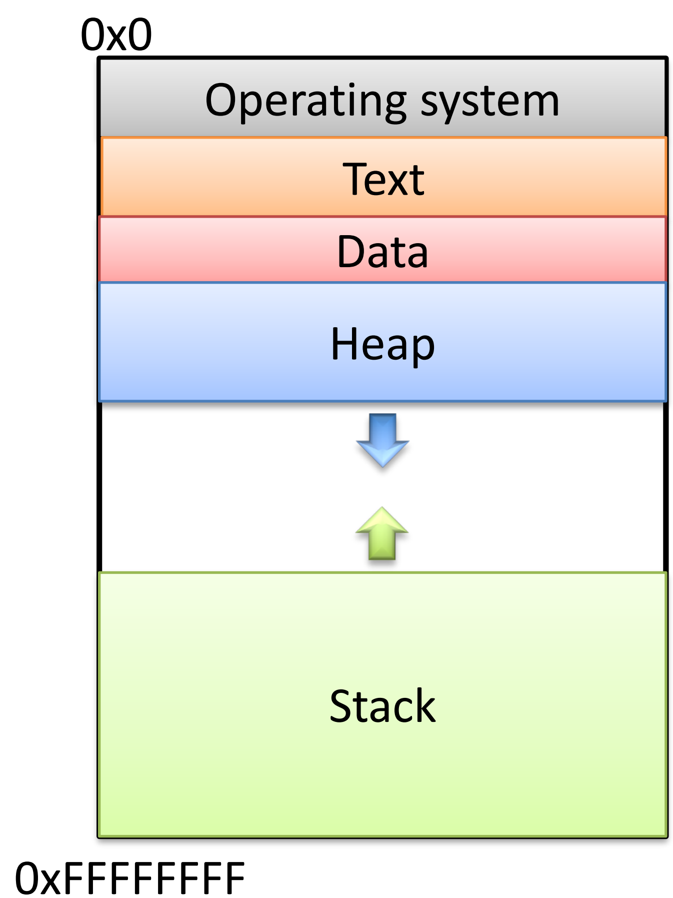


Recap

- & gives us the address of a variable (a pointer)
- * allows us to follow the address to memory, accessing the item (dereference the pointer)

- Memory model:
- So far, all variables on stack.

- Up next: using the heap.
  – We may not know the size of a variable in advance. (dynamic)



So we declared a pointer…

- 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 and point to it

The Address Of (&)

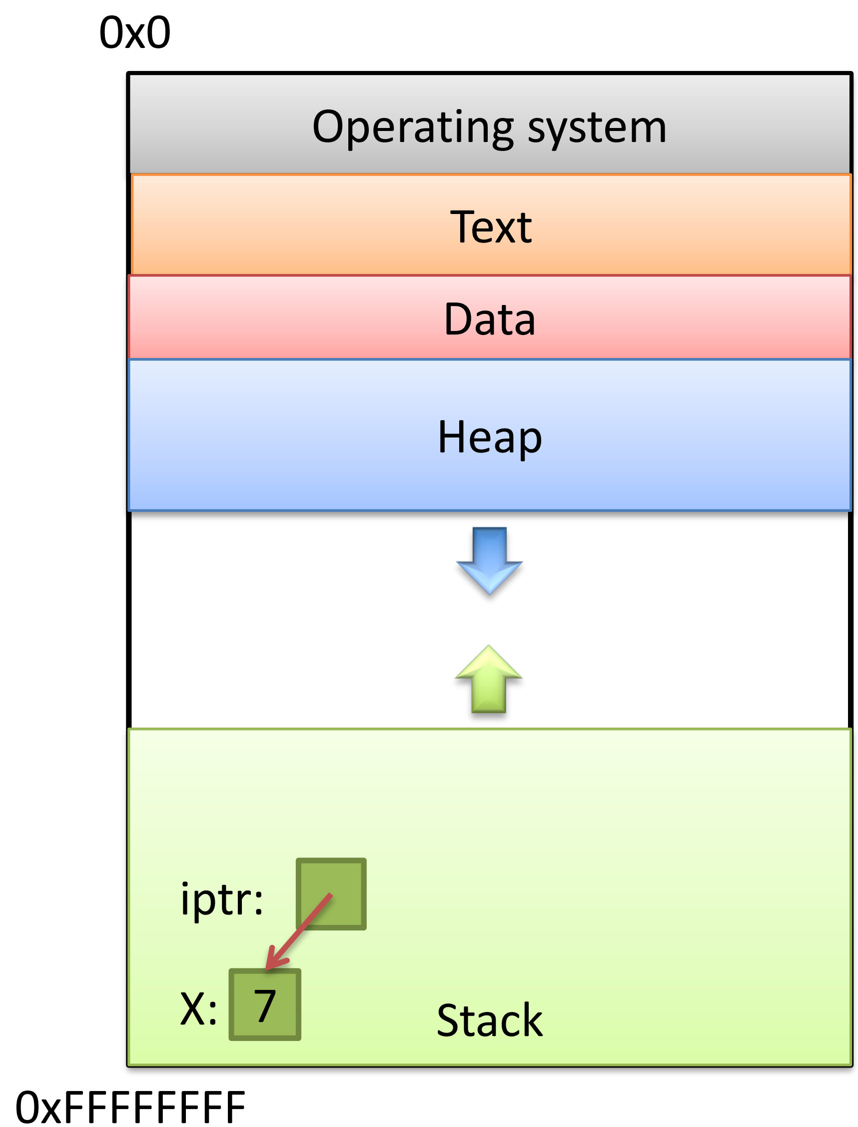
- You can create a pointer to anything by taking its address with the *address of* operator (&).

The Address Of (&)

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



  return 0;
}
```

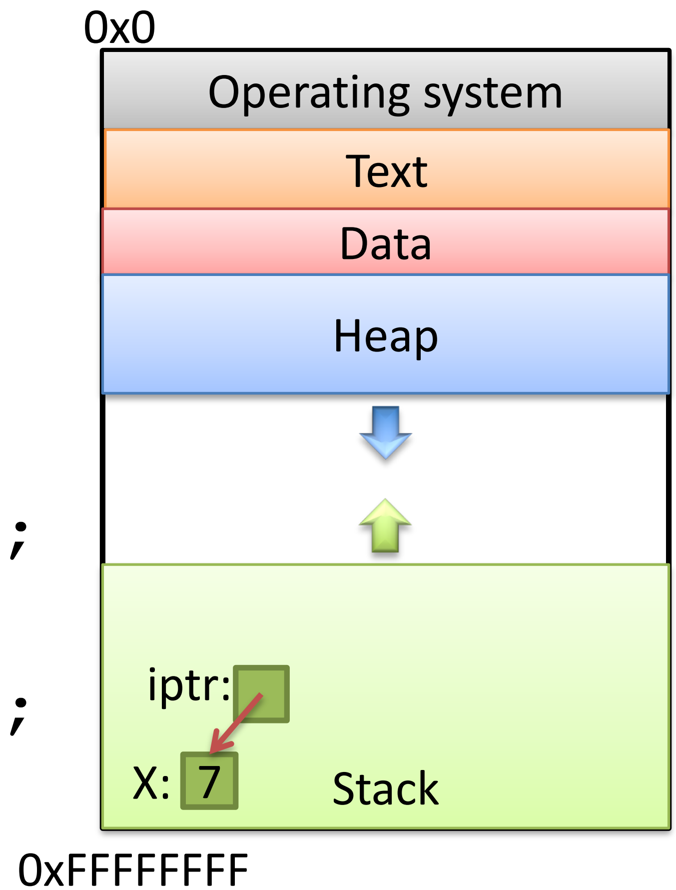


What would this print?

```
int main() {
  int x = 7;
  int *iptr  = &x;
  int *iptr2 = &x;

  printf("%d %d ", x, *iptr);
  *iptr2 = 5;
  printf("%d %d ", x, *iptr);

  return 0;
}
```



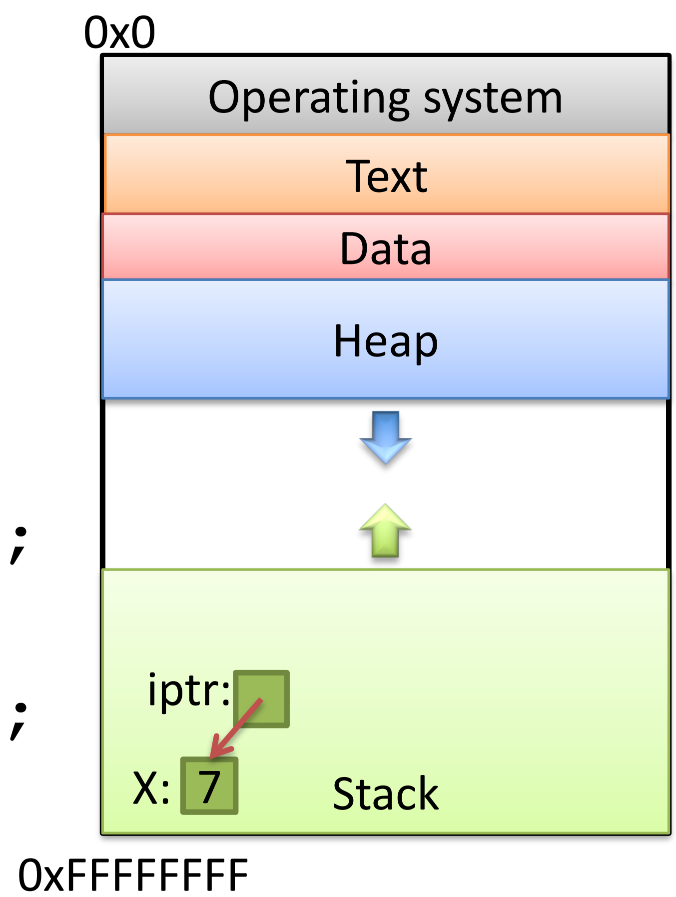
A. 7 7 7 7   B. 7 7 7 5   C. 7 7 5 5   D. Something else

What would this print?

```
int main() {
  int x = 7;
  int *iptr  = &x;
  int *iptr2 = &x;

  printf(“%d %d ”, x, *iptr);
  *iptr2 = 5;
  printf(“%d %d ”, x, *iptr);

  return 0;
}
```



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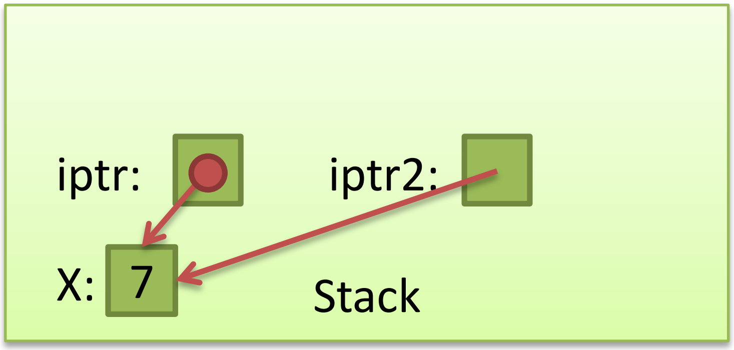
So we declared a pointer…

- 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 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;
```

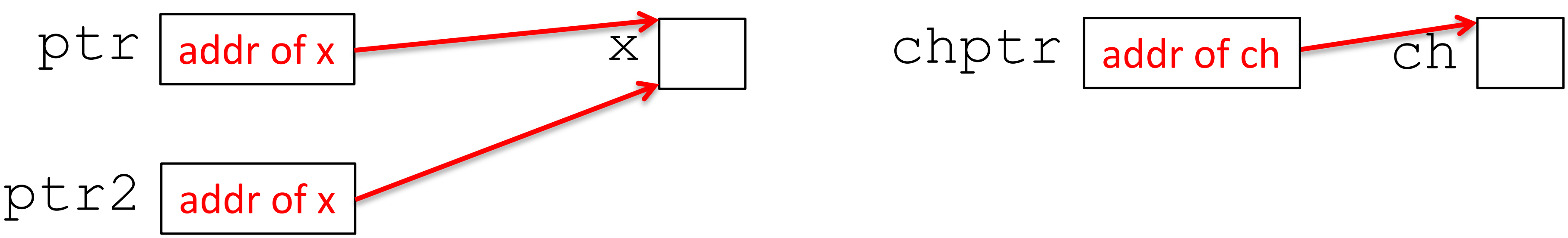
```
int x = 7;
float *fptr = &x;
```

"Warning: initialization from incompatible pointer type" (<u>Don't ignore this!</u>)

Initializing a Pointer

- Initialize it (make it point to something)

```
ptr = &x;     // ptr stores address of x
              // ptr points to x
chptr = &ch;// chptr points to ch
```




```
int *ptr2;  // init a pointer to another's value
ptr2 = ptr;   // ptr2 gets value of ptr
```

Copying a Pointer

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

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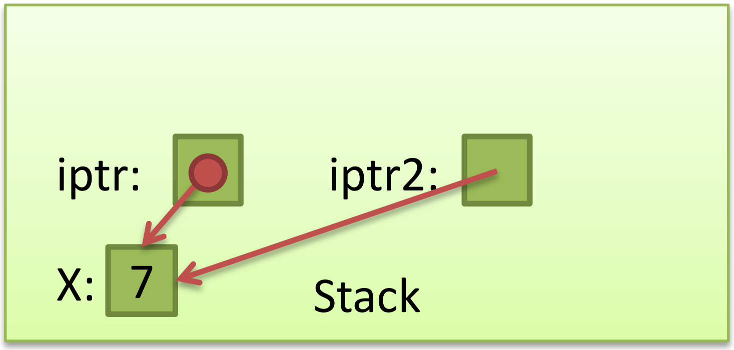
int x = 7;
int *iptr, *iptr2;
iptr = &x;
iptr2 = iptr;
```



Dereferencing a Pointer

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

How many of these are not valid dereference operations?

```
int *ptr = &x;     // ptr stores address of x
char *chptr = &ch;// chptr stores address of ch
```

```
1.  *ptr = 6;
2.  *chptr = 'a';
3.  int y = *ptr + 4;
4.  ptr = NULL, *ptr = 6;
```

A. No invalid dereferences
B. 1 invalid dereference
C. 2 invalid dereferences
D. More than two invalid dereferences.

Which of these is not a valid dereference operation?

```
int *ptr = &x;    // ptr stores address of x
char *chptr = &ch;// chptr points to ch
```

```
1.  *ptr = 6;                 // what ptr points to gets 6. i.e, x = 6
2.  *chptr = 'a';             // what chptr points to gets 'a' i.e., ch = a
3.  int y = *ptr + 4;         //y gets what ptr points to plus 4
4.  ptr = NULL, *ptr = 6;     // ptr doesn't point to valid storage location
```

A. No invalid dereferences
B. 1 invalid dereference
C. 2 invalid dereferences
D. More than two invalid dereferences.

NULL: A special pointer value.

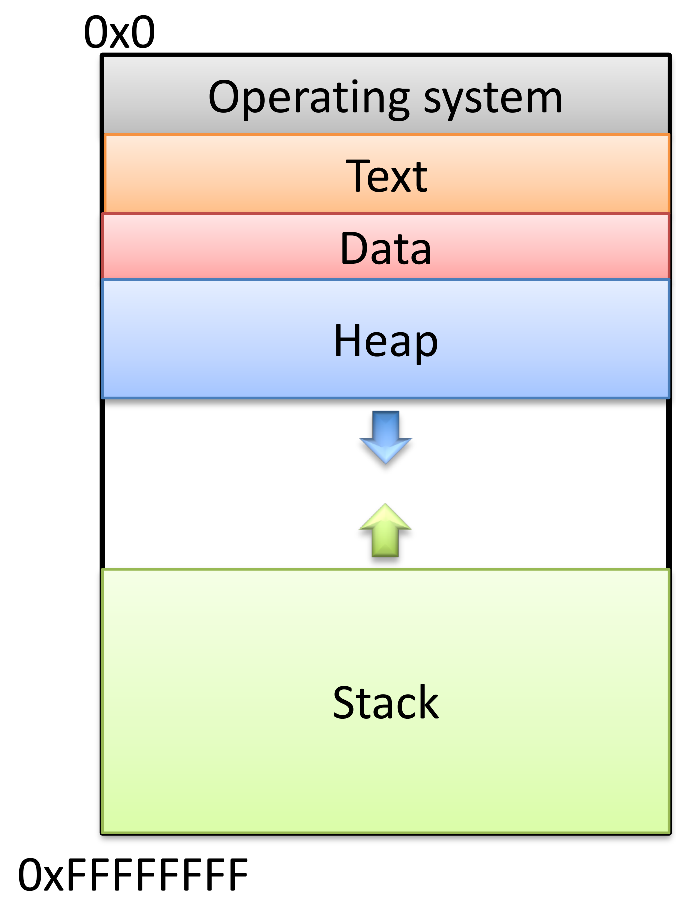
- You can assign NULL to any pointer, regardless of what type it points to (it's a void *).
  - int *iptr = NULL;
  - float *fptr = NULL;

- 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 deref it.
  - Generally a good ideal to initialize pointers to NULL.

What will this do?

```
int main() {
  int *ptr;
  printf("%d", *ptr);
}
```

A. Print 0
B. Print a garbage value
C. Segmentation fault
D. Something else



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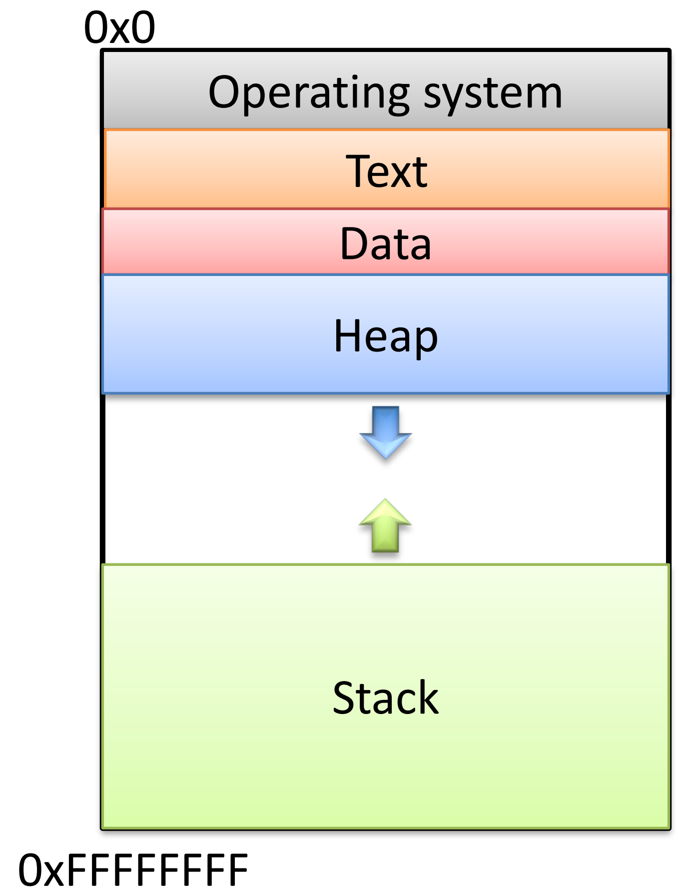

A. Print 0
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Takeaway: If you're not immediately assigning it something when you declare it, initialize your pointers to NULL.

Pointers seem to add additional overhead. Why do we need them?

A. There is no need for pointers.
B. To allocate and access heap memory
C. More than one reason.

Why Pointers?

They are additional overhead:

a level of indirection to get/set a value

Two main benefits:

1. "Pass by pointer" function parameters

   Pointer parameter points to a memory location

   Dereferencing can change value at that location

2. Dynamic Memory allocation
   - Program can allocate more memory as it needs it during its execution

Why Pointers?

Dynamic Memory allocation

- Program can allocate more memory as it needs it during its execution

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

void *

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

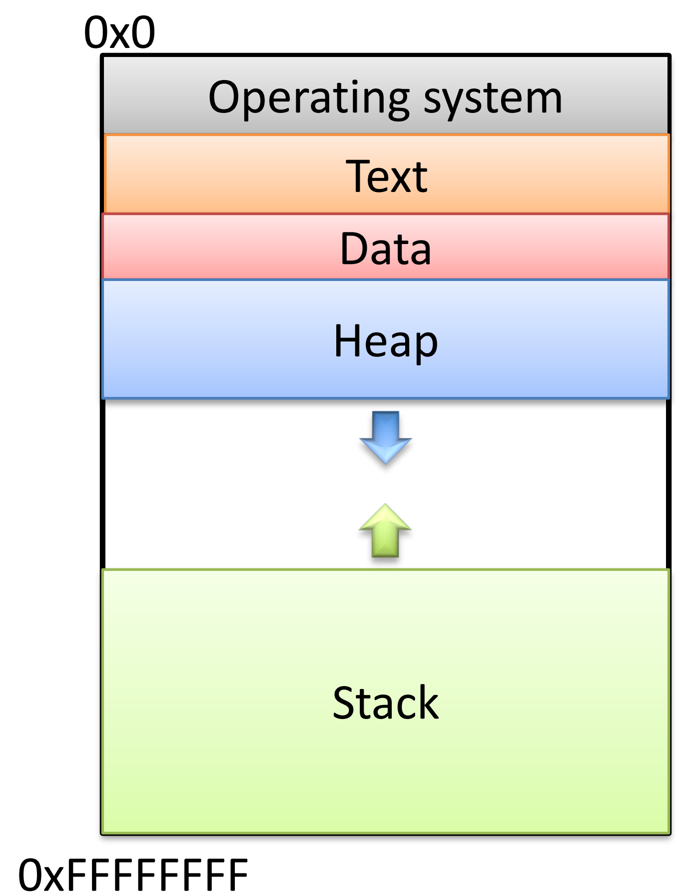
void * represents a "generic pointer"

- 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…

What will this do?

```
int main() {
  int *ptr;
  printf("%d", *ptr);
}
```



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So we declared a pointer…

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  1. Assign it the address of an existing variable
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Size Allocation

`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)

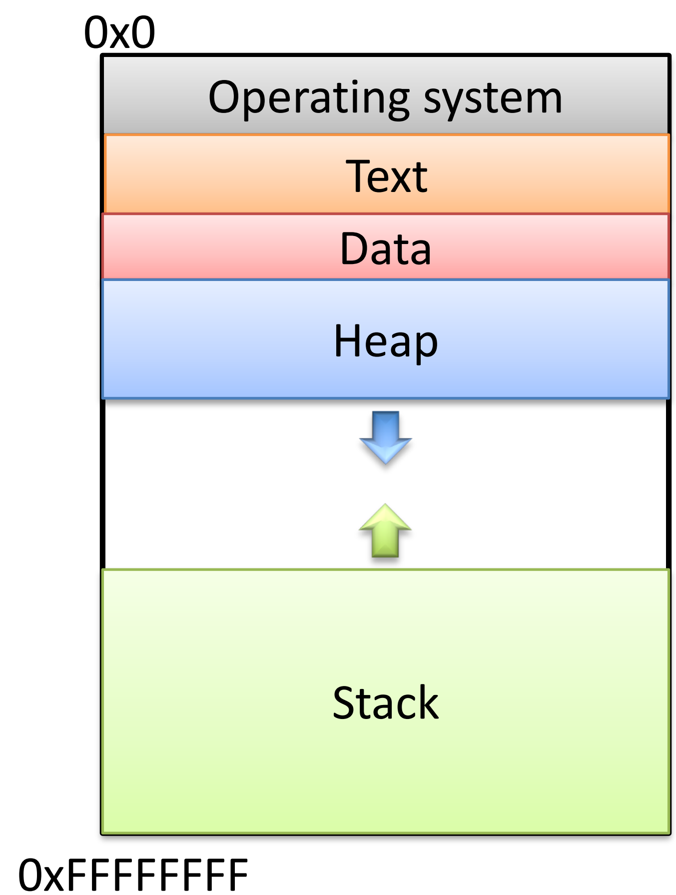
- Works on any type to tell you how much memory it needs.

Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```



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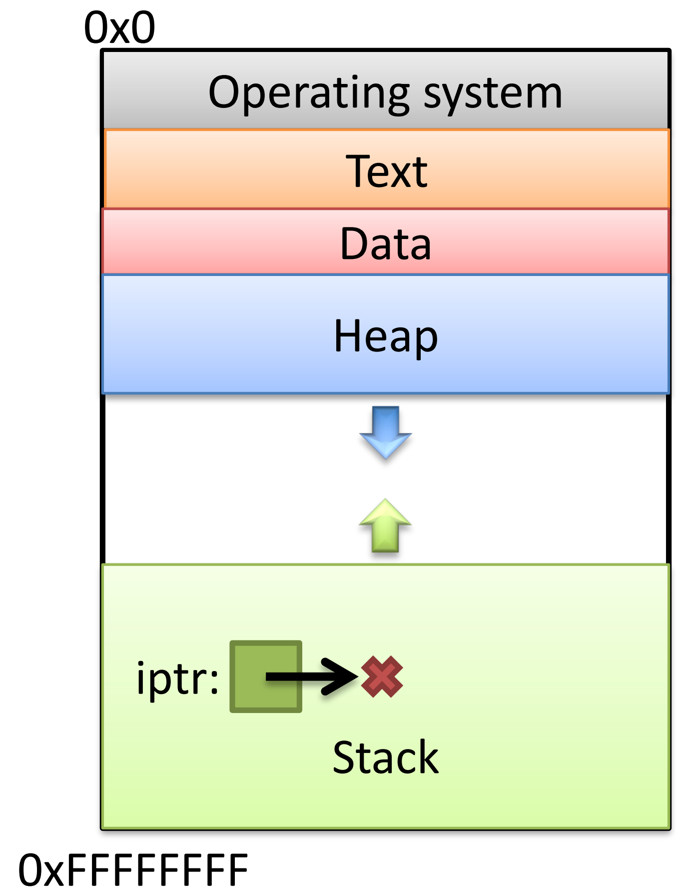


Create an integer pointer, named iptr, on the stack.

Assign it NULL.

Example

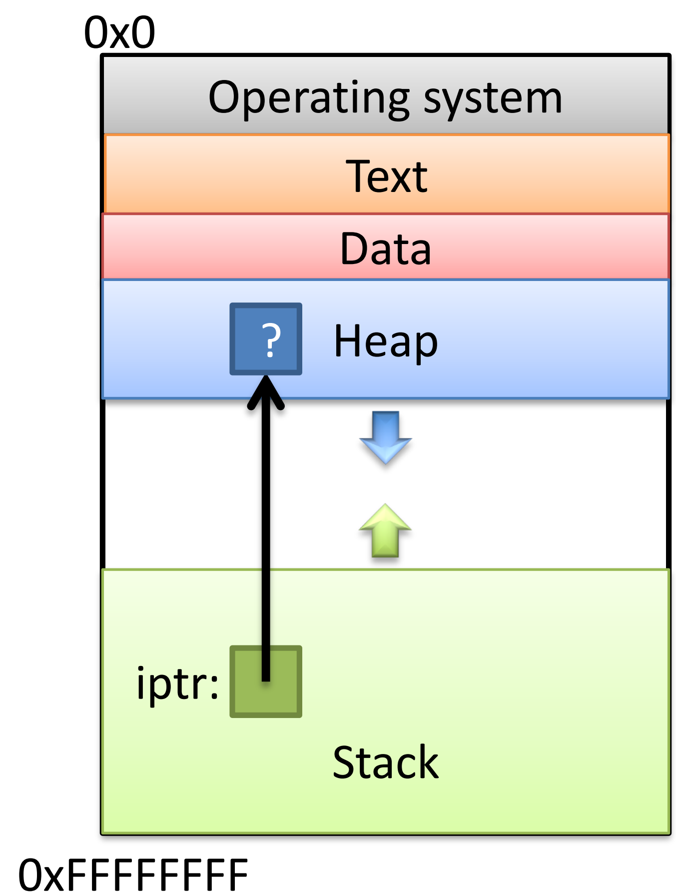
```
int *iptr = NULL;

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.

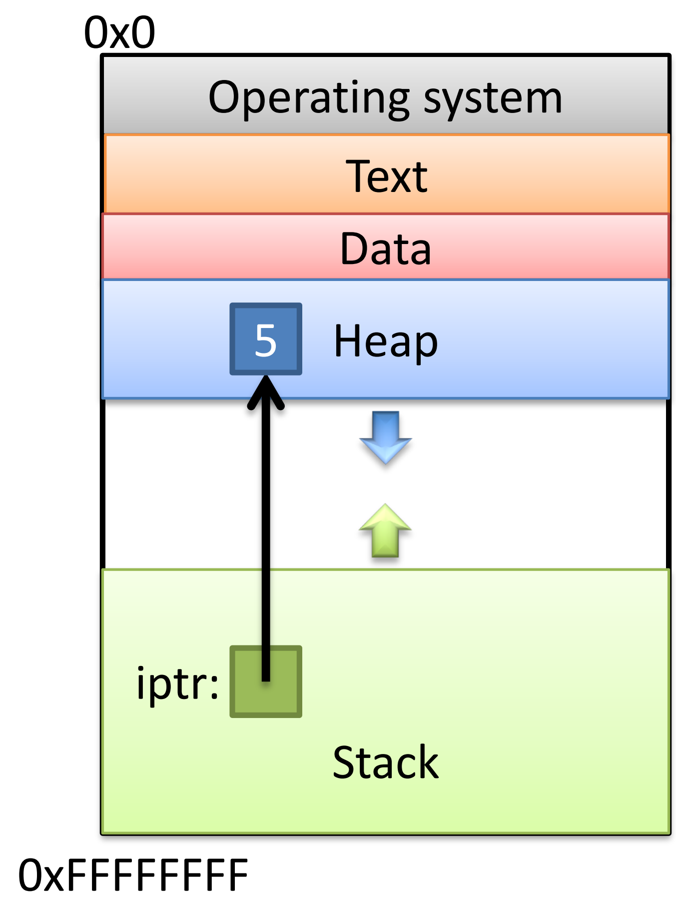
Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```

Use the allocated heap space by dereferencing the pointer.



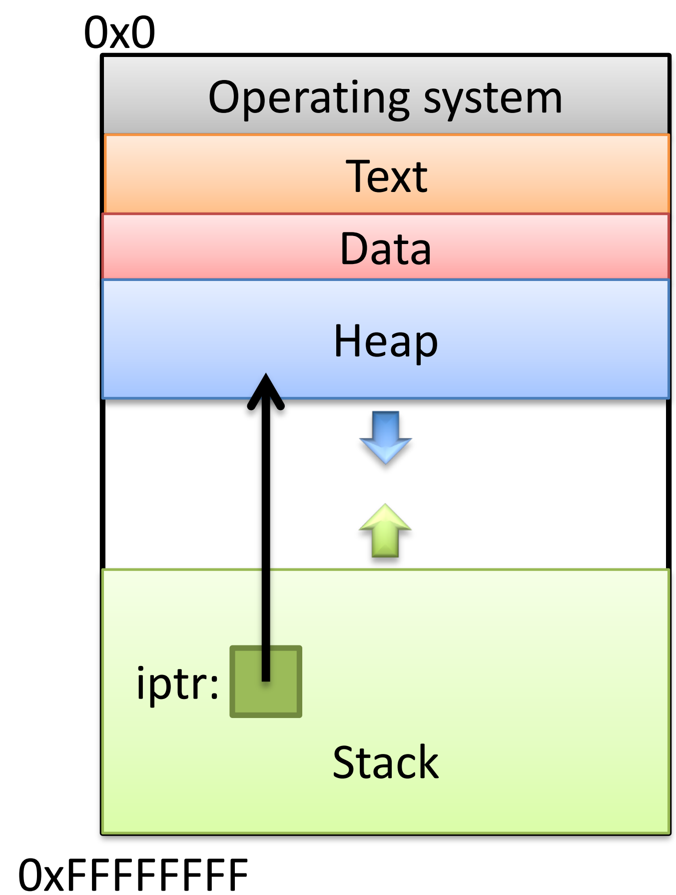
Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

free(iptr);
```



Free up the heap memory we used.

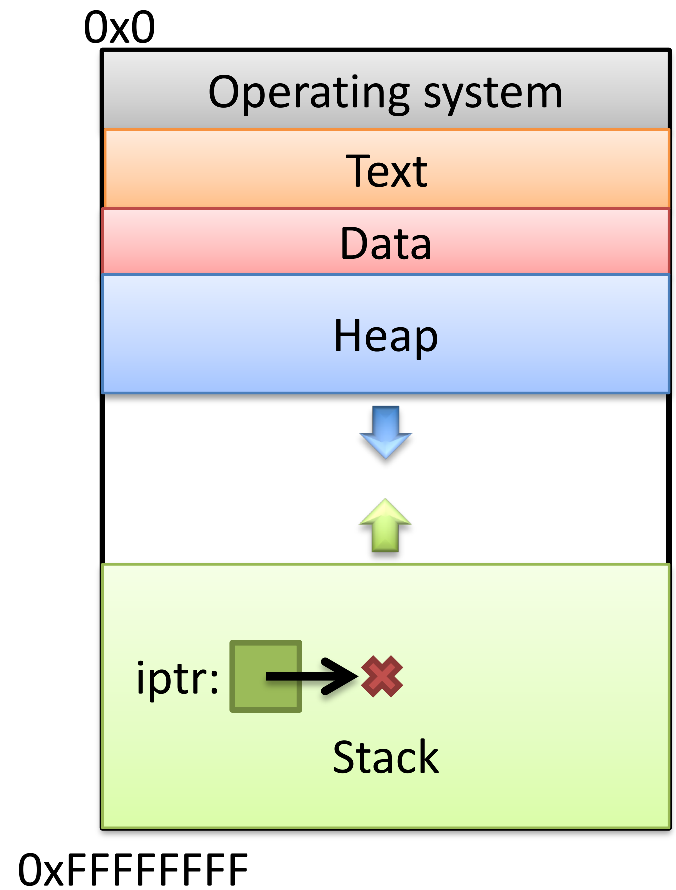
Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

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



Clean up this pointer, since it's no longer valid.

You're designing a system. What should happen if a program requests memory and the system doesn't have enough available?

A. The OS kills the requesting program.
B. The OS kills another program to make room.
C. malloc gives it as much memory as is available.
D. malloc returns NULL.
E. Something else.

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. */
}
```

“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.
  - C doesn’t does NOT do this for you!

Why doesn't C do garbage collection?

A. It's impossible in C.

B. It requires a lot of resources.

C. It might not be safe to do so. (break programs)

D. It hadn't been invented at the time C was developed.

E. Some other reason.

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…

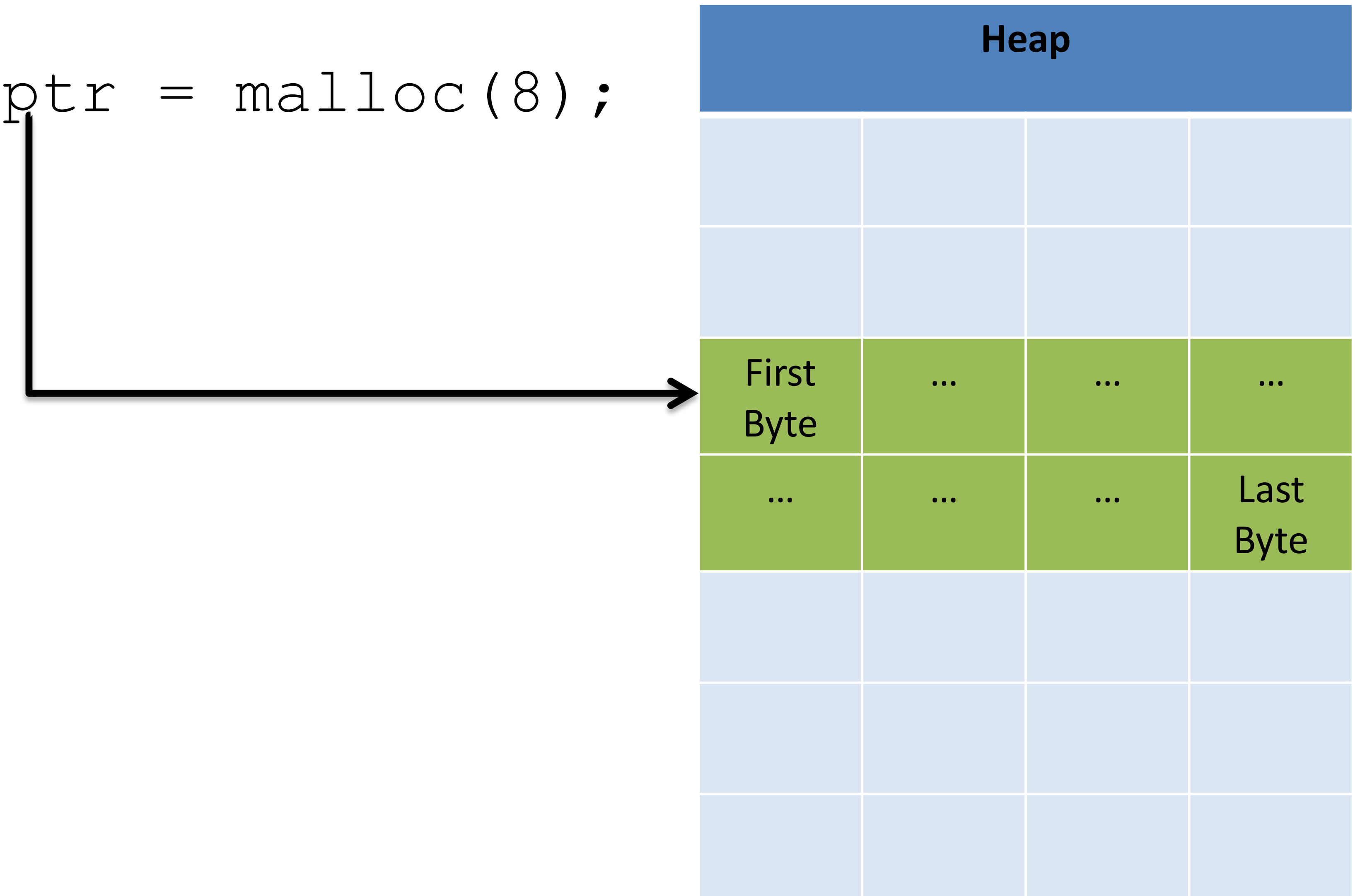
Metadata

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

Heap			

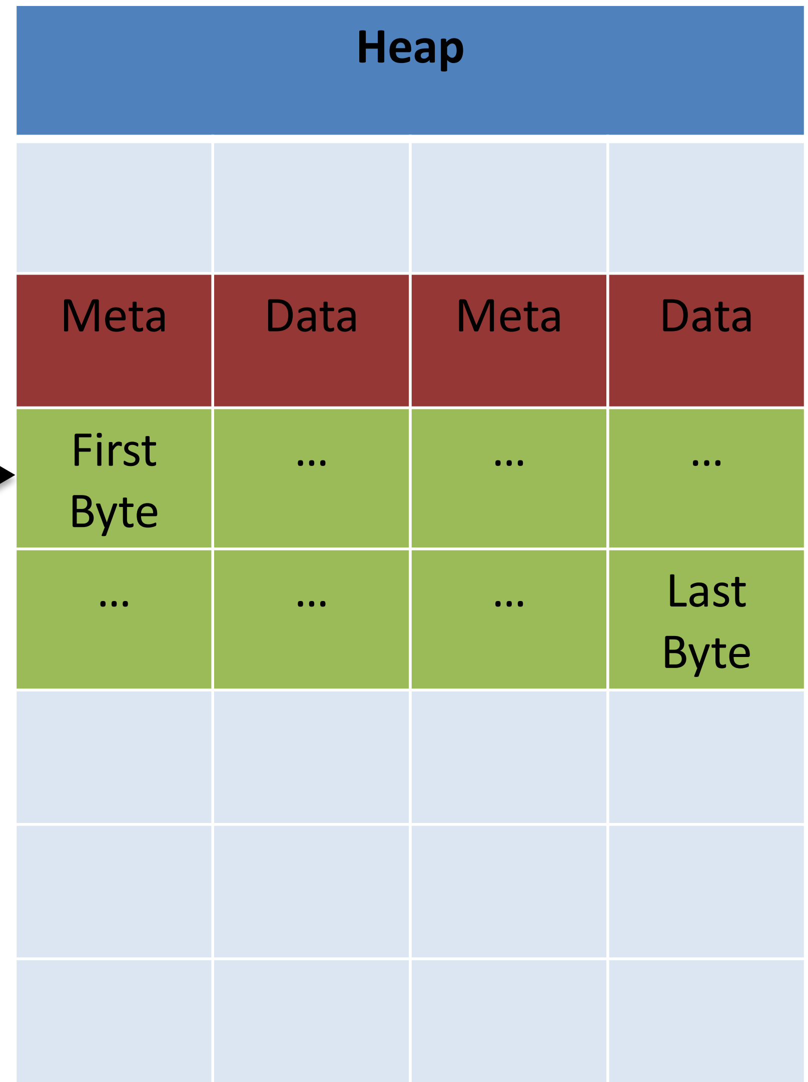
Metadata

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



Metadata

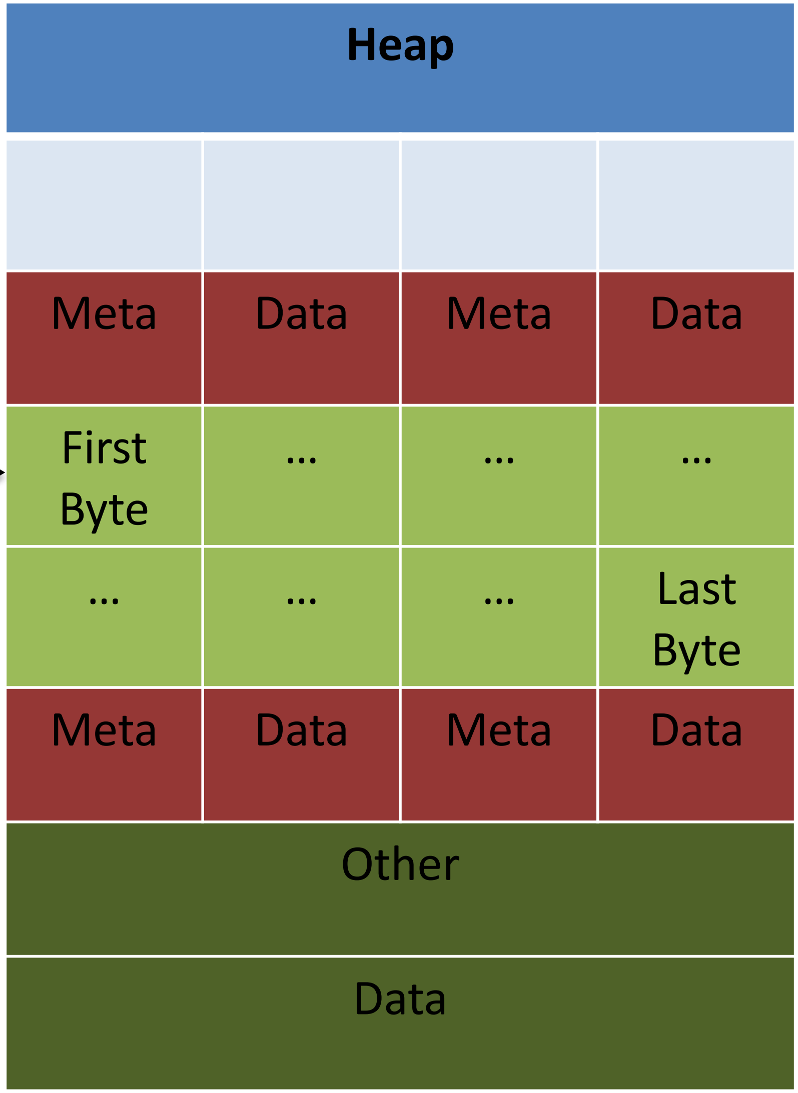
```
int *iptr = malloc(8);
```



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

Metadata

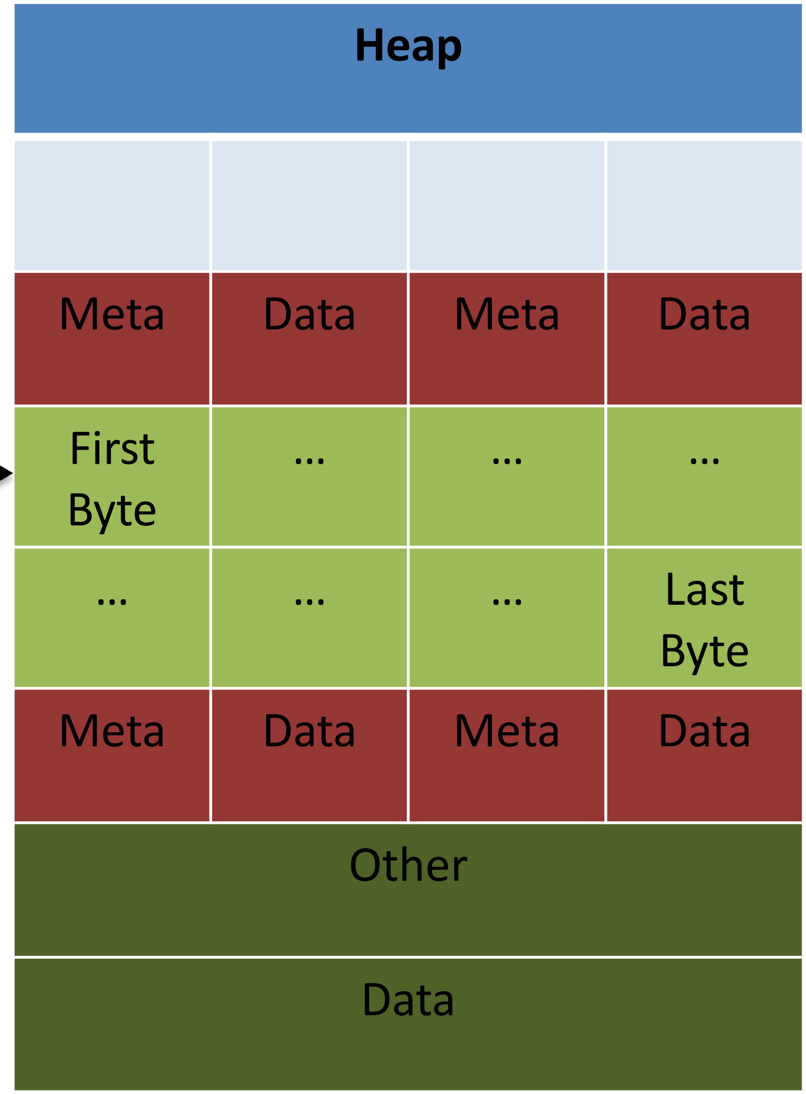
```
int *iptr = malloc(8);
```



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

Metadata

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



- 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!

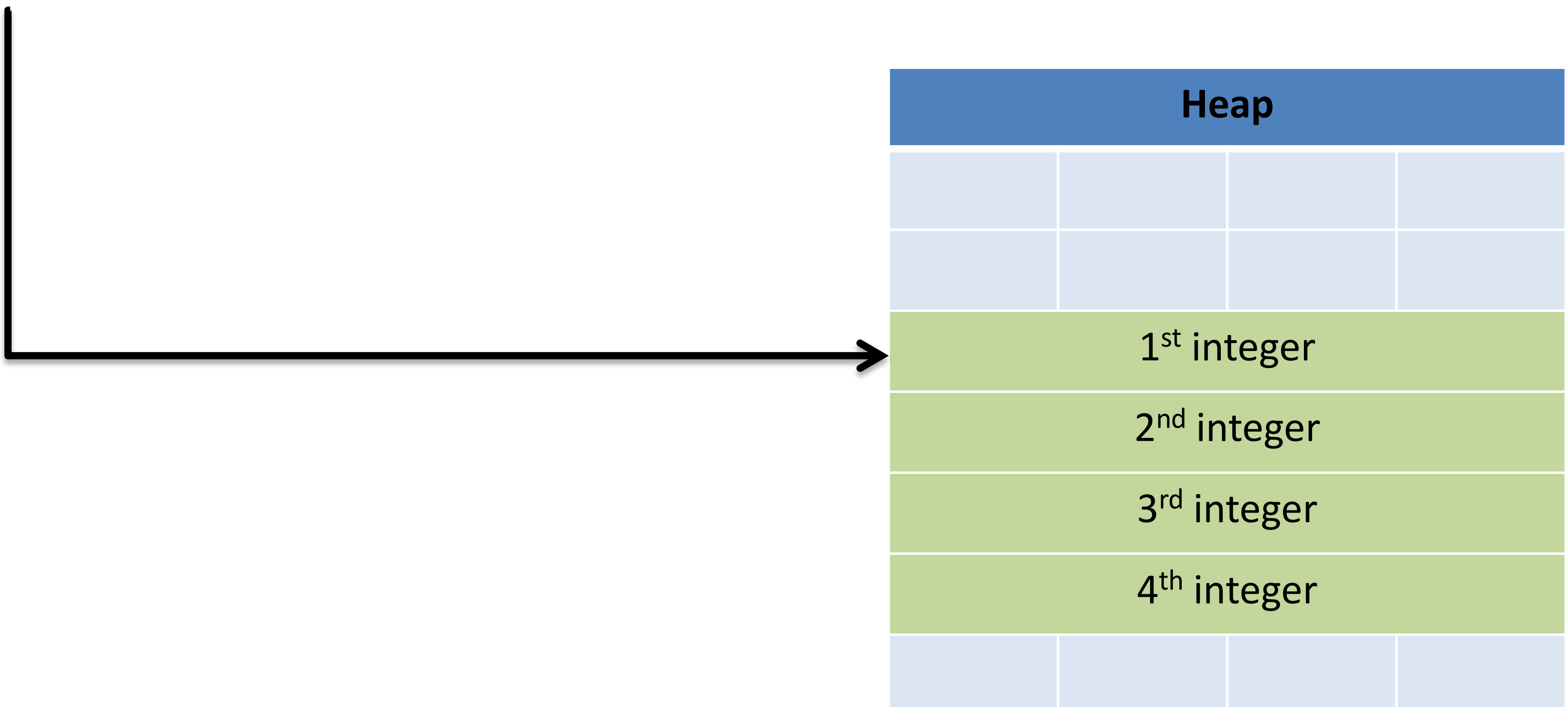
Pointers as Arrays

```
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.

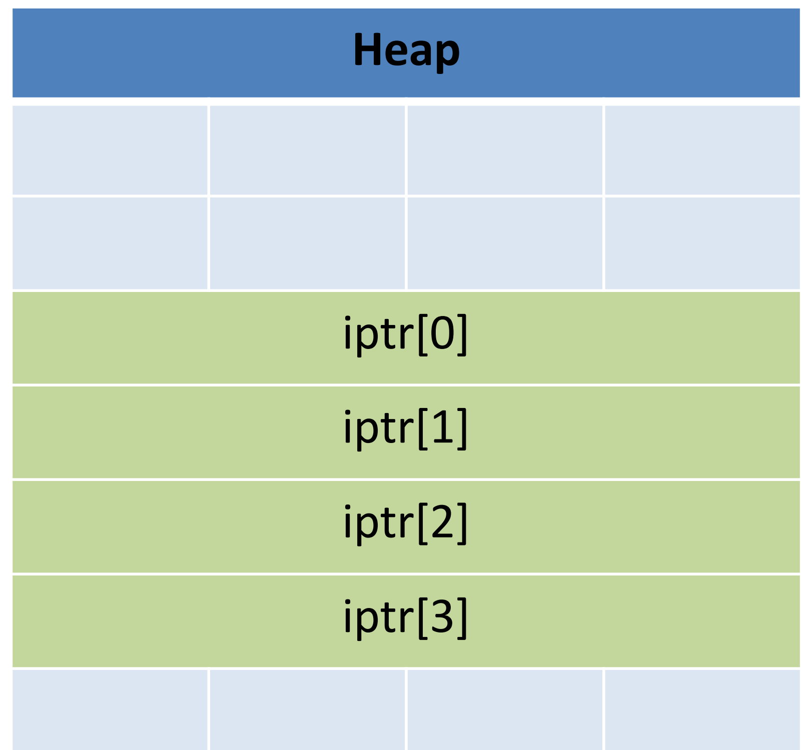
As an alternative way of dereferencing, you can use []'s like an array.

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

Heap			
1st integer			
2nd integer			
3rd integer			
4th integer			

Pointers as Arrays

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

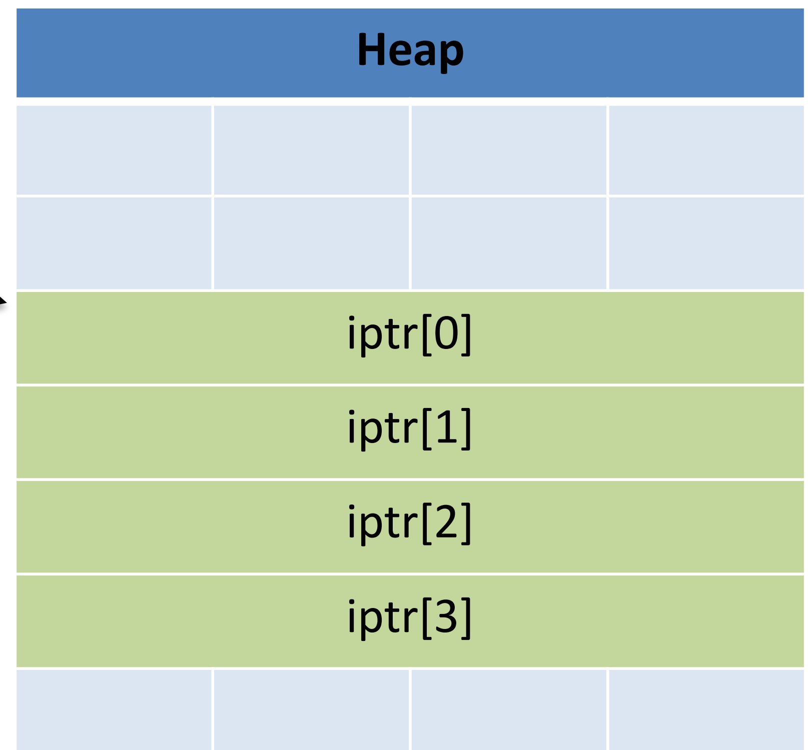


Pointers as Arrays

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

1. Start from the base of iptr.

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



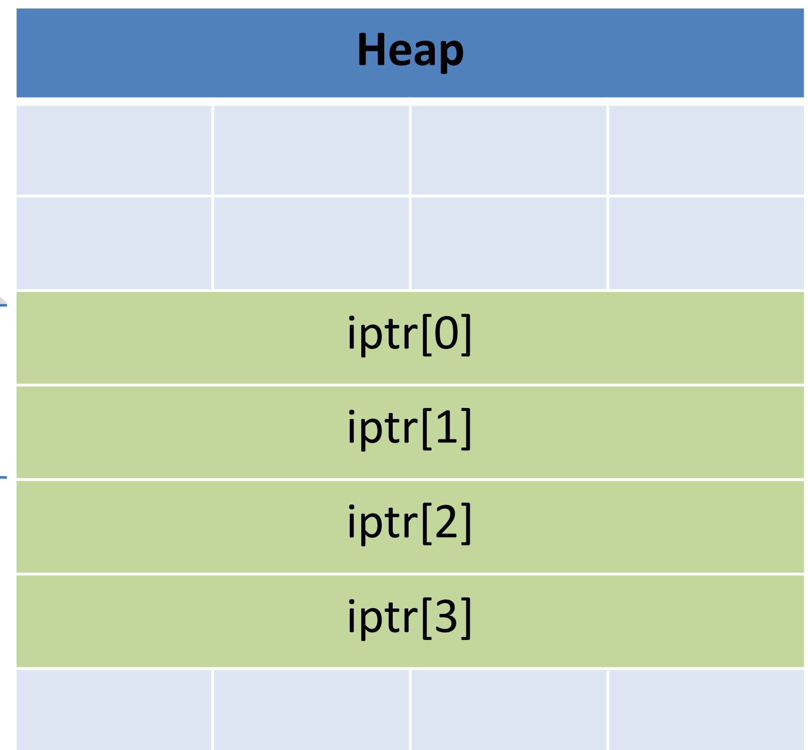
Pointers as Arrays

```
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

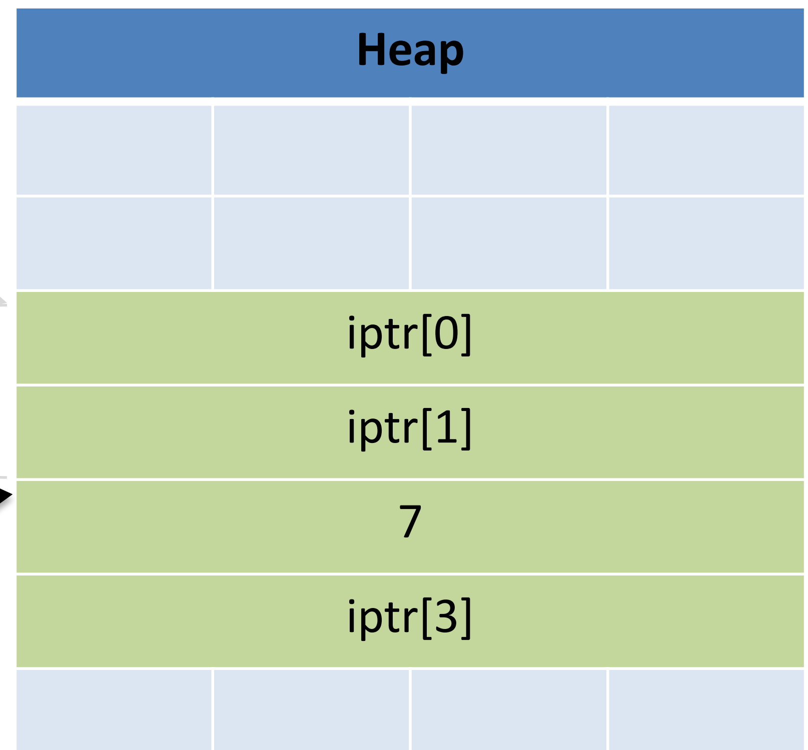
```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```

1. Start from the base of iptr.

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

2. Skip forward by the size of two ints.

3. Treat the result as an int. (Access the memory location like a typical dereference.)



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] = …;
```

Why Pointers?

"Pass by pointer" function parameters

- *Pointer parameter points to a memory location*
- *Dereferencing can change value at that location*

Recall: Pass by value

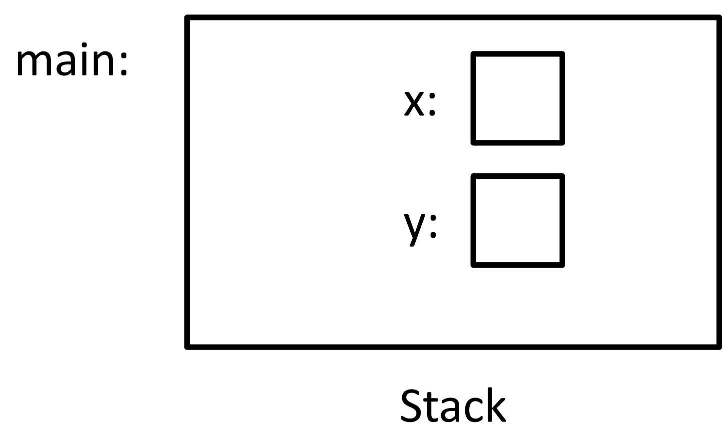
- In C, all function parameters are passed by value:
  - parameter *gets the value of* its argument

Function Arguments

Arguments are **passed by value:** The function gets a separate <u>copy</u> of the passed variable

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

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



Function Arguments: Draw the stack diagram with the final values of variables in func and main

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

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

main:

Your stack diagram

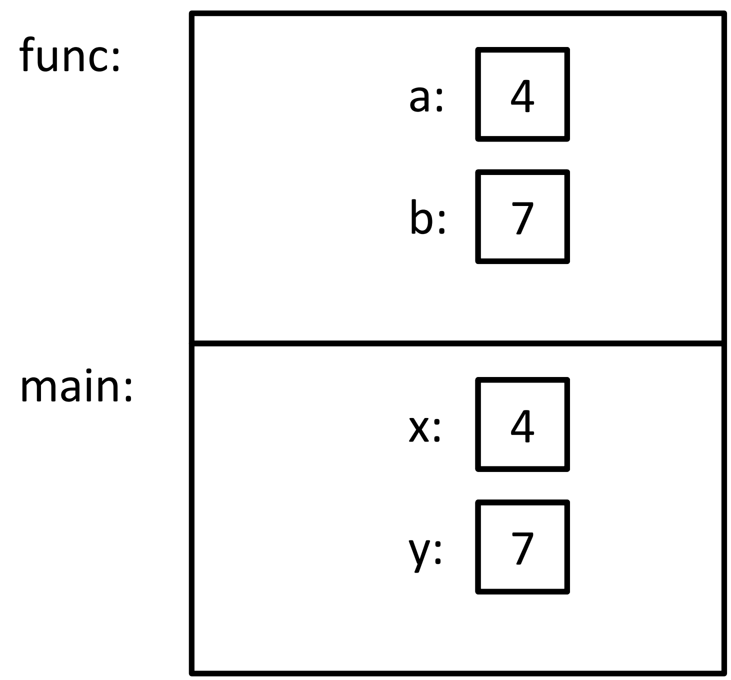
Stack

Function Arguments

Arguments are **passed by value:** The function gets a separate <u>copy</u> of the passed variable

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

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



Stack

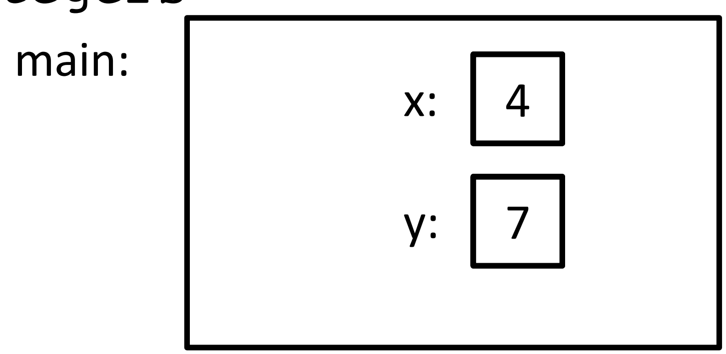
Function Arguments

Arguments are **passed by value:** The function gets a separate <u>copy</u> of the passed variable

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

int main() {
    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.



Stack

Pass by Pointer

- Pass a pointer: can modify the 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
- Have used functions like this:
  - `readfile` library functions and `scanf`
  - pass address of argument to these functions

Function Arguments

Arguments can be pointers!

```
void func(int *a) {
    *a = *a + 5;
    //DRAW THE STACK
}

int main() {
    int x = 4;

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

main:

Your Stack Diagram

Stack

Function Arguments

Arguments can be pointers! <u>The function gets the address of the passed variable.</u>

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

int main() {
   int x = 4;

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

main:

Stack

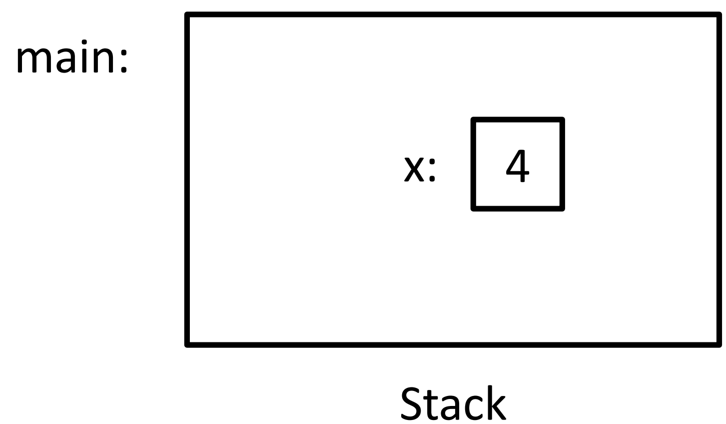
Pointer Arguments

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

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

int main() {
    int x = 4;

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



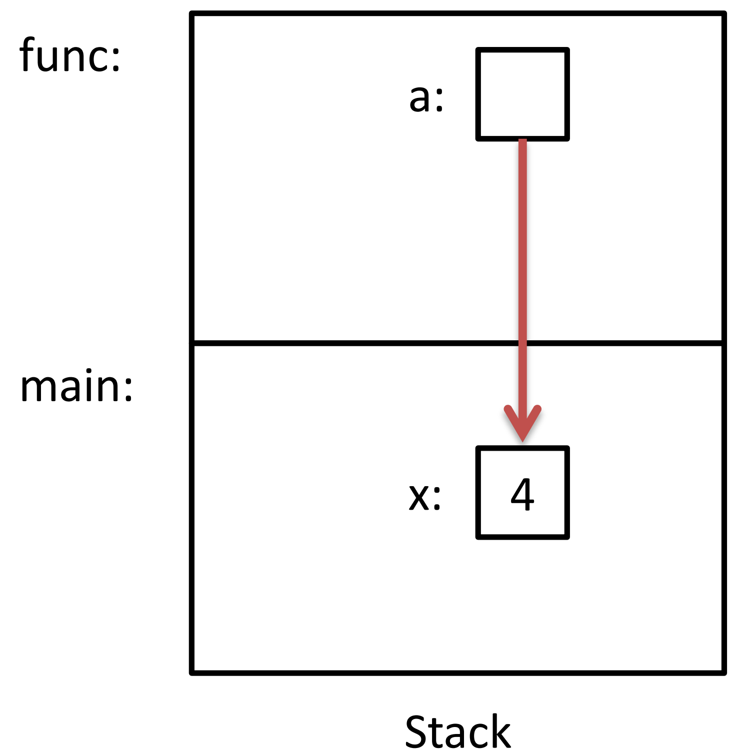
Pointer Arguments

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

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

int main() {
    int x = 4;

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



Pointer Arguments

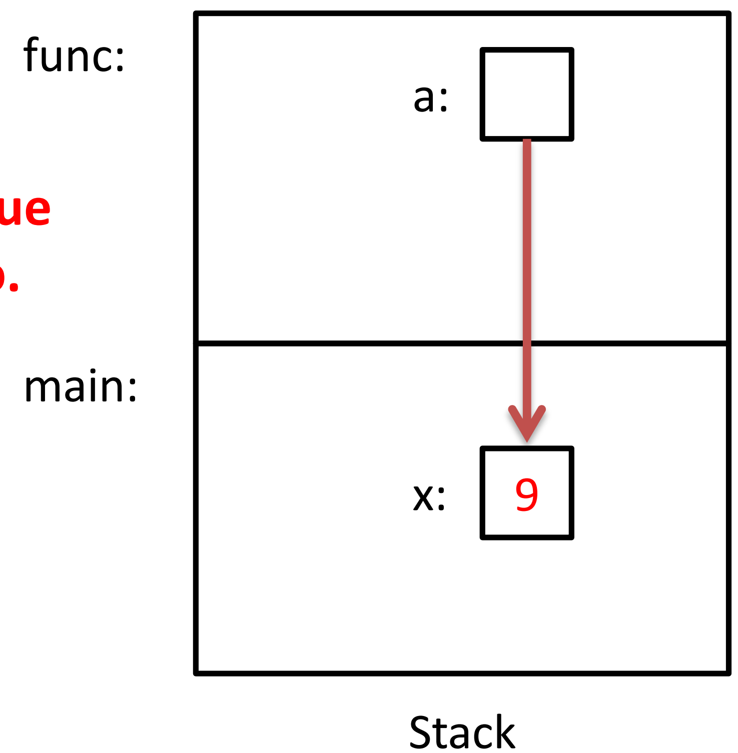
- Arguments can be pointers!
  - The function gets the address of the passed variable!

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

int main() {
    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!

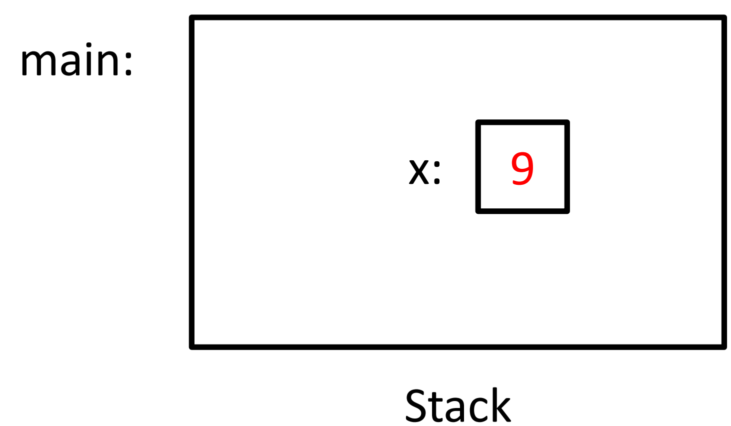
```
void func(int *a) {
    *a = *a + 5;
}

int main() {
    int x = 4;

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

Prints: 9

Haven’t we seen this somewhere before?



Readfile Library

- We saw this in lab 2 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

- Parameters are pointer types
- Arguments are address values

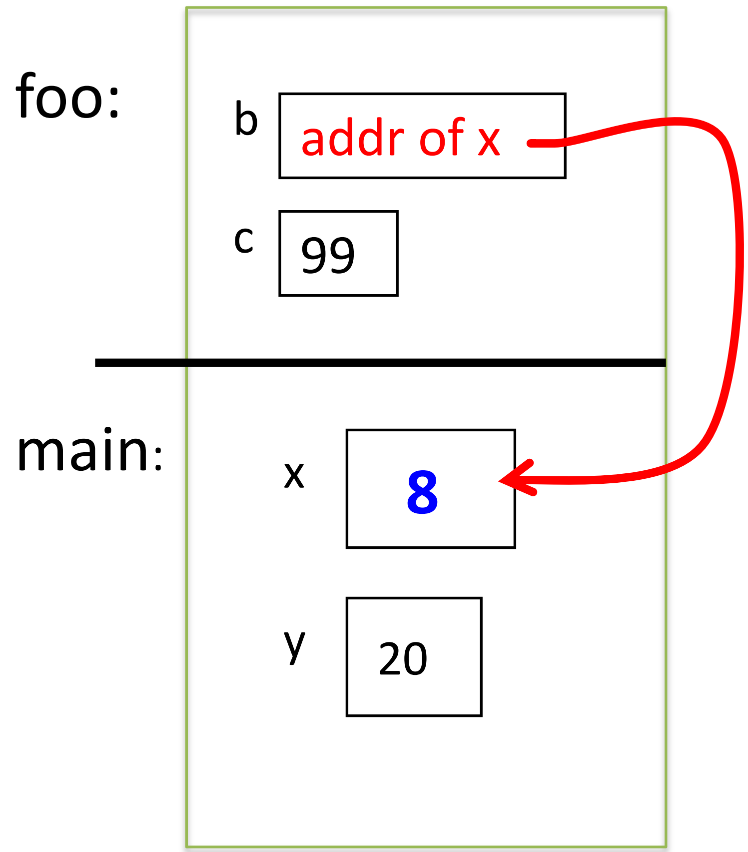
```
main(){
   int x, y;
   x = 10; y = 20;
   foo(&x, y);
}
```

pass the value of &x

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

dereference parameter b to set argument x's value

Stack



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

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

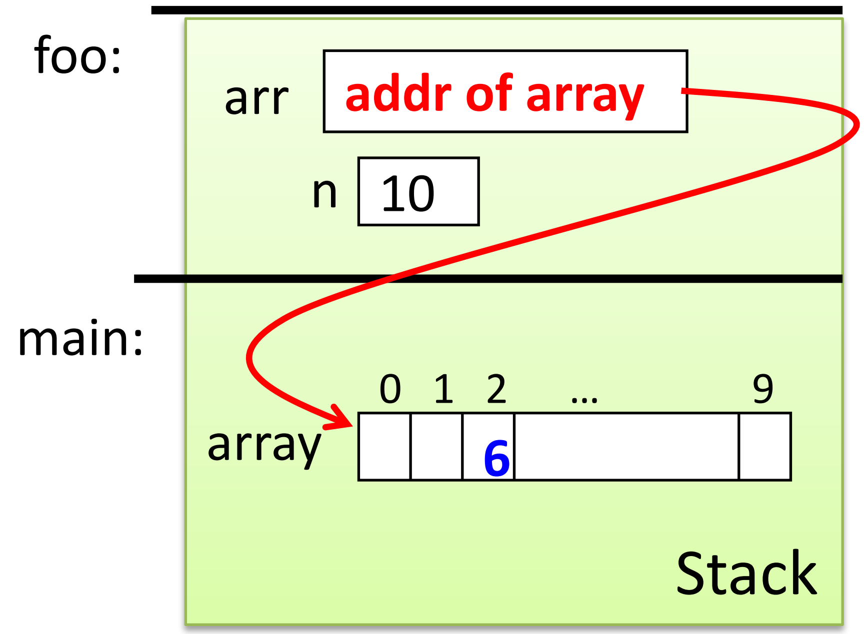
Passing Arrays

An array argument's value is its base address

Array parameter "points to" its array argument

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

array base address



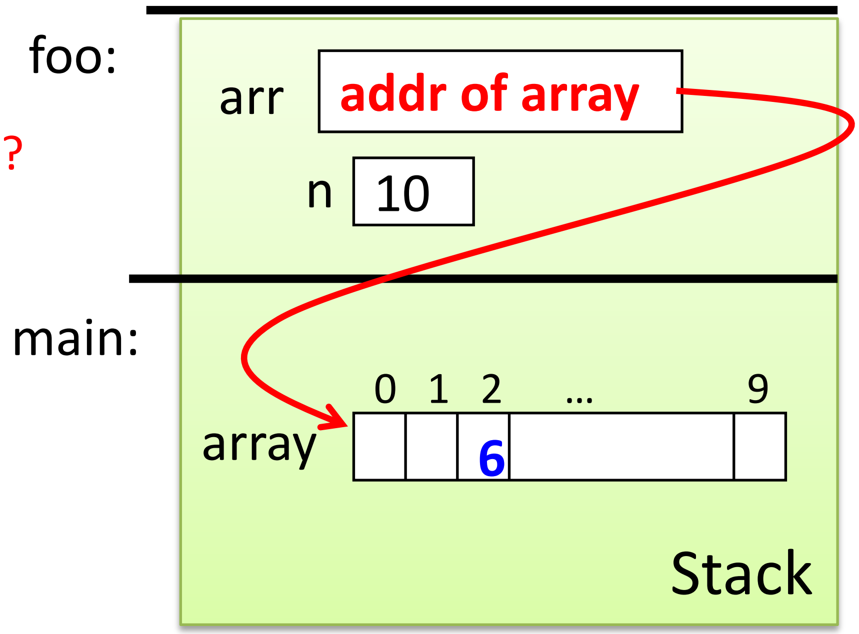
Passing Arrays

An array argument's value is its base address

Array parameter "points to" its array argument

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

alternative declaration?



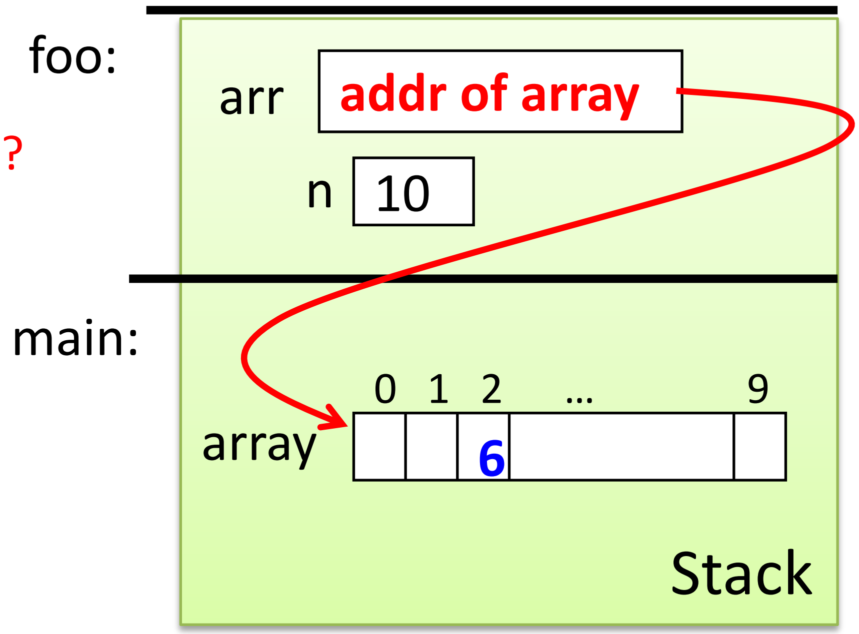
Passing Arrays

An array argument's value is its base address

Array parameter "points to" its array argument

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

alternative declaration?



Can you return an array?

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

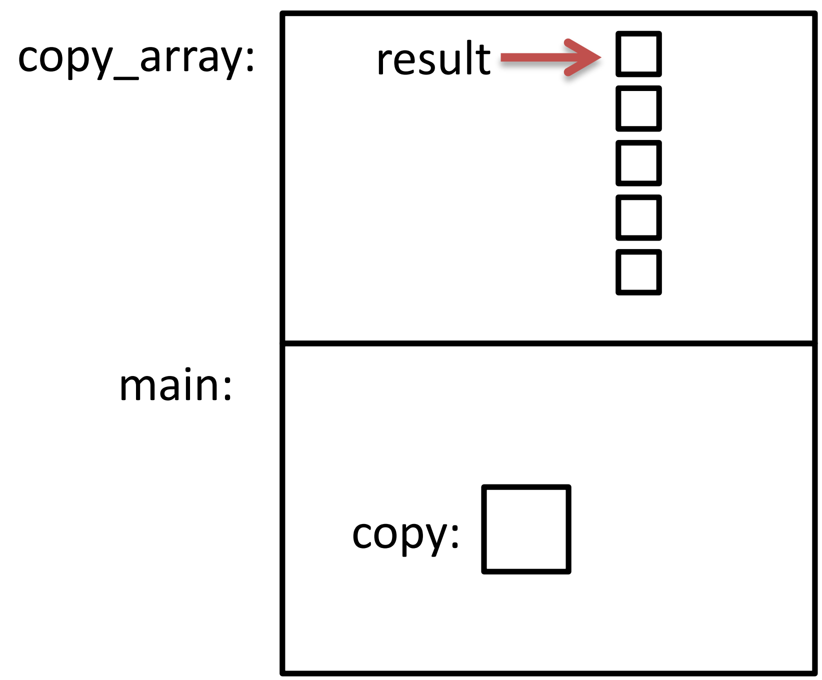
```
copy_array(int array[]) {
   int result[5];
   result[0] = array[0];
   …
   result[4] = array[4];
   return result;
}
```

As written above, this would be a terrible way of implementing this.
(Don’t worry, compiler wont 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;
}

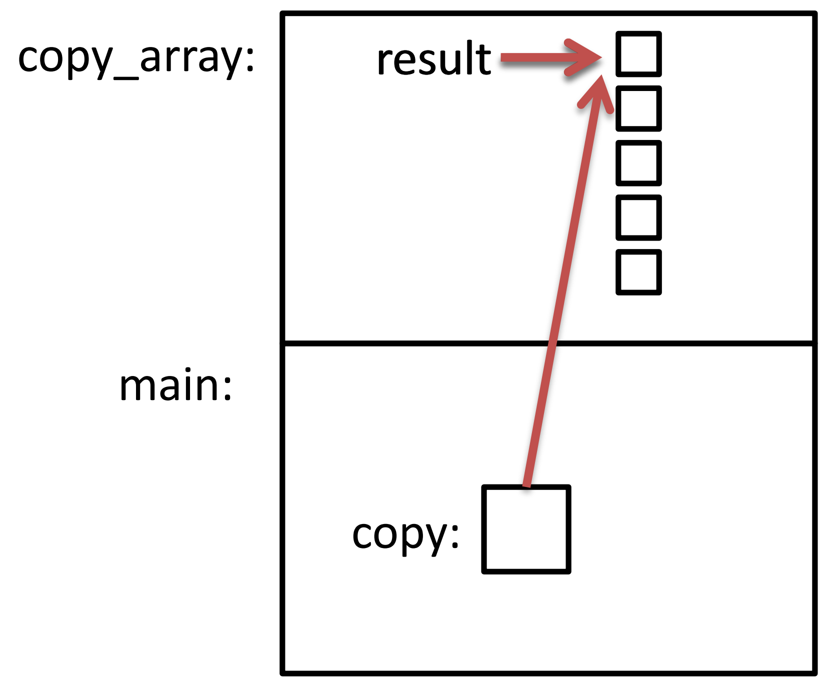
(In main):
copy = copy_array(…)
```



Consider the memory…

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

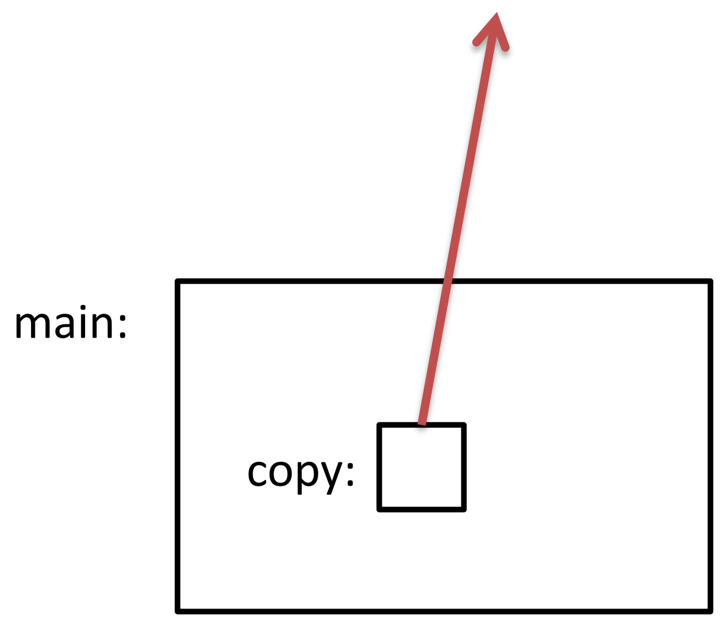
(In main):
copy = copy_array(…)
```



Consider the memory…

Left with a pointer to nowhere.

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




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

Using the Heap

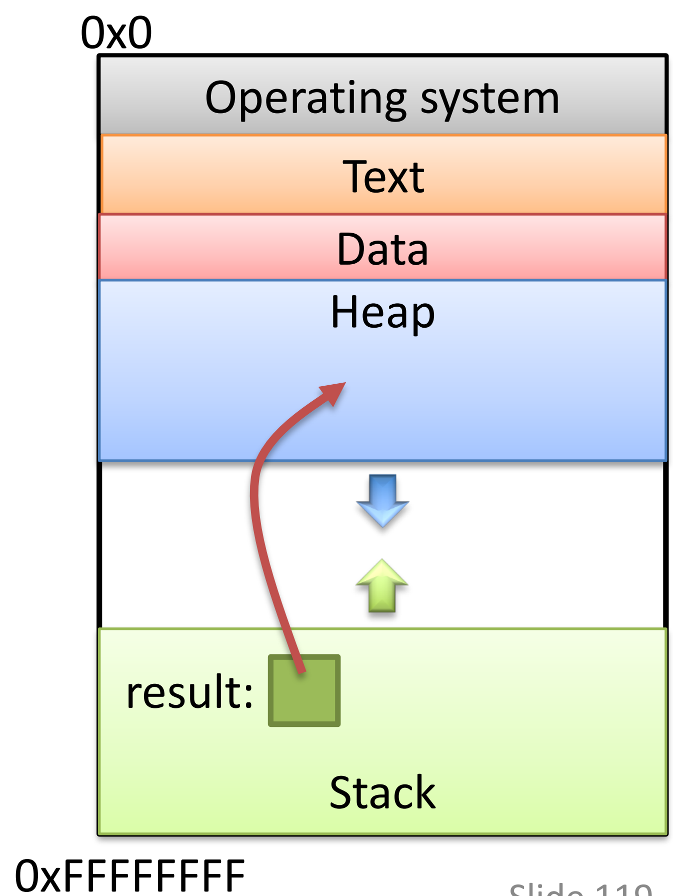
```
int *copy_array(int num, int array[]) {
  int *result = malloc(num * sizeof(int));

  result[0] = array[0];
  …

  return result;
}
```

malloc memory is on the heap.

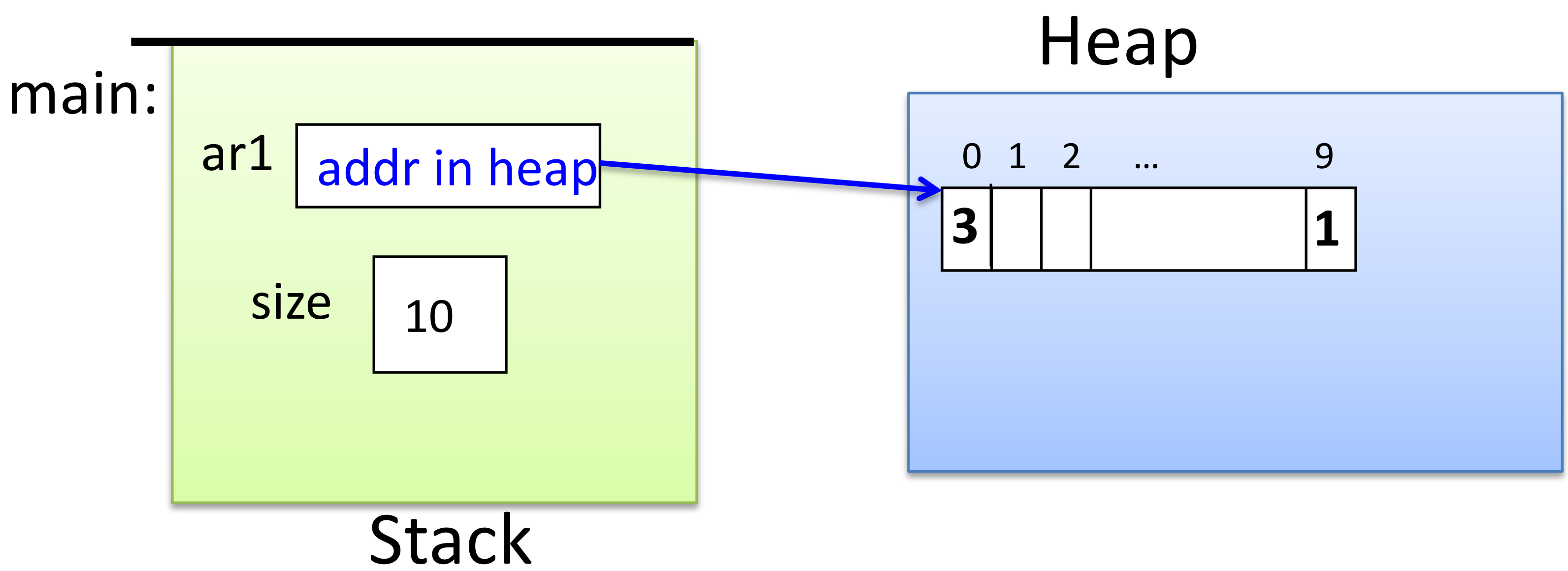
Doesn't matter what happens on the stack (function calls, returns, etc.)



Dynamically allocate array

```
int main(){
  int size, *ar1;

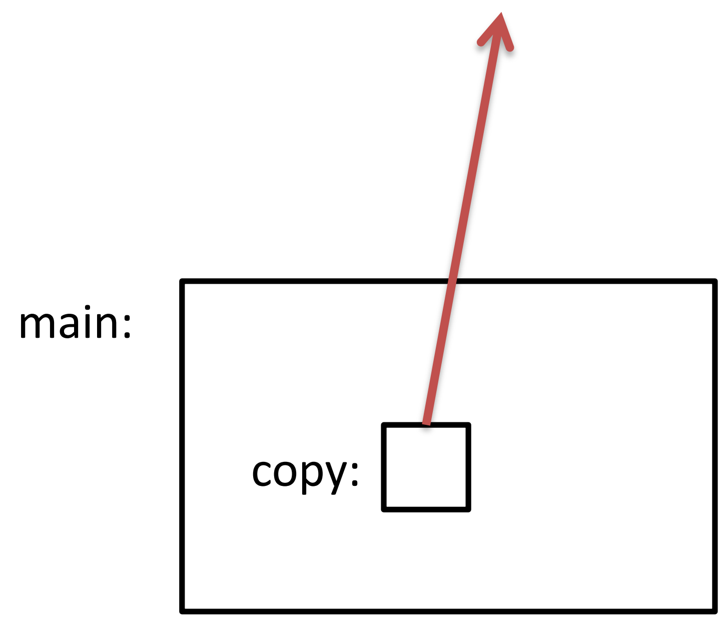
  size = 10;
  ar1 = malloc(sizeof(int)*size);
  if(ar1 != NULL) {
     ar1[0] = 3;
     ar1[9] = 1;
 …
```



Bad implementation: Copying an array on the stack

Left with a pointer to nowhere.

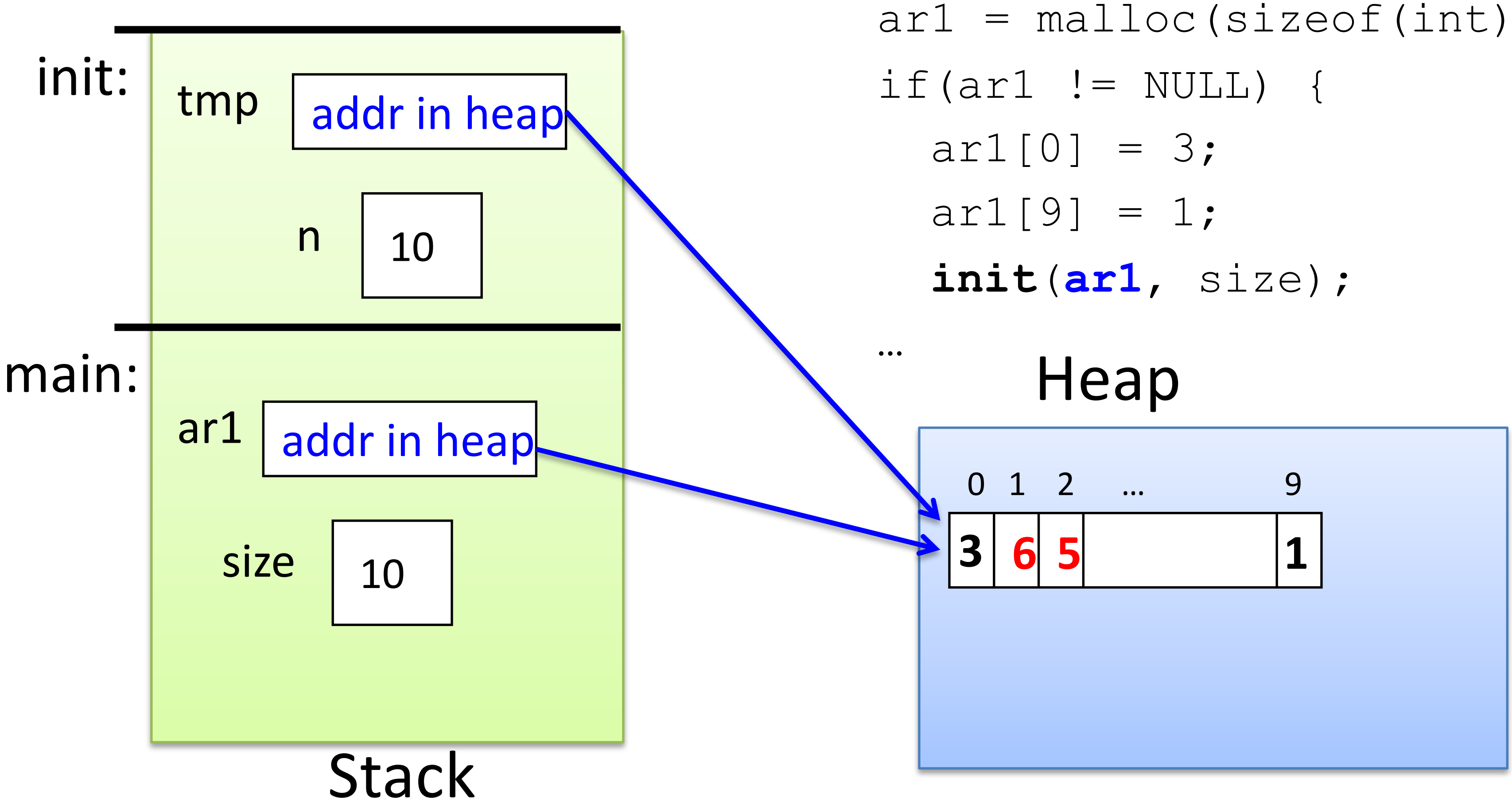
When we return from copy_array, its stack frame is gone!




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

Example: pass pointer value to function

```
void init(int *tmp, int n) {
    tmp[1] = 6;
    tmp[2] = 5;
}
int main(){
    int size, *ar1;
    size = 10;
    ar1 = malloc(sizeof(int)*size);
    if(ar1 != NULL) {
      ar1[0] = 3;
      ar1[9] = 1;
      init(ar1, size);
…
```



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.)

Trace and Draw Memory:

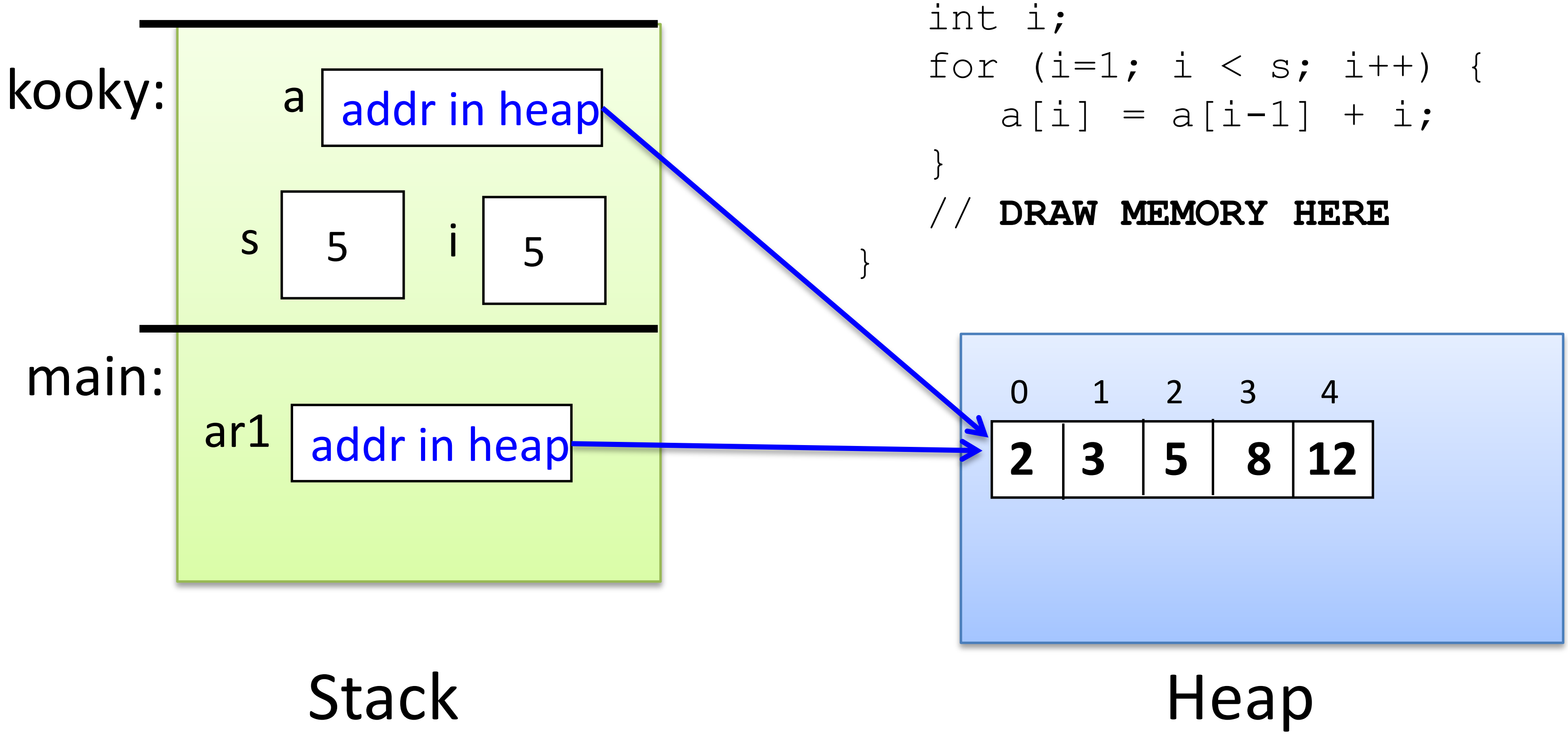
```
int main(){
  int *ar1;
  ar1 = foo(5);
  kooky(ar1, 5);
  free(ar1);
}
int *foo(int s){
  int *tmp;
  tmp=(int *)malloc(sizeof(int)*s);
  // assume malloc succeeds (just for this example)
  tmp[0] = 2;
  return tmp;
}
void kooky(int *a, int s){
   int i;
   for (i=1; i< s; i++) {
      a[i] = a[i-1] + i;
   }
   // DRAW MEMORY HERE
}
```

Trace and Draw Memory:

```
int main(){
  int *ar1;
  ar1 = foo(5);
  kooky(ar1, 5);
  free(ar1);
}
```

```
int *foo(int s){
  int *tmp;
  tmp=(int *)malloc(sizeof(int)*s);
  // assume malloc succeeds
  // (just for this example)
  tmp[0] = 2;
  return tmp;
}

void kooky(int *a, int s){
   int i;
   for (i=1; i < s; i++) {
      a[i] = a[i-1] + i;
   }
   // DRAW MEMORY HERE
}
```



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