CS 31: Intro to Systems C Programming

L09-L10: Pointers and Functions

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Swarthmore College

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Announcements

- Midterm is next week, in-class on Thursday.

- Please respond to accommodations scheduling emails

Reading Quiz

- Note the red border!
- 1 minute per question
- No talking, no laptops, phones during the quiz

<u>Check your frequency:</u>

- Iclicker2: frequency AA
- Iclicker+: green light next to selection

For new devices this should be okay,
For used you may need to reset frequency

Reset:

1. hold down power button until blue light flashes (2secs)
2. Press the frequency code: AA vote status light will indicate success

Today

- Assembly programming (x86_64)

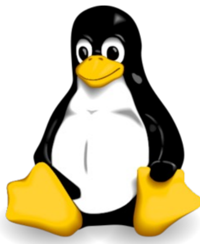
- Pointers and memory

Abstraction

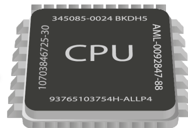
Applications
Specific functionality

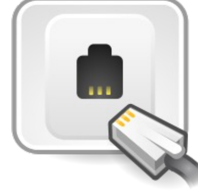
This week: Machine Interface

Operating system
Manage resources



Complex devices
Compute & I/O





CPU Game Plan

- Fetch instruction from memory
- Decode what the instruction is telling us to do
  - Tell the ALU what it should be doing
  - Find the correct operands
- Execute the instruction (arithmetic, etc.)
- Store the result

Types of assembly instructions

- Data movement
  - Move values between registers and memory
  - Examples: `mov`, `movl`, `movq`

The suffix letters specify how many bytes to move (not always necessary, depending on context).

l -> 32 bits
q -> 64 bits

- Load: move data from memory to register

- Store: move data from register to memory

Addressing Modes

- Instructions need to be told where to get operands or store results
- Variety of options for how to *address* those locations
- A location might be:
  - A register
  - A location in memory
- In x86_64, an instruction can access *at most* one memory location

Addressing Mode: Displacement

- Like memory mode, but with a constant offset
  - Offset is often negative, relative to %rbp

```
movl -16(%rbp), %rax
```

- Take the address in %rbp, subtract 24 from it, index into memory and store the result in %rax.

Addressing Mode: Displacement

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movl -16(%rbp), %rax
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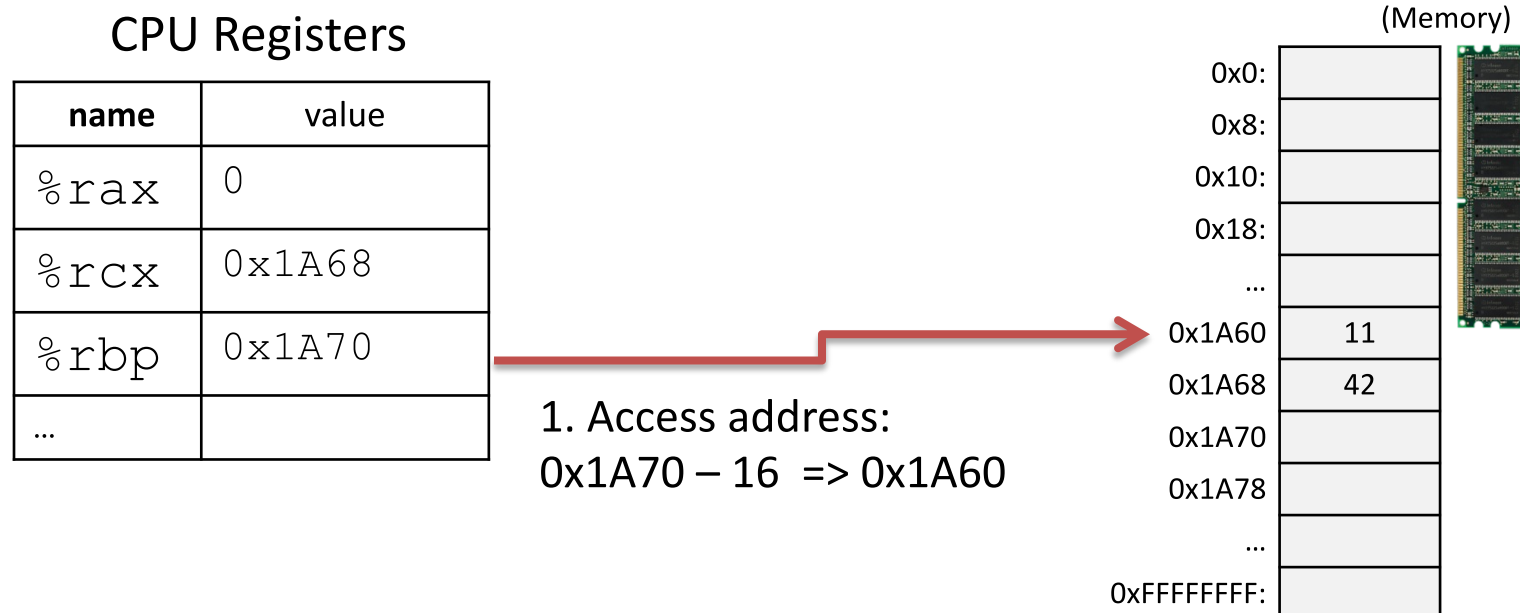

Addressing Mode: Displacement

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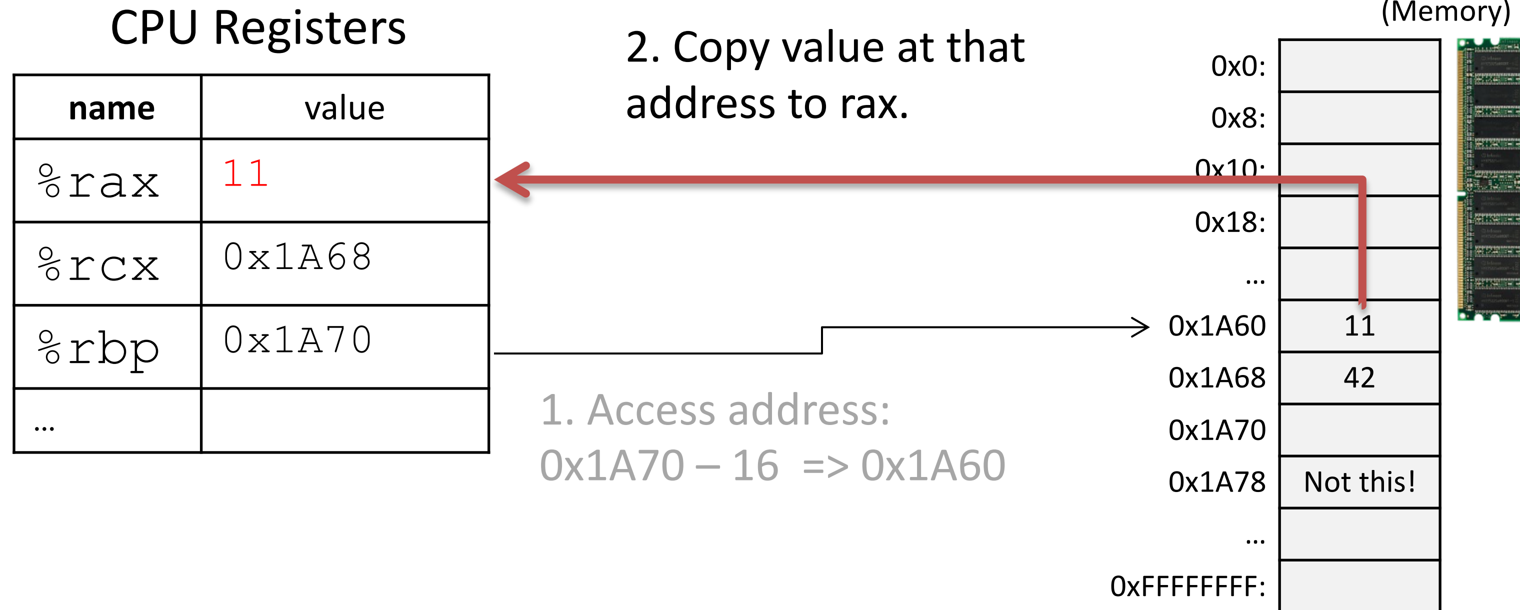


Next Up

- 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

C Pointers Introduction

What is a pointer?

C Pointers Introduction

What is a pointer?

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

Every object (including simple data types)
reside in the **memory** of the machine.

A **pointer** is an “address” telling you
where that variable is **located** in **memory**.

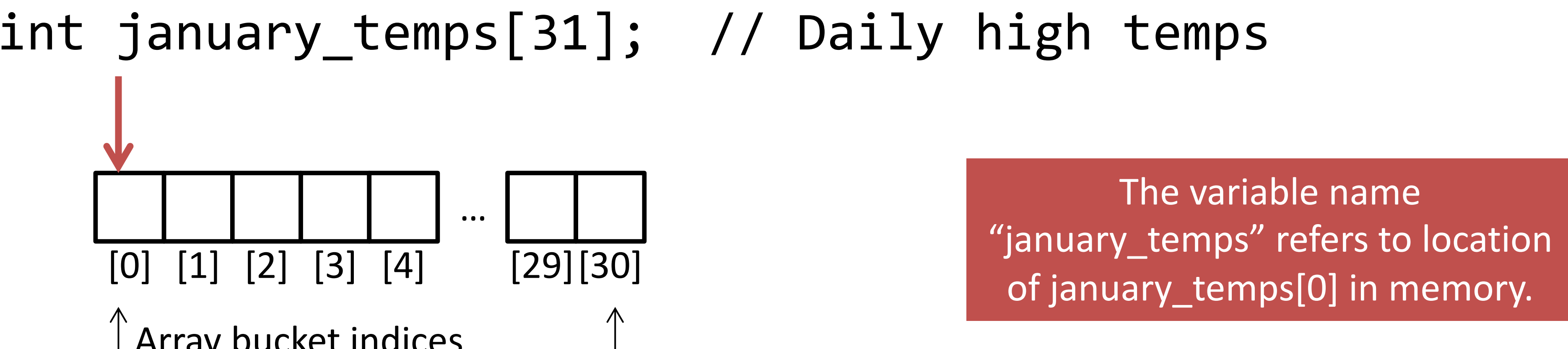
Pointers

- <u>Pointer: A variable that stores a reference (index) 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



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

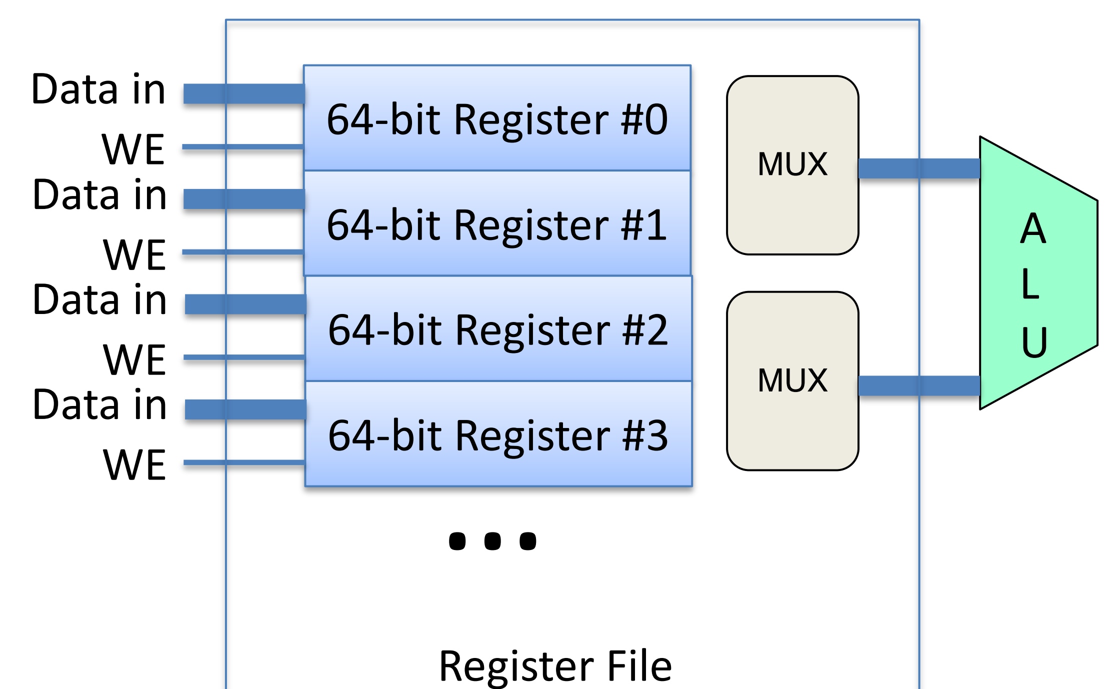
Recall: Program Counter

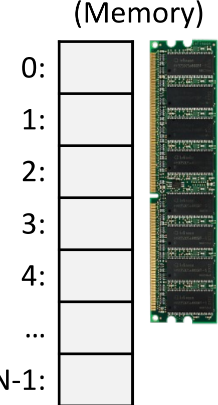
Program Counter (PC): **Memory address of next instr**

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

X86_64 refers to the PC as %rip.

Instruction Pointer

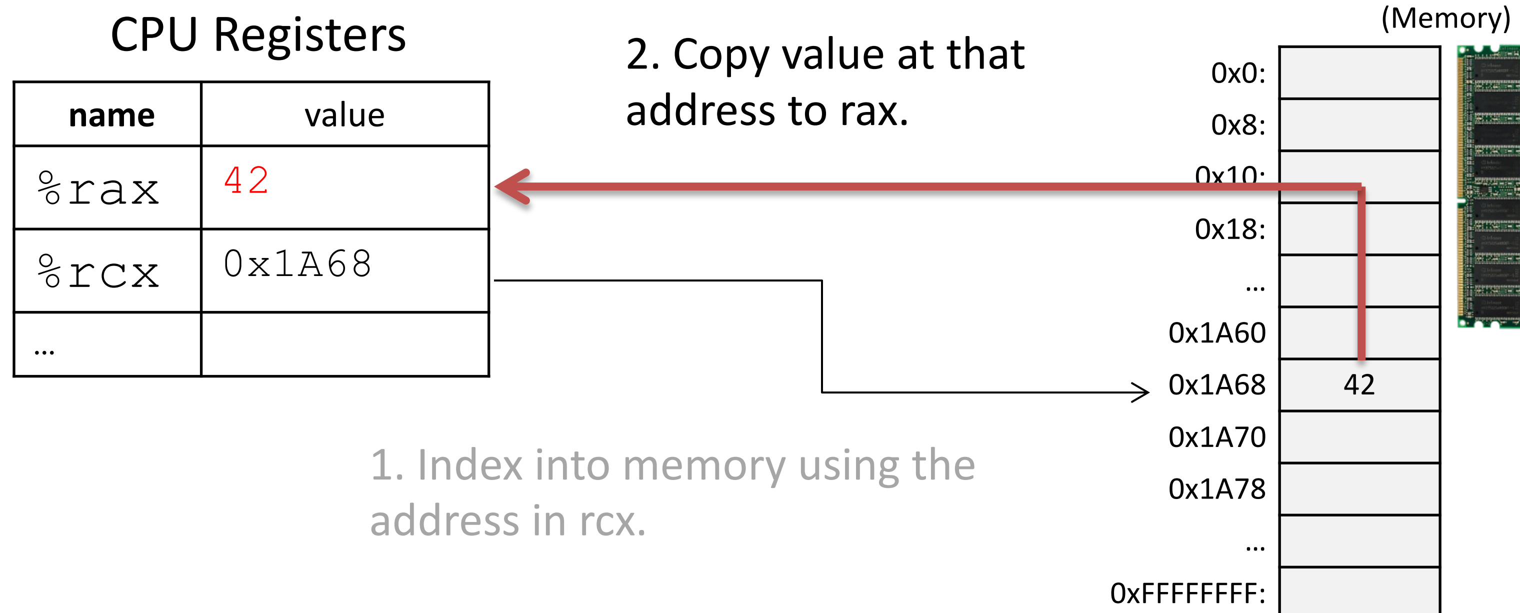




Recall: Addressing Mode: Memory

```
movl (%rcx), %rax
```

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



Pointers in C

- Like any other variable, must be declared:
  - Using the format: `type *name;`
- Example:
  - `int *myptr;`
  - promise to the compiler:
    - This variable 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,
  `*iptr` will follow the address it stores to find an integer in memory.

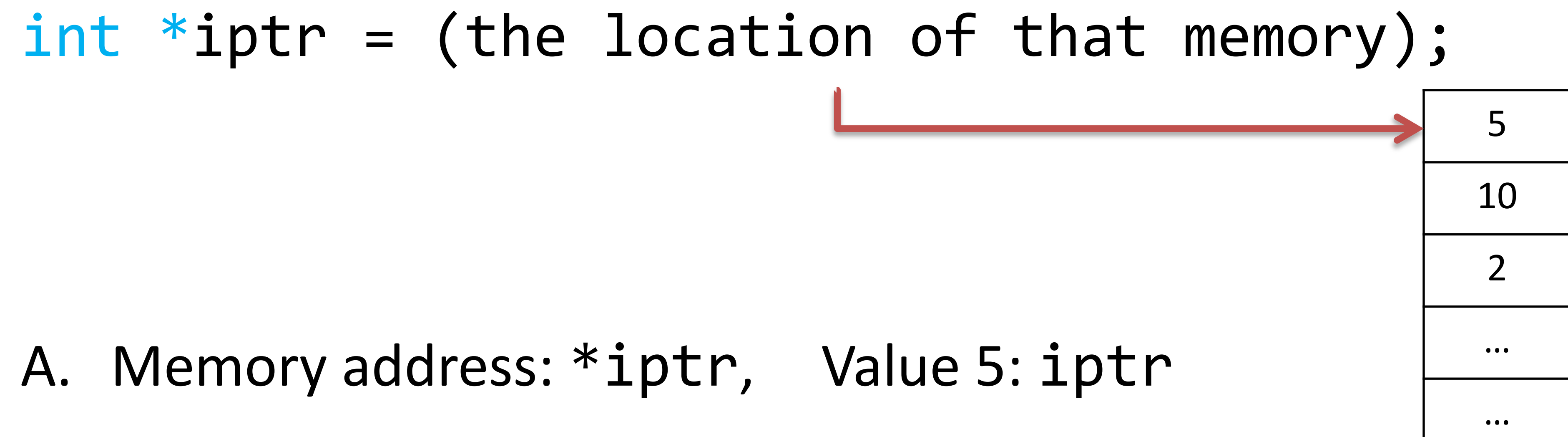
Putting a * in front of a variable…

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

- When you *get the value* at mem. location in the pointer (dereference):
  - Like putting () around a register name
  - We follows the pointer out to memory, get the value
  - Data we access will be of the specified type
    - e.g., pointer (mem. address) to an int, pointer (mem. address) to a float .., etc.

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

* in front of a pointer, gets the value at that memory location



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

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

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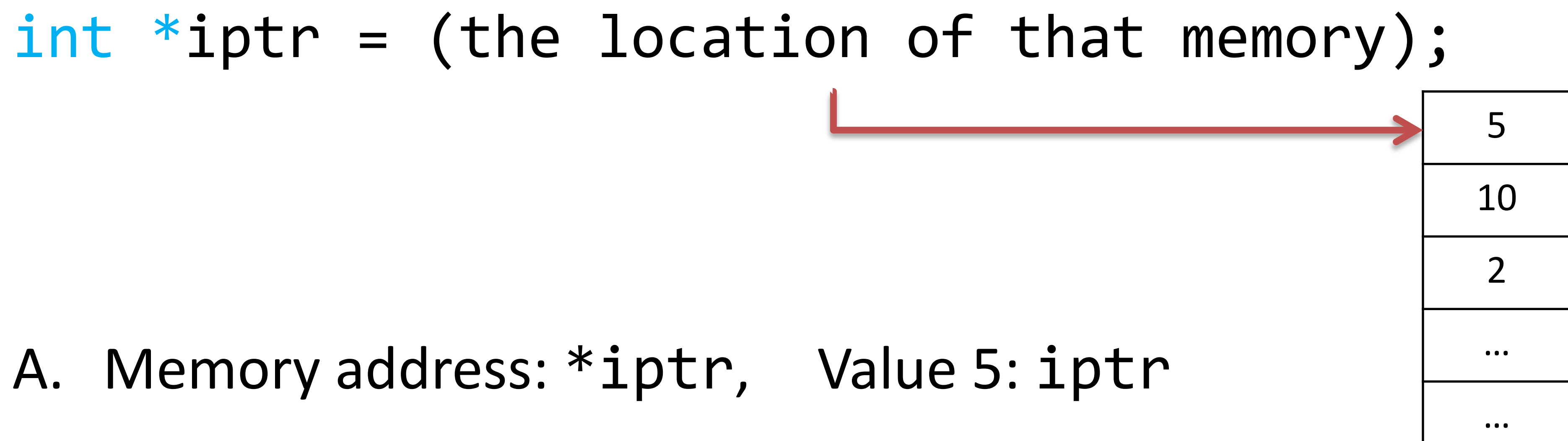


B. Memory address: iptr, Value 5: *iptr

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

- First, let’s look at how memory is organized.
  (From the perspective of one executing program.)

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.

0x0

Operating system

0xFFFFFFFF

Memory - Text

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

0x0

Operating system

Code (aka. Text)

0xFFFFFFFF

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

0x0

Operating system

Code (aka. Text)

Data

0xFFFFFFFF

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;`

0x0

Operating system

Code (aka. Text)

Data

X: Stack

0xFFFFFFFF

Memory - Stack

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

0x0

Operating system

Code (aka. Text)

Data

array [0] [4]

X: Stack

0xFFFFFFFF

Memory - Heap

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

0x0

Operating system

Code (aka. Text)

Data

Heap

X:

Stack

0xFFFFFFFF

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. (Primary reason)

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

E. Some other reason.

"Static" vs. "Dynamic"

Static

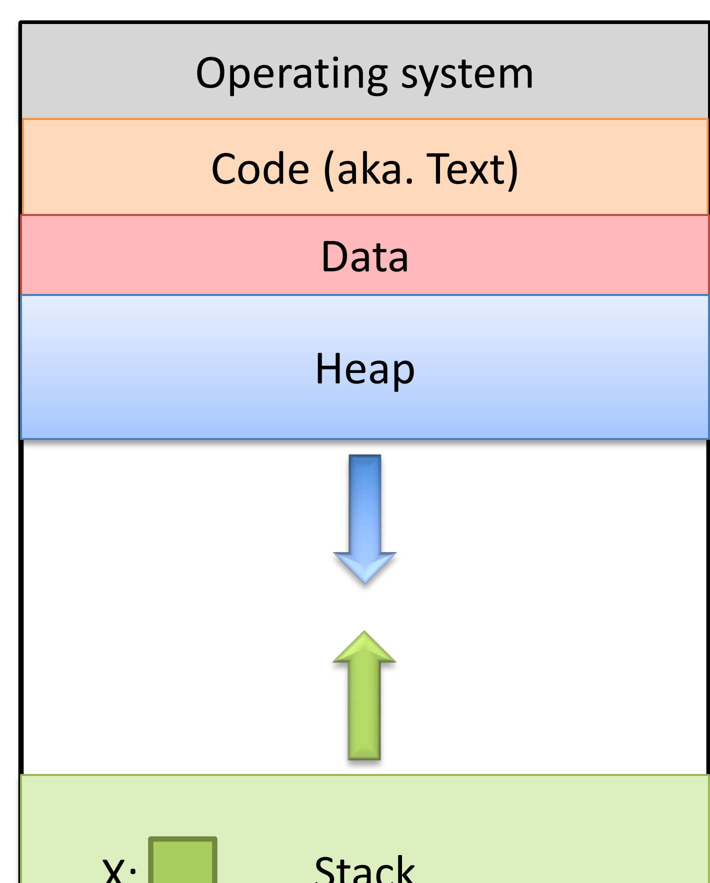
- The compiler can know in advance.
- The size of a C variable (based on its type).
- Hard-coded constants.

Dynamic

- The compiler cannot know -- must be determined at run time.
- User input (or things that depend on it).
- E.g., create an array where the size is typed in by user (or file).

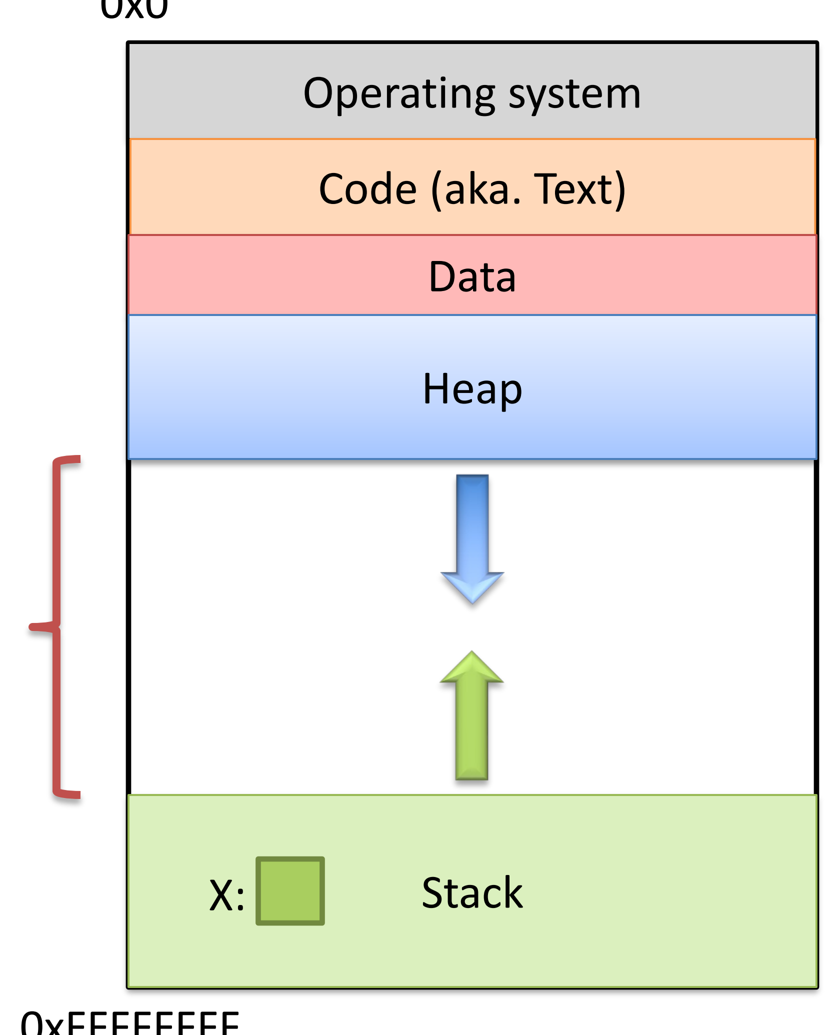
Memory - Heap

- 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?

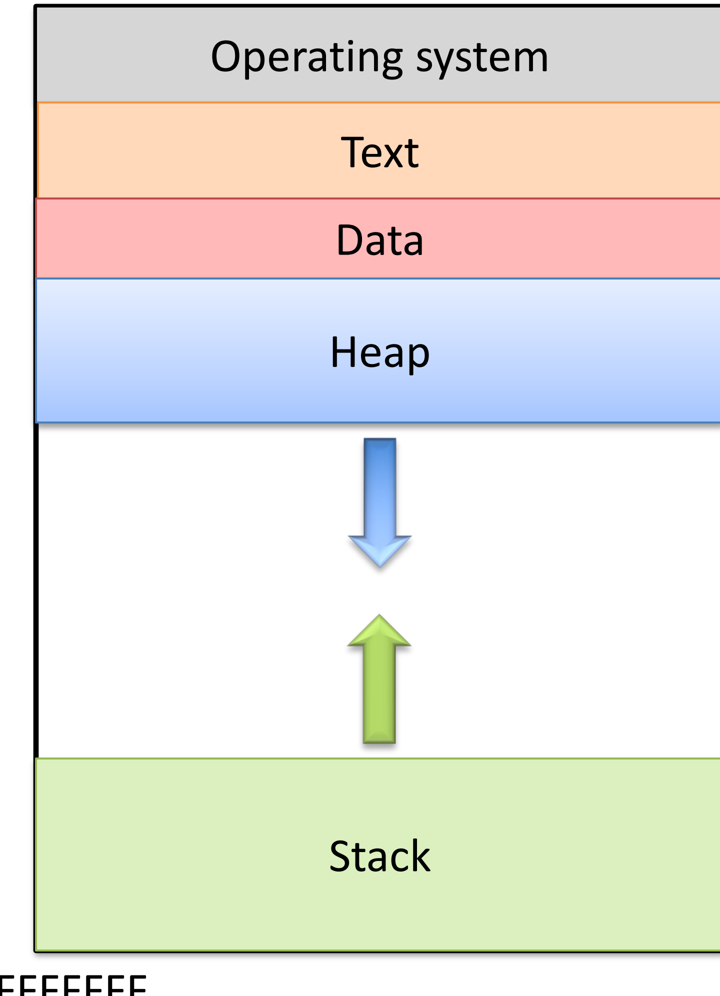
A. OS

B. Text

C. Data

D. Heap

E. Stack



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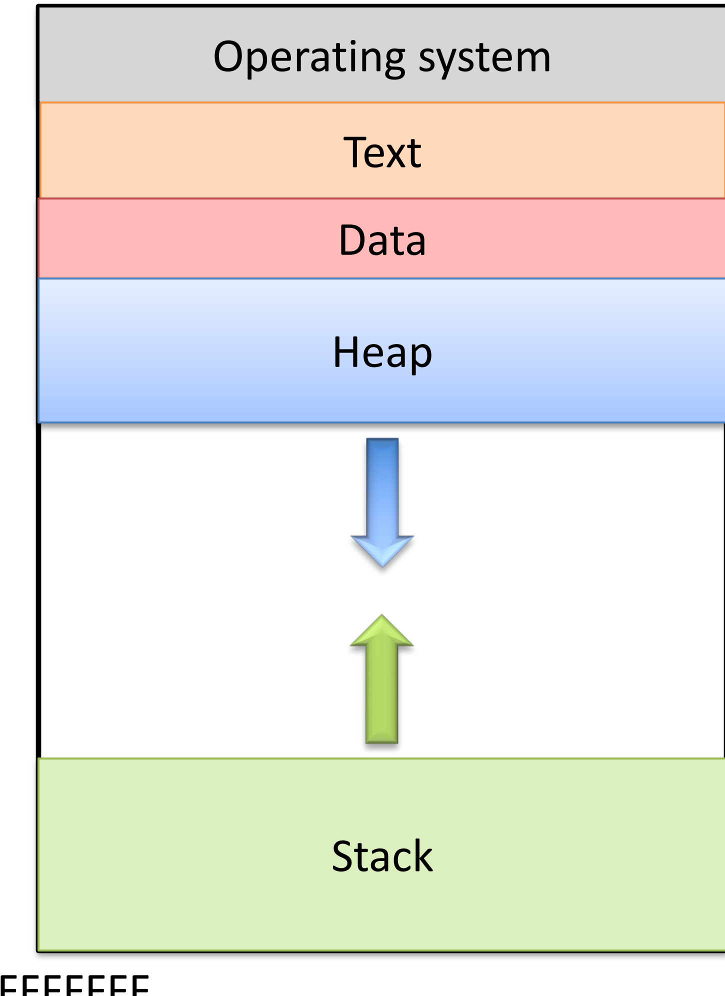


What should happen if we try to access an address that's NOT in one of these regions?

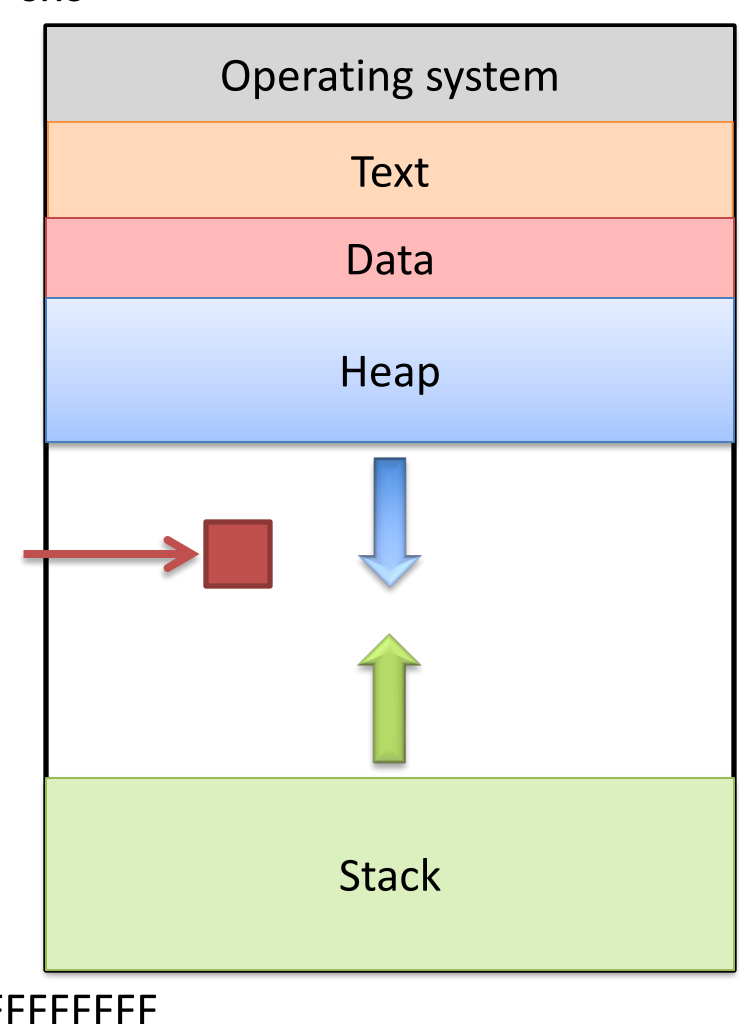
A. The address is allocated to your program.

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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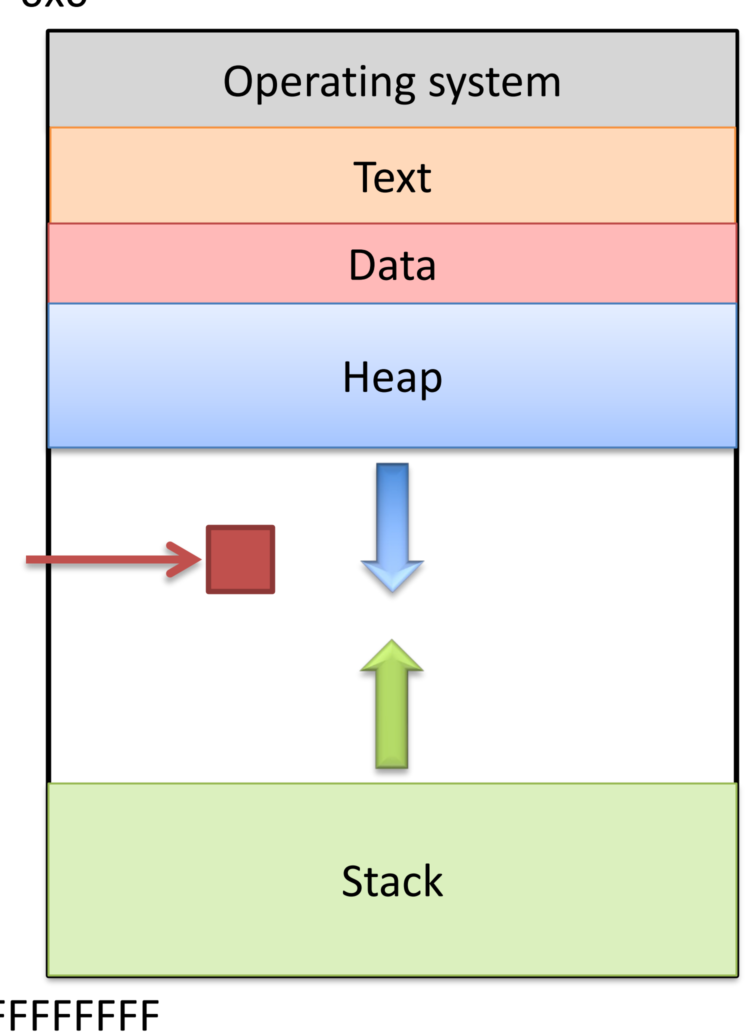
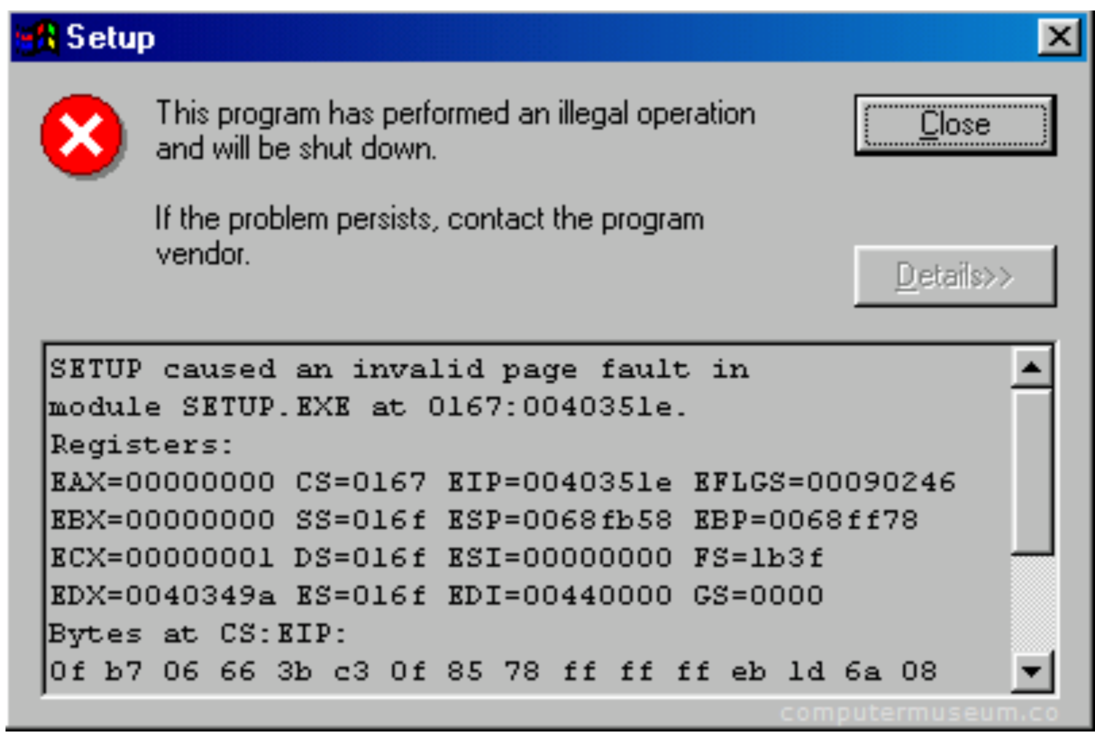


Segmentation Violation



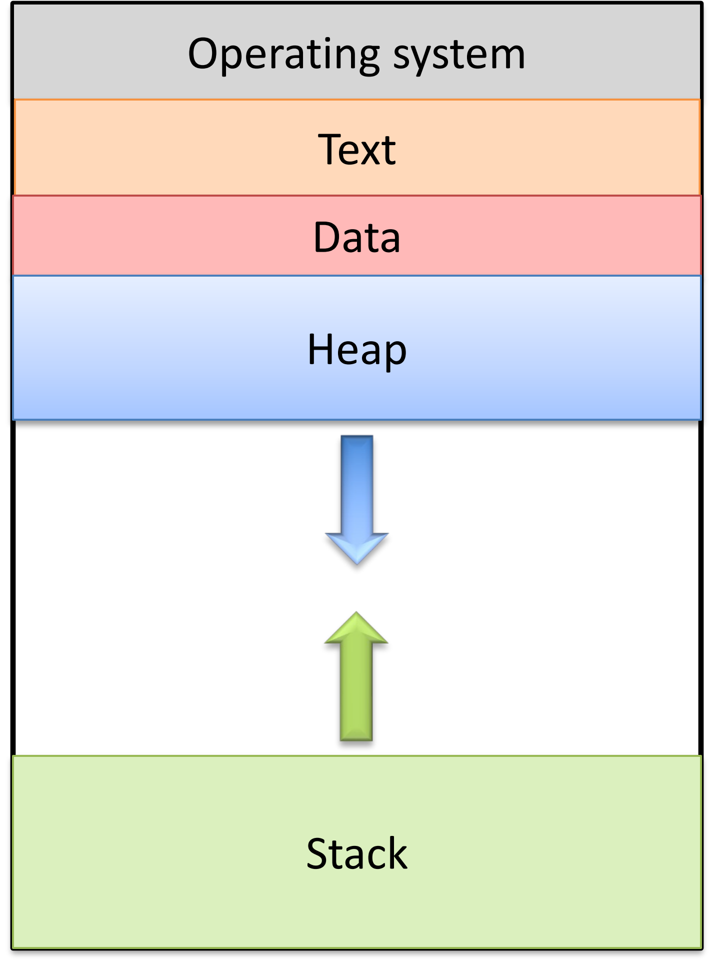
Terminal

File Edit View Search Terminal Help

```
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 is usually read-only



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 (&)

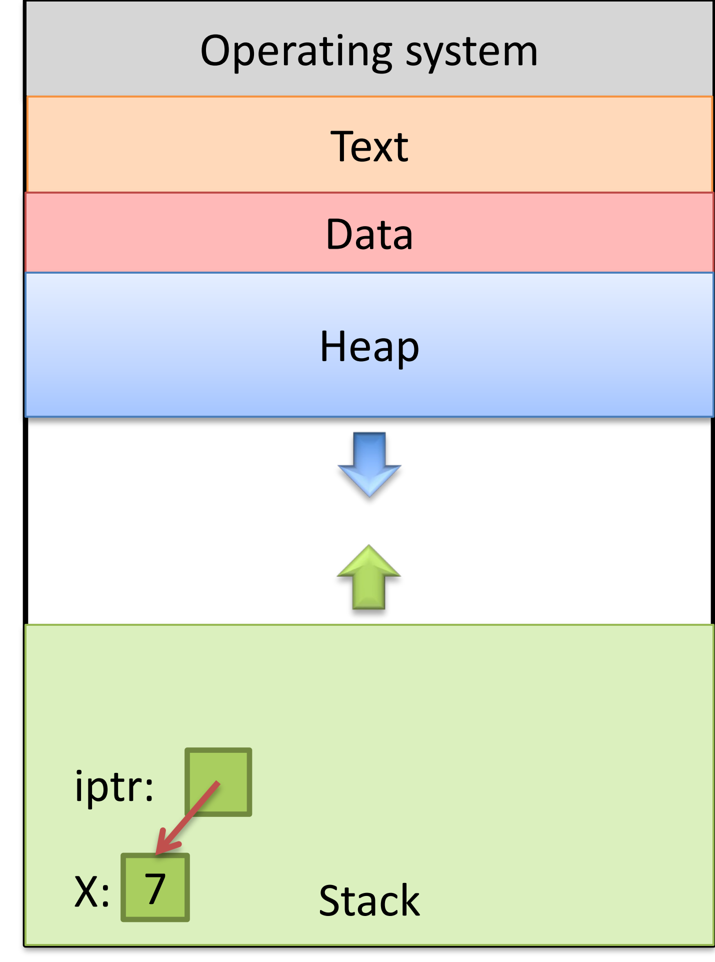
- You can create a pointer to anything by taking its address with the *address of* operator (&).

The Address Of (&)

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




   return 0;
}
```

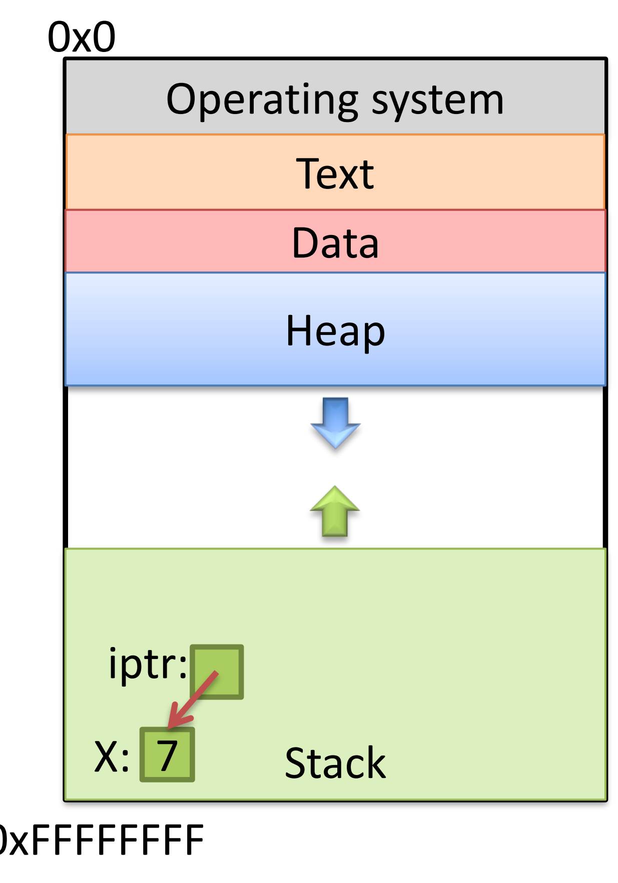


What would this print?

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

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

  return 0;
}
```



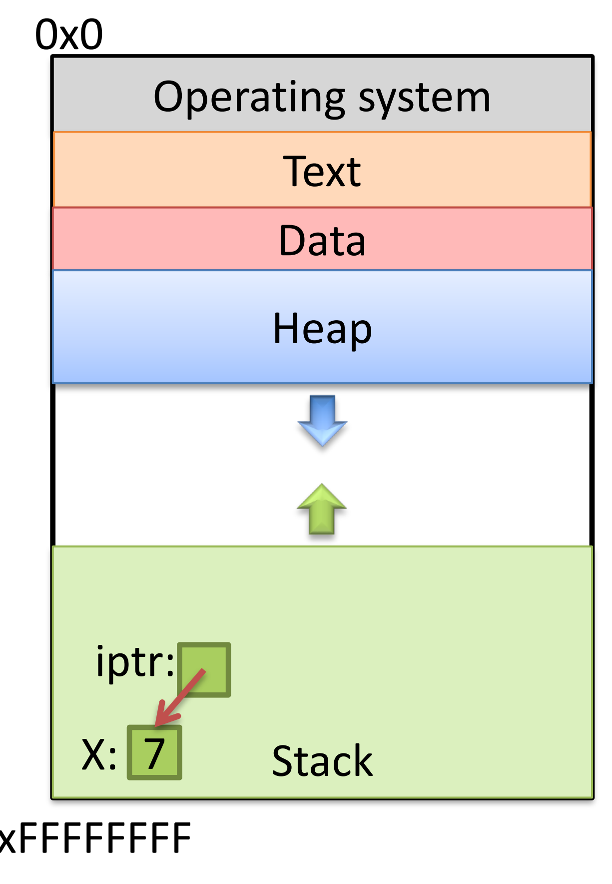
A. 7 7 7 7   B. 7 7 7 5   C. 7 7 5 5   D. Something else

What would this print?

```c
int main(void) {
  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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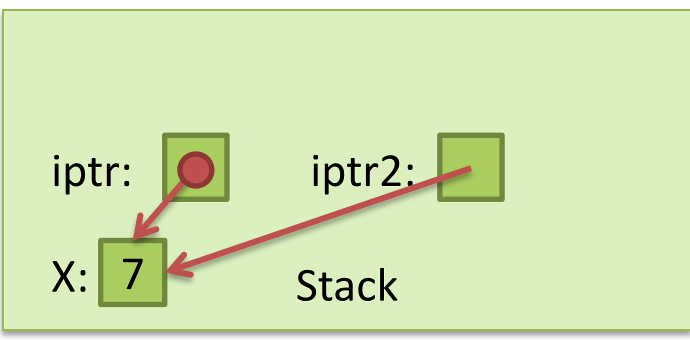
So we declared a pointer…

- 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;
```

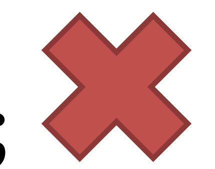


Pointer Types

- 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"
(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 (usually not the case for cs31 ☺)

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.

Given these two setup statements, how many of the following dereference operations are **invalid**?

Setup:

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

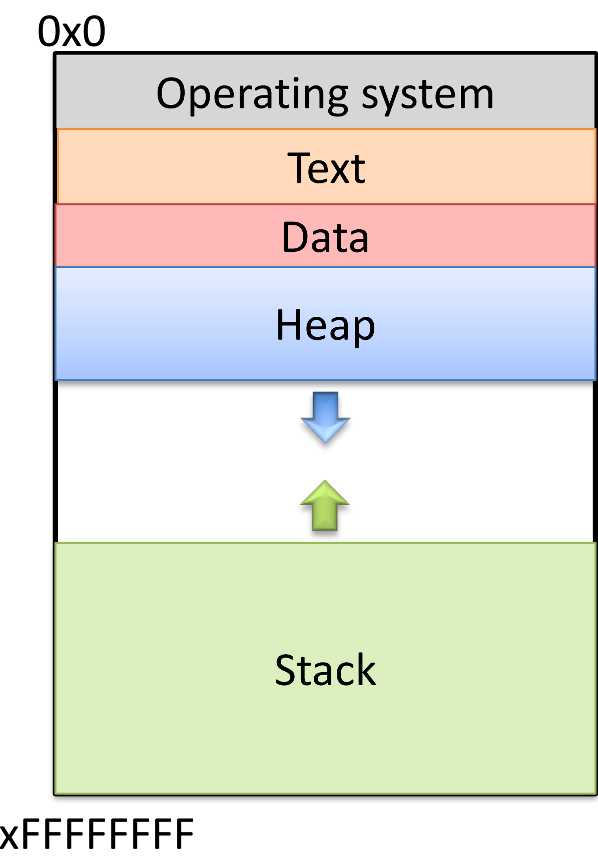
Dereference operations:

```
1) *ptr = 6;
2) *chptr = ‘a’;
3) int y = *ptr + 4;
4) ptr = NULL, *ptr = 6;
```

A: 1   B: 2   C: 3   D: 4

What will this do?

```
int main(void) {
   int *ptr;
   printf(“%d”, *ptr);
}
```



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

Takeaway: If you’re not immediately assigning it something when you declare it, initialize your pointers to NULL.

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

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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. (`size_t` is an unsigned int of 8 bytes on x86_64)

```
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".
- 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.

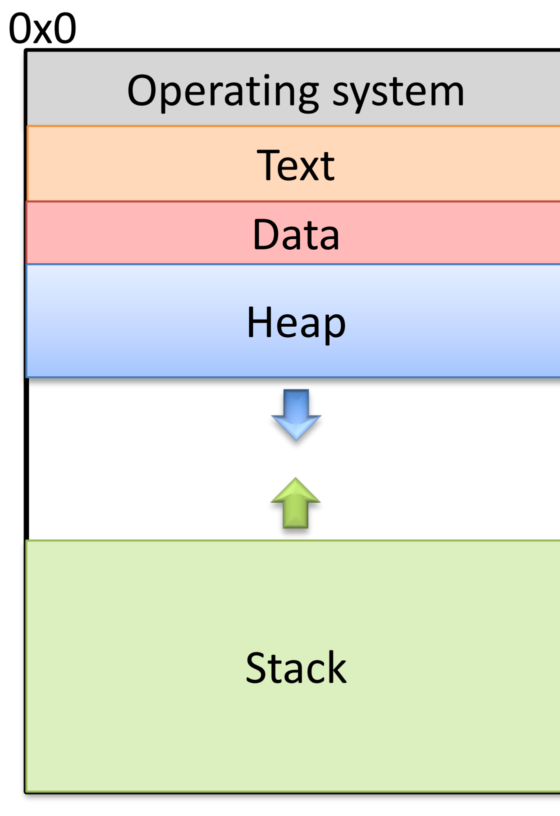
- Size value is determined at compile time (static).

Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```

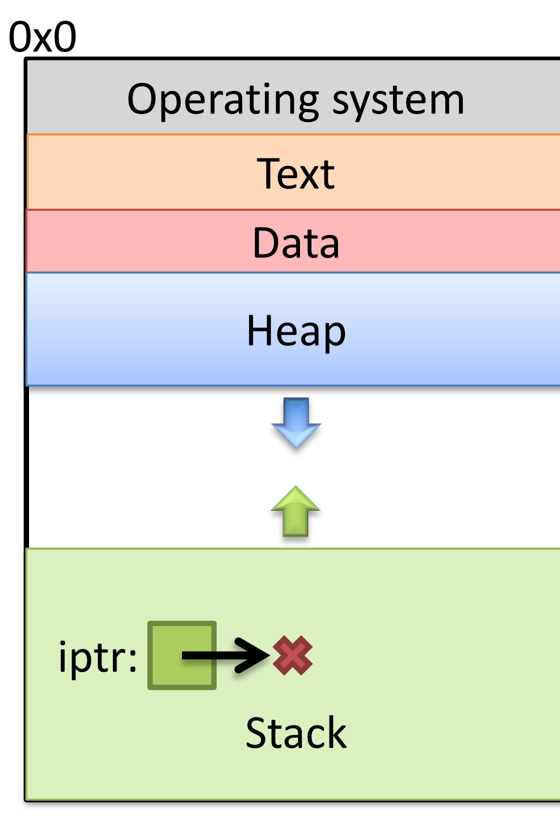


Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```



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

Assign it NULL.

Example

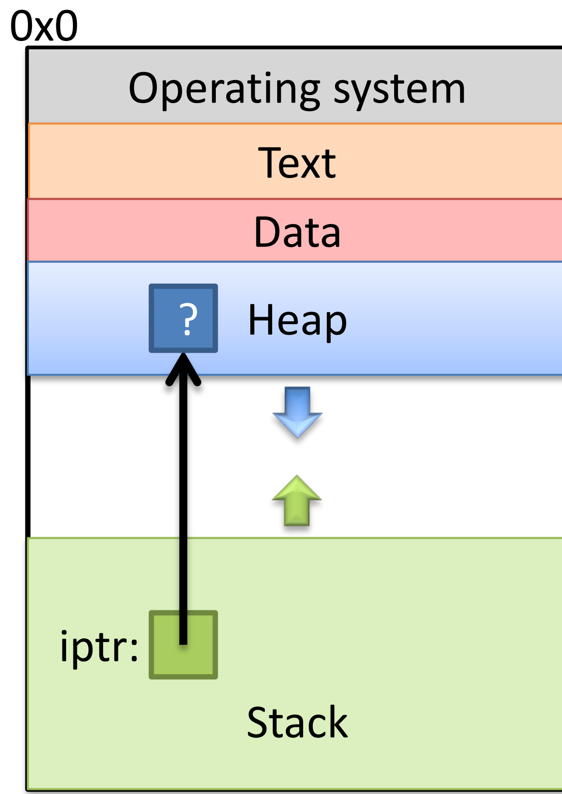
```
int *iptr = NULL;

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.

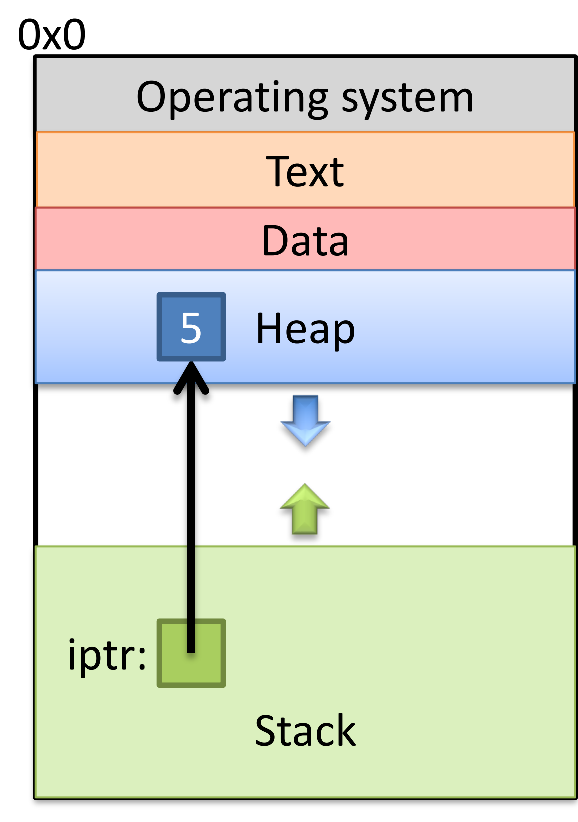
Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;
```

Use the allocated heap space by dereferencing the pointer.



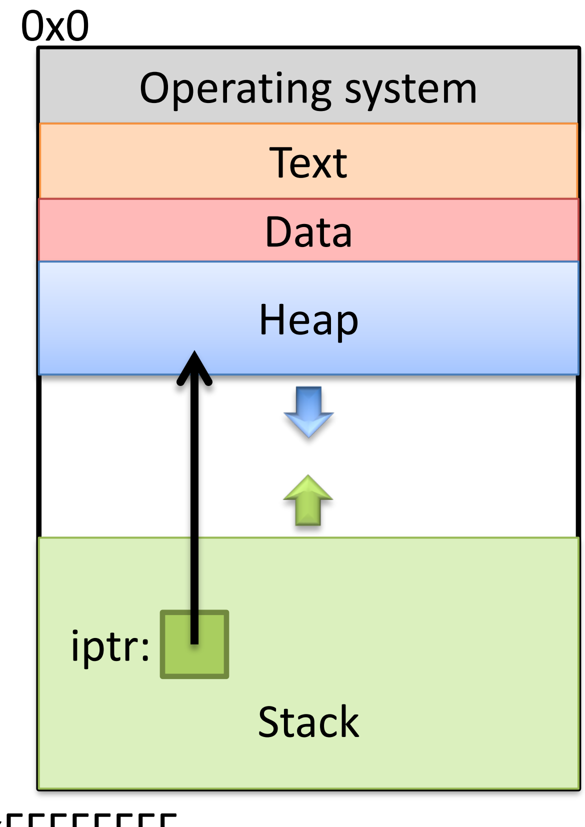
Example

```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

free(iptr);
```



Free up the heap memory we used.

Example

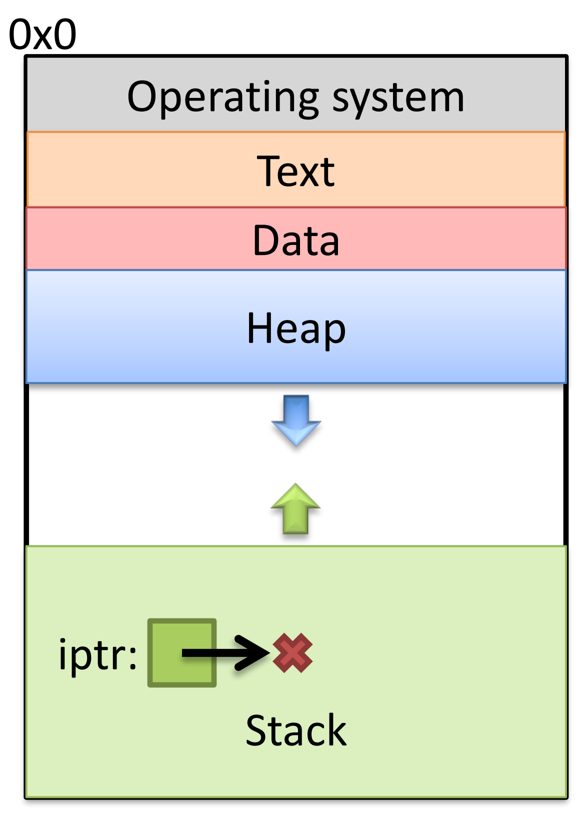
```
int *iptr = NULL;

iptr = malloc(sizeof(int));

*iptr = 5;

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

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



Why is `sizeof()` 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!

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

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. */
}
```

What do you expect to happen to the 100-byte chunk if we do this?

```
// What happens to these 100 bytes?
int *ptr = malloc(100);

ptr = malloc(2000);
```

A. The 100-byte chunk will be lost.

B. The 100-byte chunk will be automatically freed (garbage collected) by the OS.

C. The 100-byte chunk will be automatically freed (garbage collected) by C.

D. The 100-byte chunk will be the first 100 bytes of the 2000-byte chunk.

E. The 100-byte chunk will be added to the 2000-byte chunk (2100 bytes total).

"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 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

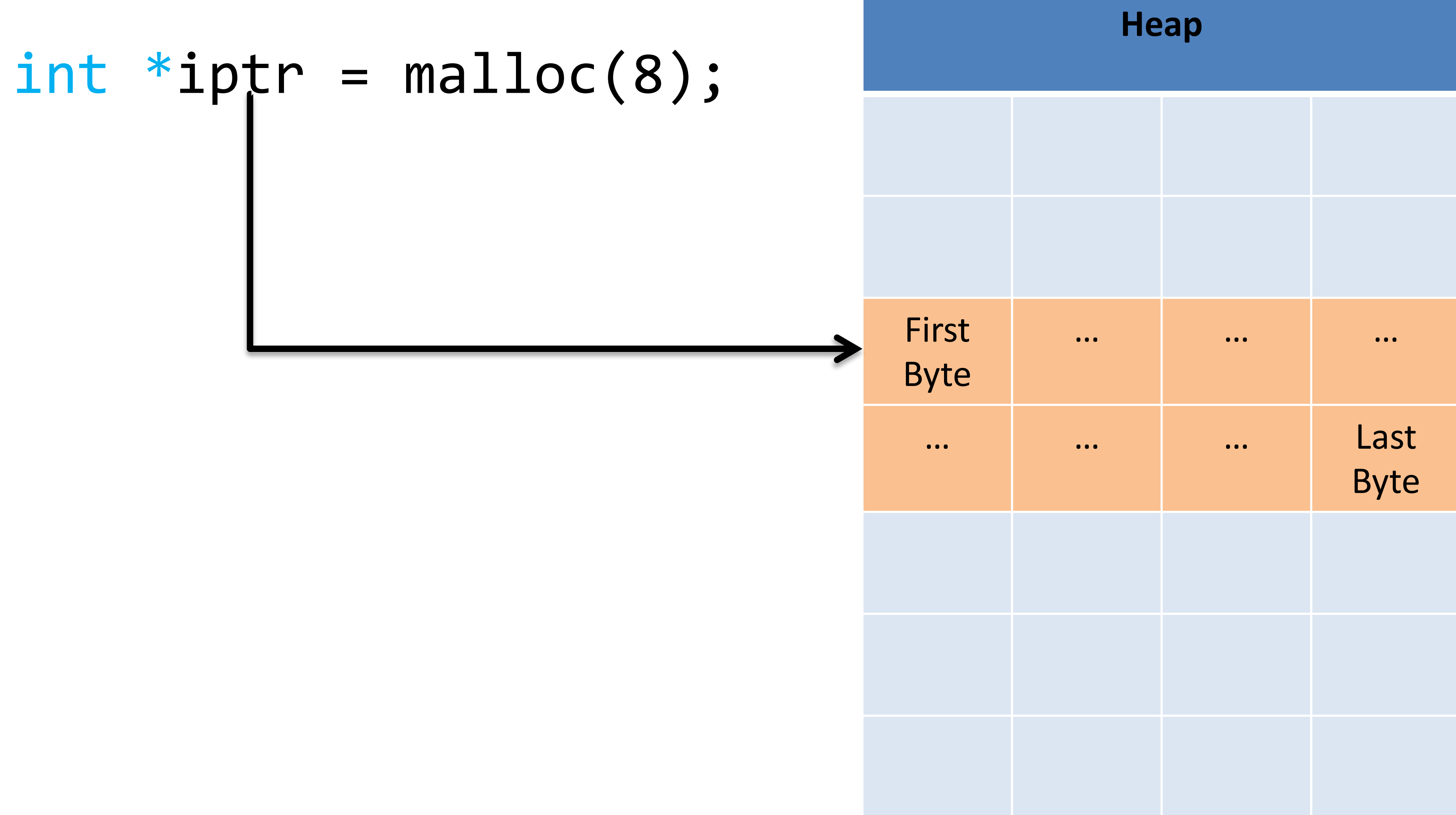
- To free a chunk, you MUST call `free` with the same pointer that `malloc` gave you. (or a copy)
- The standard C library keeps track of the chunks that have been allocated to your program.
  - This is called “metadata” – data about your data.
- Wait, where does it store that information?
  - It’s not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

Metadata

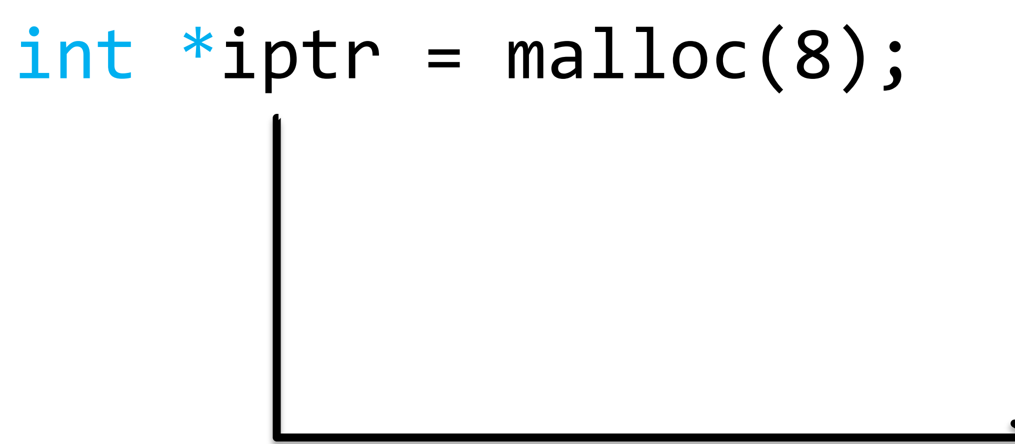
```
int *iptr = malloc(8);
```

Heap			

Metadata



Metadata

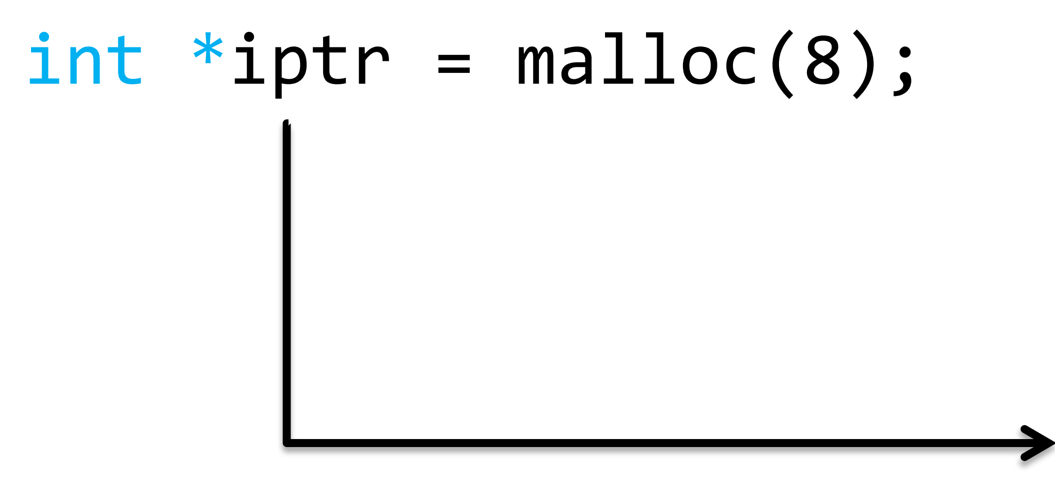


Heap			
Meta	Data	Meta	Data
First Byte	…	…	…
…	…	…	Last Byte

C Library:
"Let me record this allocation's info here."

- Size of allocation
- Maybe other info

Metadata



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

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			

stay within the memory chunks you allocate.

If you corrupt the metadata, you will get weird behavior.

Metadata

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

stay within the memory chunks you allocate.

If you corrupt the metadata, you will get weird behavior.

Valgrind is your new best friend! ☺

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

Pointers as Arrays

"Why did you allocate 8 bytes for an int pointer?

– `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));
```

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

Pointers as Arrays

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

The C compiler knows how big an integer is.

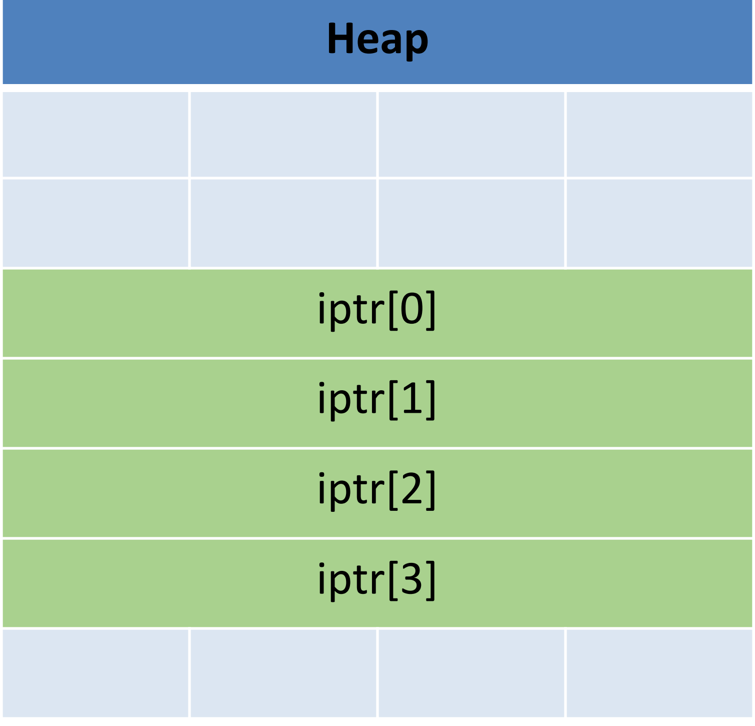
As an alternative way of dereferencing, you can use []'s like an array.

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));
```

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

Heap

iptr[0]
iptr[1]
iptr[2]
iptr[3]

Pointers as Arrays

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

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

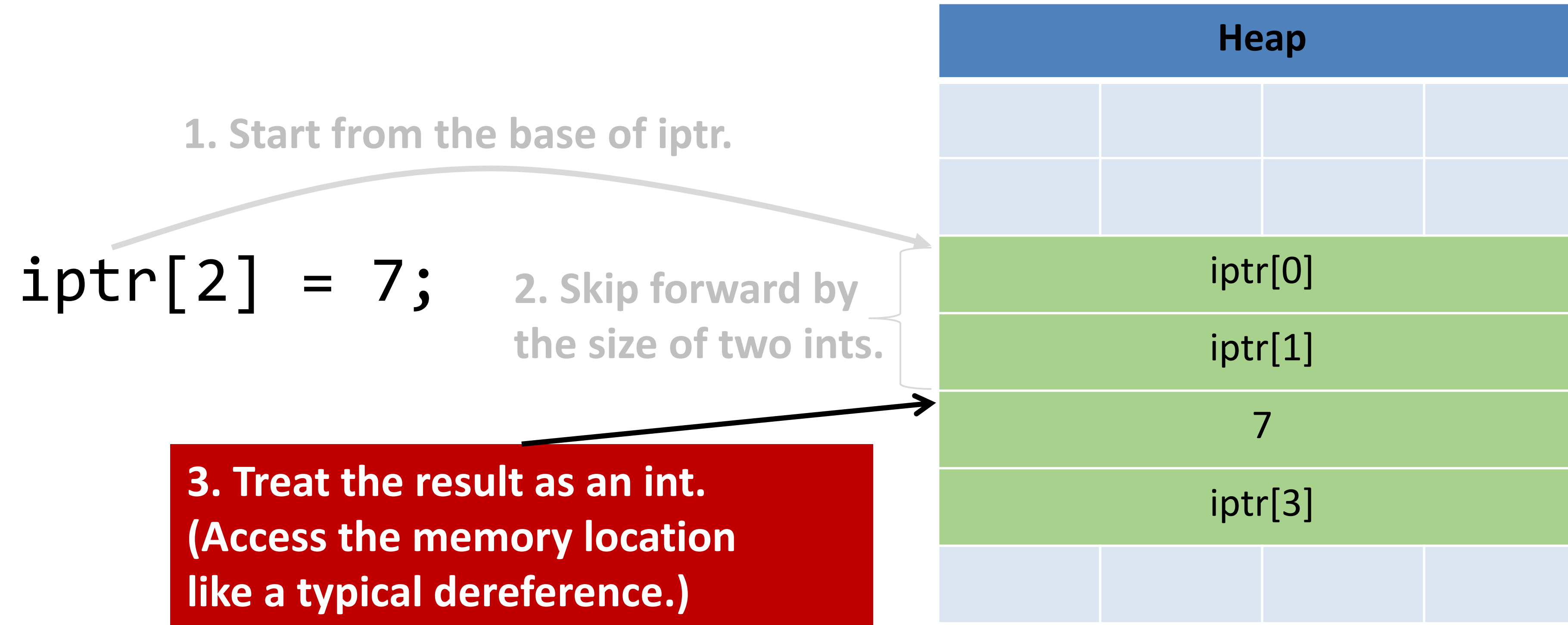
1. Start from the base of iptr.

2. Skip forward by the size of two ints.

Heap			
iptr[0]			
iptr[1]			
iptr[2]			
iptr[3]			

Pointers as Arrays

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



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));
```

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

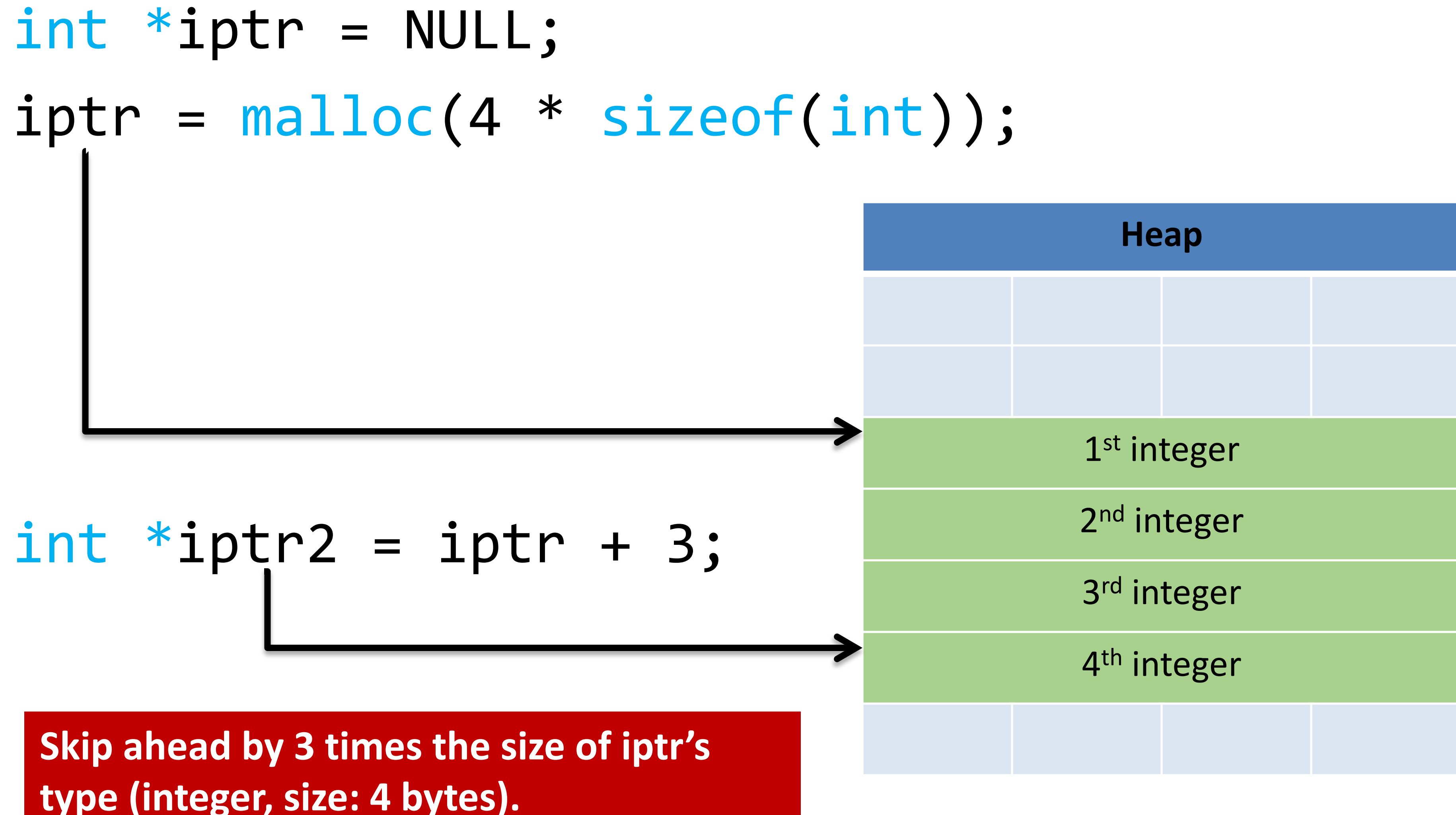
Pointer Arithmetic

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

int *iptr2 = iptr + 3;
```

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

Pointer Arithmetic



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);
}
```

Stack		
func:	a:	4
	b:	7
main:	x:	4
	y:	7

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.

main:

x: 4

y: 7

Stack

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);
}
```

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(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.

func:

a:

main:

x: 9

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(void) {
        int x = 4;

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

main:

x: 9

Stack

Prints: 9

Haven't we seen this somewhere before?

Readfile Library

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

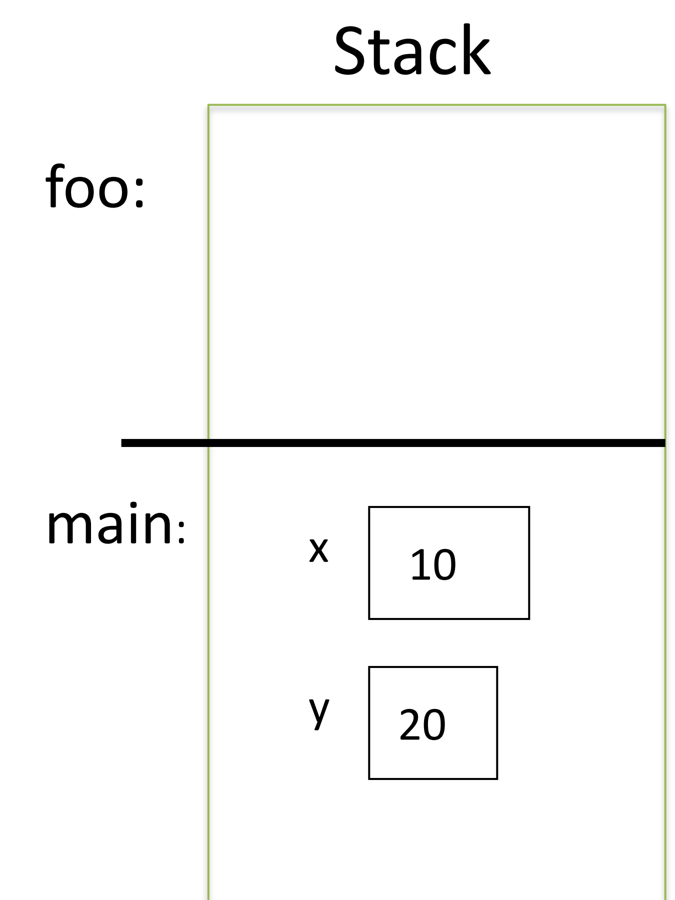
```
int value;
status_code = read_int(&value);
```

- 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
}
```



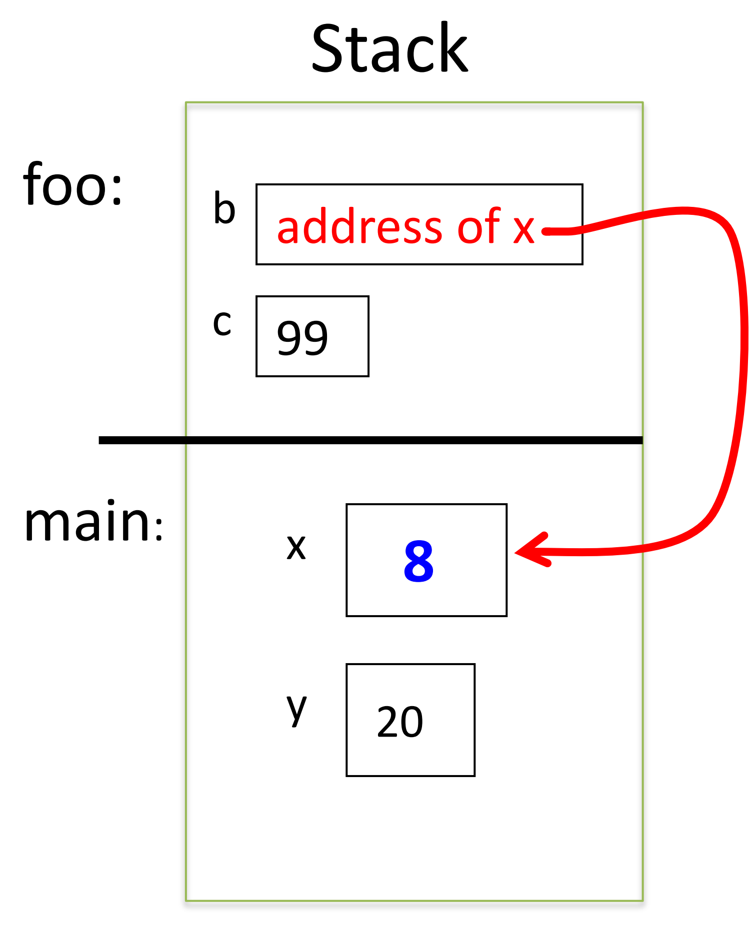
Pass by Pointer - Example

```
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;
}
```

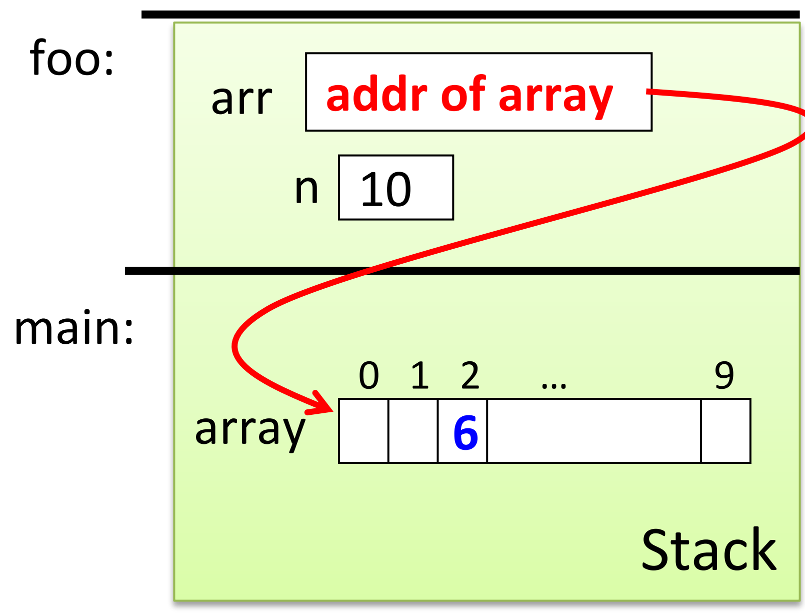
array base address

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 arr[], int n){
   arr[2] = 6;
}
```

array base address

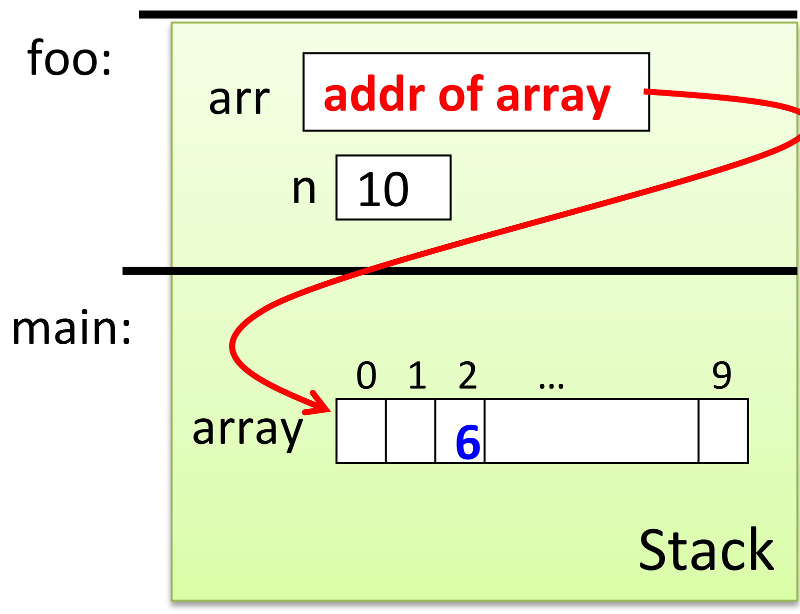


Passing Arrays

- 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?

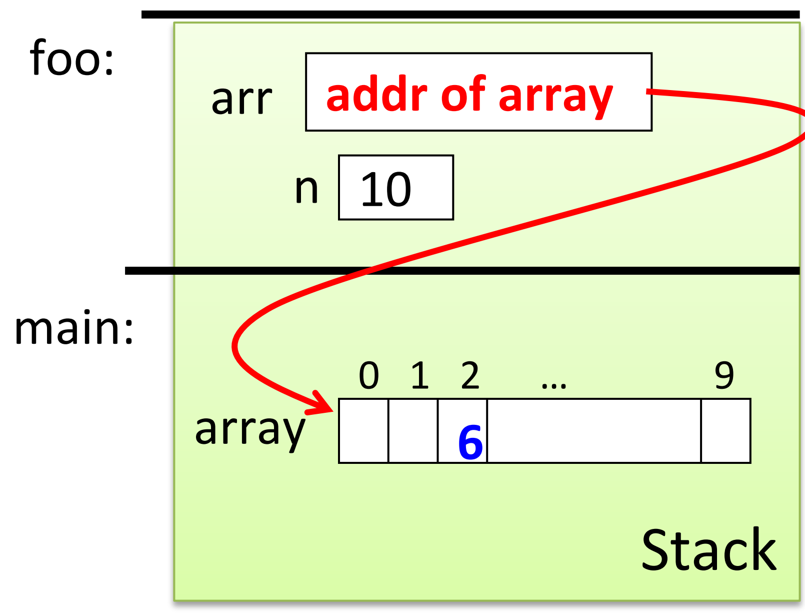


Passing Arrays

- 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(…)
```

copy_array:
result
main:
copy:

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(…)
```

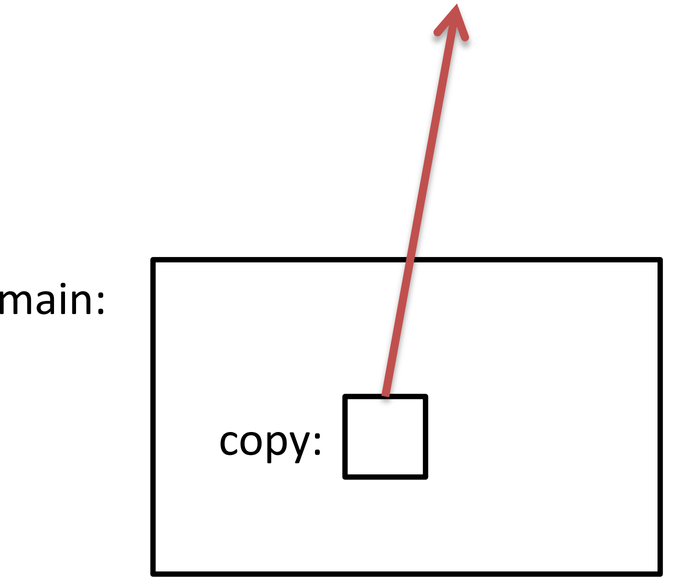
Consider the memory…

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

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

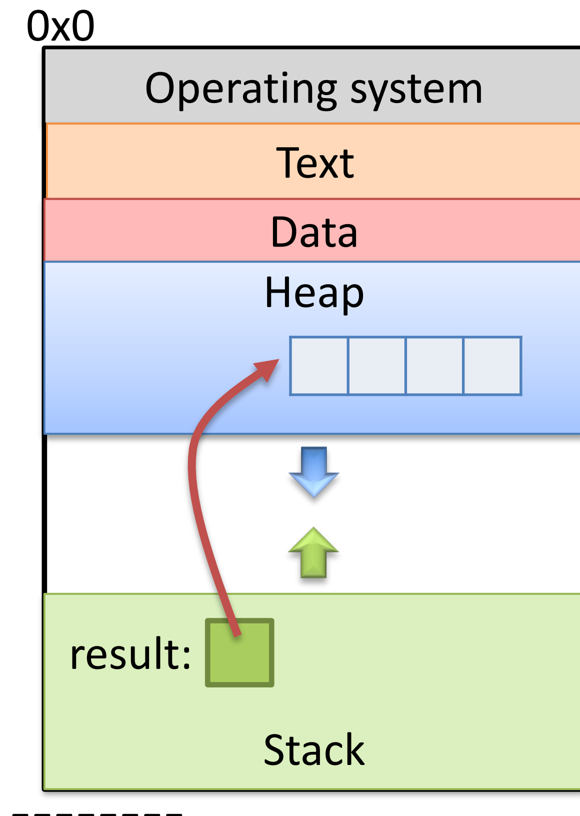
```
int *copy_array(int num, int array[]) {
  int *result = malloc(num * sizeof(int));

  result[0] = array[0];
  …

  return result;
}
```

malloc memory is on the heap.

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



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.)