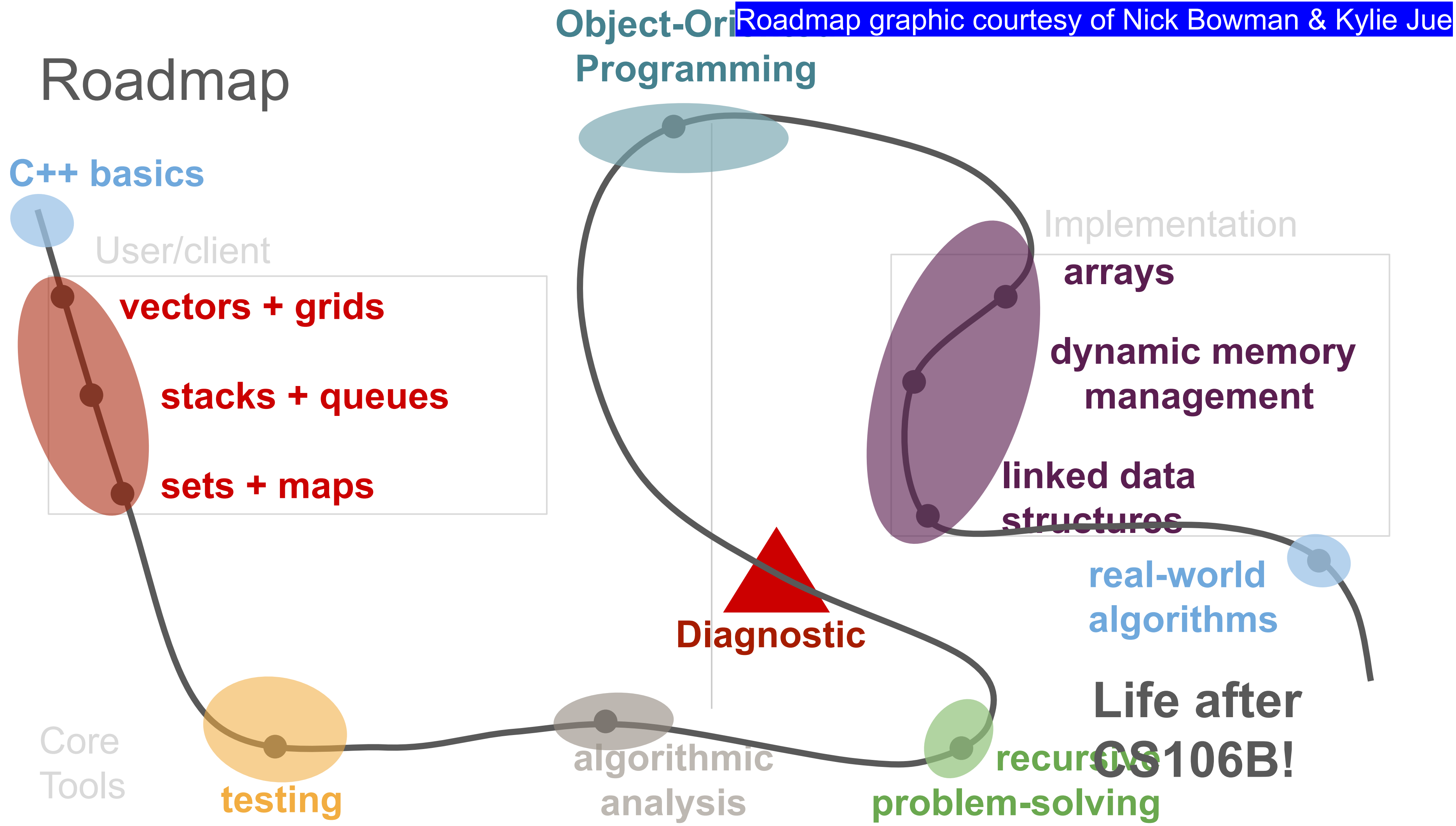
Memory and Pointers

What might be some applications of priority queues in your life?

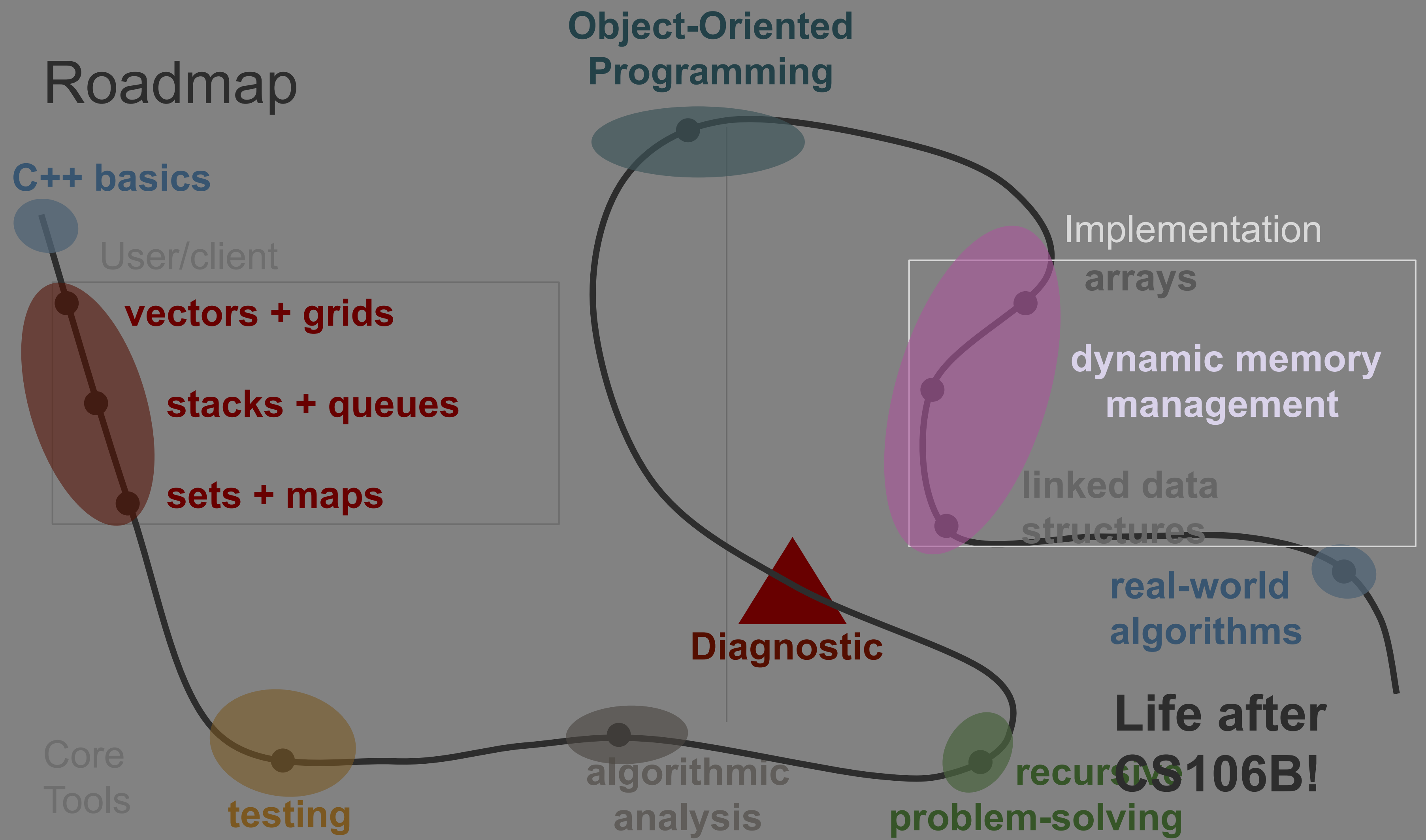
(put your answers in the chat)

Roadmap

Roadmap graphic courtesy of Nick Bowman & Kylie Jue



Roadmap


Object-Oriented Programming
C++ basics
User/client
vectors + grids
stacks + queues
sets + maps
Implementation
arrays
dynamic memory management
linked data structures
real-world algorithms
Diagnostic
Life after CS106B!
Core Tools
testing
algorithmic analysis
recursive problem-solving

Today's question

How is a computer's memory system organized?

How can we navigate and directly manipulate computer memory in C++?

Today's topics

1. Review (Priority Queues and Heaps)

2. Computer Memory

3. Pointed Points on Pointers

Review

[priority queues and heaps]

Implementing ADT Classes

- The first step of implementing an ADT class (as with any class) is answering the three important questions regarding its public interface, private member variables, and initialization procedures.

- Most ADT classes will need to store their data in an underlying array. **The organizational patterns of data in that array may vary**, so it is important to illustrate and visualize the contents and any operations that may be done.

- The paradigm of "growable" arrays allows for fast and flexible containers with dynamic resizing capabilities that enable storage of large amounts of data.

Levels of abstraction

What is the interface for the user?
(Priority Queue)

How is our data organized?
(sorted array, binary heap)

What stores our data?
(arrays)

Abstract Data Structures

Data Organization Strategies

Fundamental C++ Data Storage

What is a priority queue?

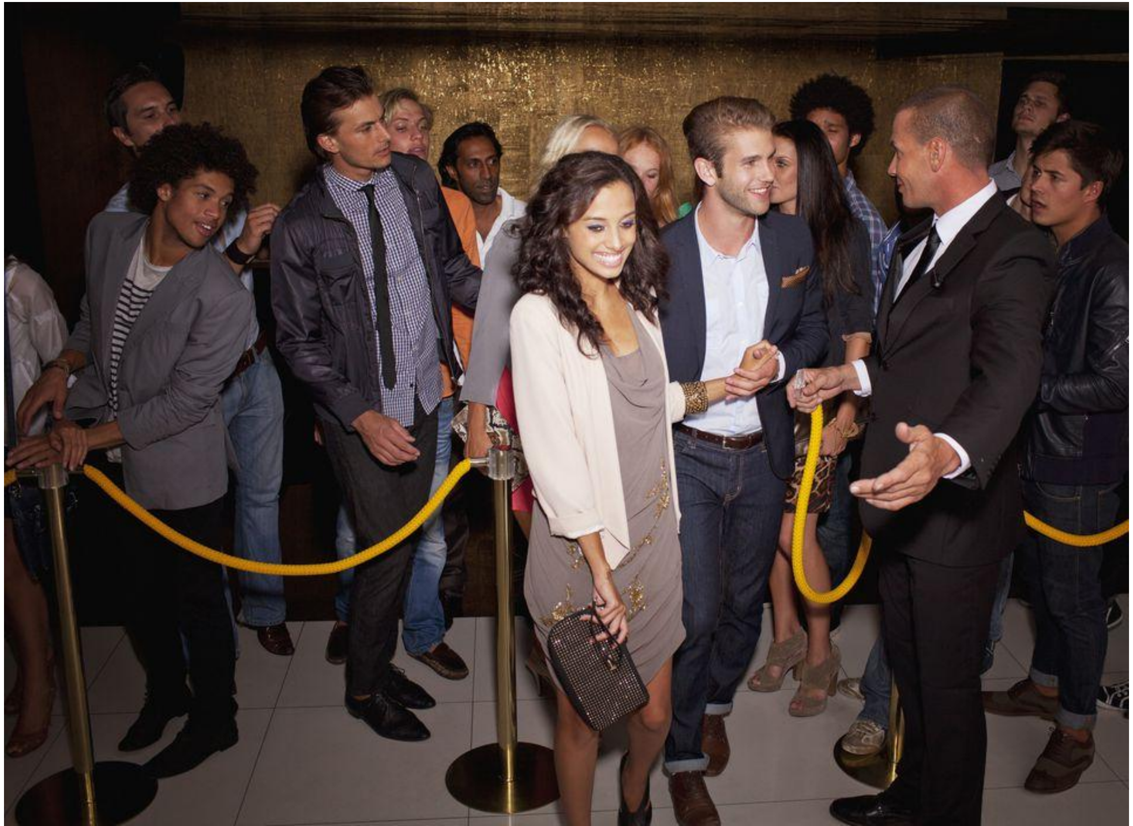
- A queue that orders its elements based on a provided “priority”

- Like regular queues, you cannot index into them to get an item at a particular position.

- Useful for maintaining data sorted based on priorities
    - Emergency room waiting rooms
    - Different airline boarding groups (families and first class passengers, frequent flyers, boarding group A, boarding group B, etc.)
    - Filtering data to get the top X results (e.g. most popular Google searches or fastest times for the Women’s 800m freestyle swimming event)

Ethical Qs and Priority Qs

Deciding who is prioritized




WHEN TO
PAY TO
PROMOTE
VIDEOS
video creators .TV
5:51
When You Should Pay to
Promote your Videos
YouTube
92K views


BudgetVertalingOnline
Sponsored Posts
on Instagram:
The Ultimate Guide

TECH + ENGINEERING

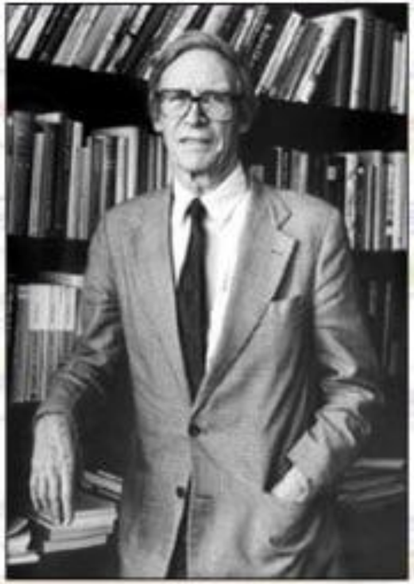
Radical ideas spread through social media. Are the algorithms to blame?

Originally designed to drive revenue on social media platforms, recommendation algorithms are now making it easier to promote extreme content. Addressing this problem will require more than a technical fix.

BY KATHERINE J. WU THURSDAY, MARCH 28, 2019 NOVA NEXT

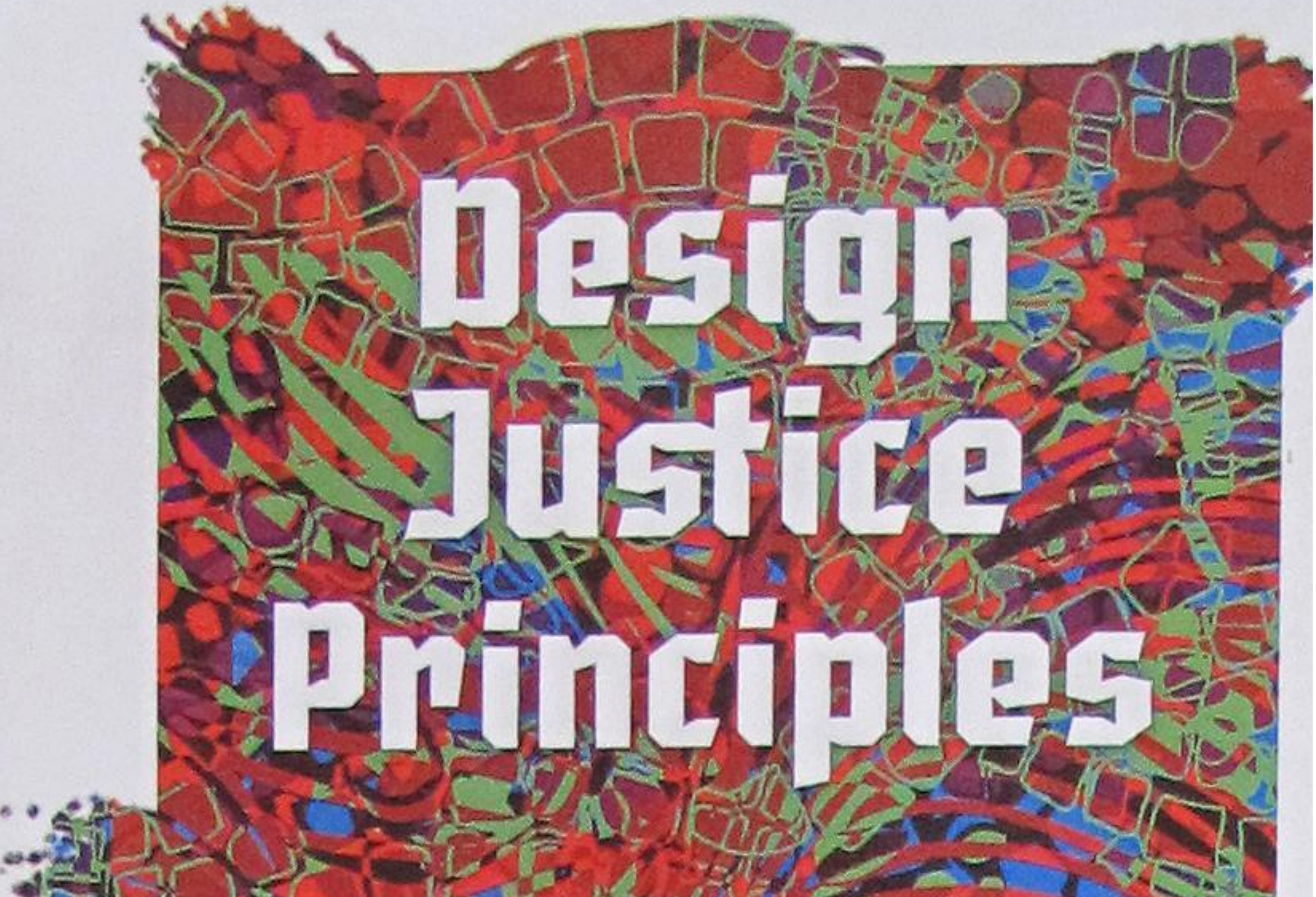

3
Group
2
Group
1

John Rawls, 1970



"Veil of ignorance"

Justice comes from making decisions that maximize liberty for all people and without considering which outcome will give us personally the biggest benefit.


Design
Justice
Principles

Supported operations

- **enqueue(priority, elem)**: inserts **elem** with given **priority**
- **dequeue()**: removes the element with the highest priority from the queue
- **peek()**: returns the element with the highest priority in the queue (no removal)
- **size()**: returns the number of elements in the queue
- **isEmpty()**: returns true if there are no elements in the queue, false otherwise
- **clear()**: empties the queue

What is a binary heap?

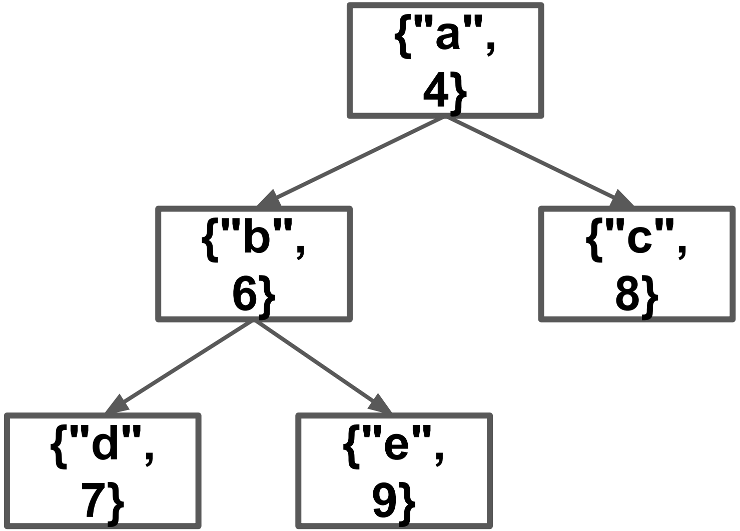
- A heap is a tree-based structure that satisfies the *heap property* that **parents have a higher priority than any of their children**.

- Additional properties
  - **Binary**: Two children per parent (but no implied orderings between siblings)
  - **Completely filled** (each parents must have 2 children) except for the bottom level, which gets populated from **left to right**

- Two types → which we use depends on what we define as a “higher” priority
  - **Min-heap**: smaller numbers = higher priority (closer to the root)
  - Max-heap: larger numbers = higher priority (closer to the root)

Binary heaps + implementation

Node: i
Left child: **2*i + 1**
Right child: **2*i + 2**
Parent: **(i-1) / 2**

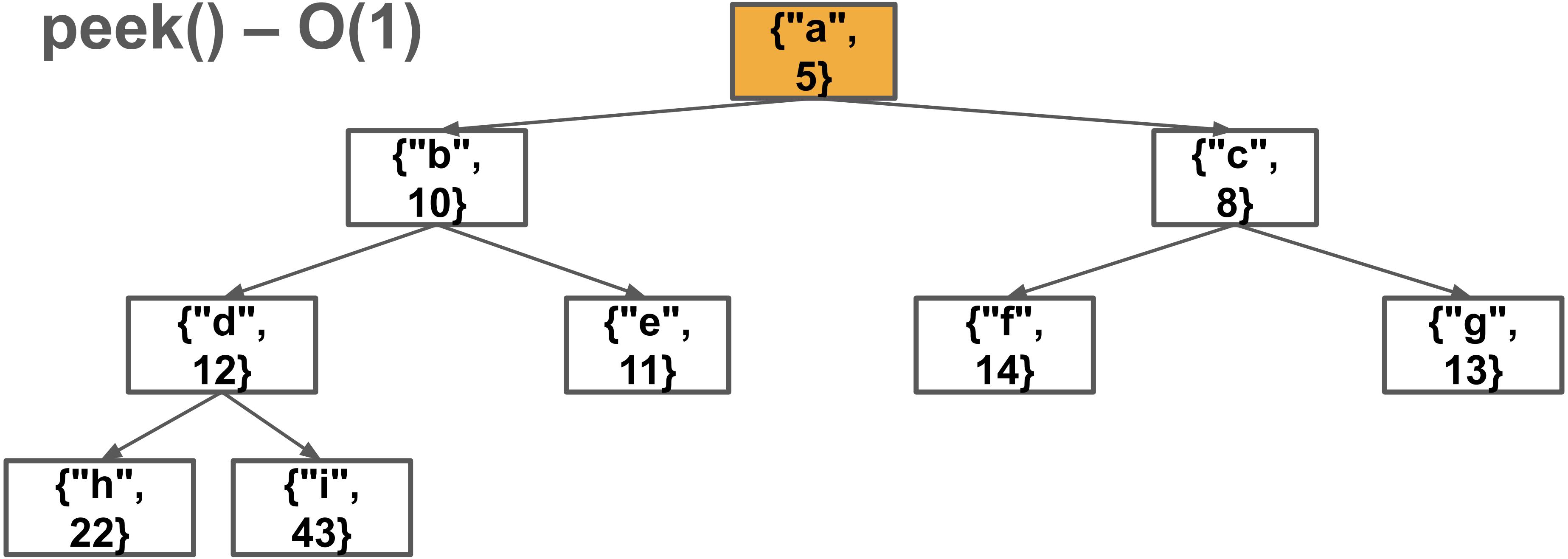


{“a”, 4}	{“b”, 6}	{“c”, 8}	{“d”, 7}	{“e”, 9}
0	1	2	3	4

Node index: 0
Left child: 1
Right child: 2
Parent: N/A

Node index: 1
Left child: 3
Right child: 4
Parent: 0

peek() – O(1)



{"a", 5}	{"b", 10}	{"c", 8}	{"d", 12}	{"e", 11}	{"f", 14}	{"g", 13}	{"h", 22}	{"i", 43}	?	?	?
0	1	2	3	4	5	6	7	8	9	10	11

enqueue()

- Add the new element into the first empty slot in the array.
- Bubble up to regain the *heap property*!
- Runs in time **O(log n)**

dequeue()

- Remove the minimum element: the root of the tree.
- Replace the root with the “last” element in our tree (last level, farthest right) since we know that location will end up empty.
- Bubble down to regain the *heap property*!
- Runs in time **O(log n)**

Summary

- **Priority queues** are queues ordered by **priority** of their elements, where the **highest priority** elements get dequeued first.

- **Binary heaps** are a good way of organizing data when creating a priority queue.
  - Use a min-heap when a smaller number = higher priority (what you'll use on the assignment) and a max-heap when a larger number = higher priority.

- There can be multiple ways to implement the same abstraction! For both ways of implementing our priority queues, we'll use **arrays** for data storage.

Levels of abstraction

What is the interface for the user?
(Vector, Set, Priority Queue, etc.)

How is our data organized?
(sorted array, binary heap, tree, etc.)

What stores our data?
(arrays, linked lists, etc.)

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Levels of abstraction

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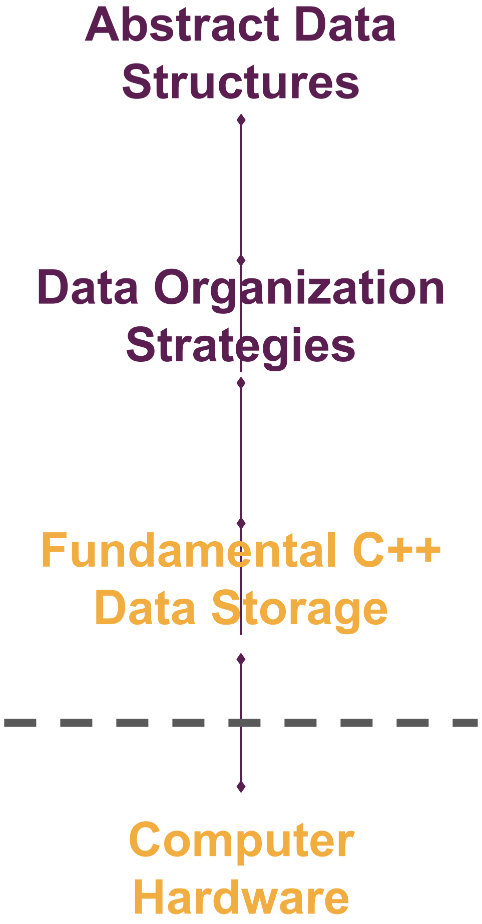
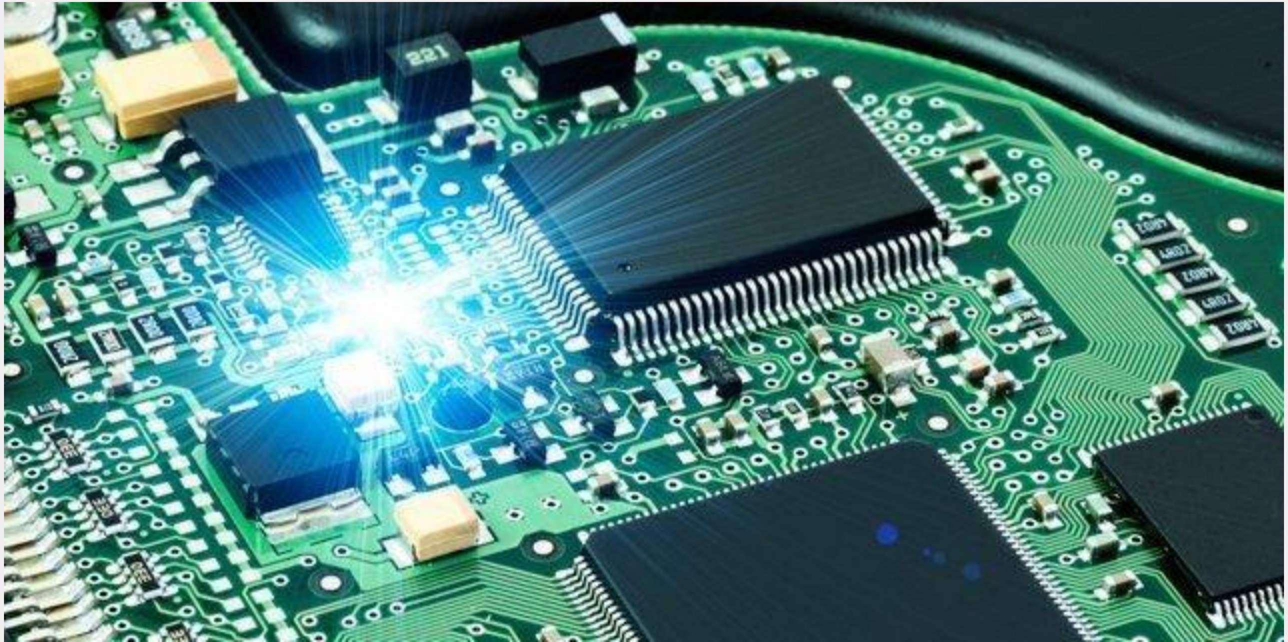
Levels of abstraction



The Hardware/Software Boundary



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- When we write computer programs (which we refer to as **software**), we are able to send specific instructions to the computer's hardware to do calculations, store information, etc.

- The programs we write all make use of a specific component of the computer's hardware called **Random Access Memory (RAM)**.
    - This is what we usually refer to when we talk about "computer memory."
    - C++ gives us a variety of fundamental ways to access computer hardware from our code.

Why is computer memory important?

- We've already seen the power and importance of being able to **dynamically allocate arrays** and use these as **data storage foundations** for ADT classes.

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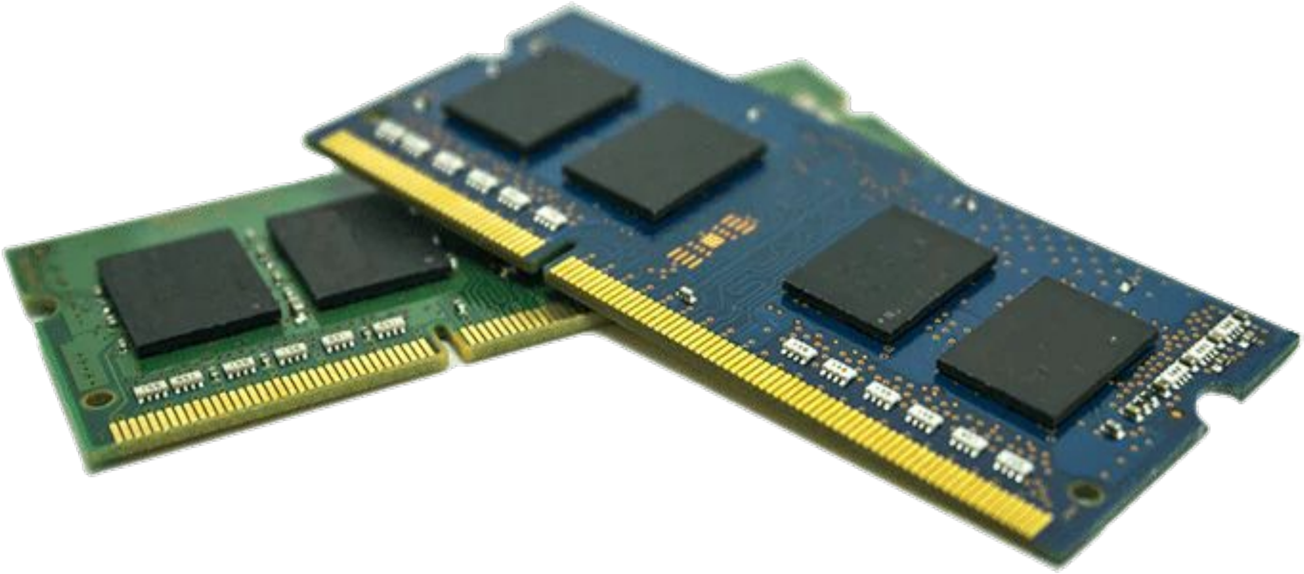
- Being able to directly work with computer memory opens up the doors to even more interesting data storage and organization techniques (beyond arrays).

- After today's lecture, we'll spend the next two weeks talking about **linked data structures**, which are a powerful, alternative way to impose structure and meaning on data that is scattered over different places in computer memory.
    - In order to understand linked data structures, we first need to develop our toolbox of working directly with computer memory in C++!

How is computer memory organized?

- Let's build a mental model of how data is organized in computer memory.



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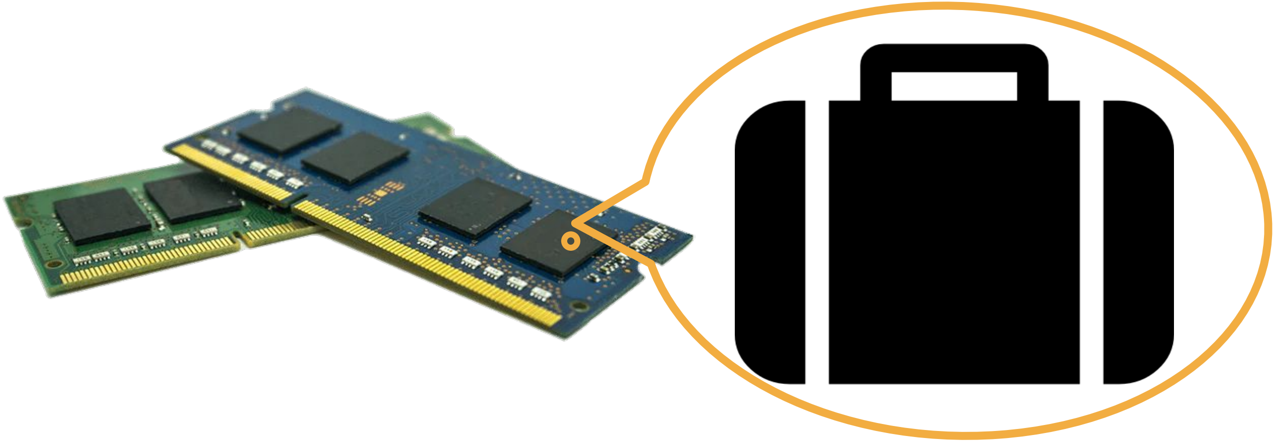

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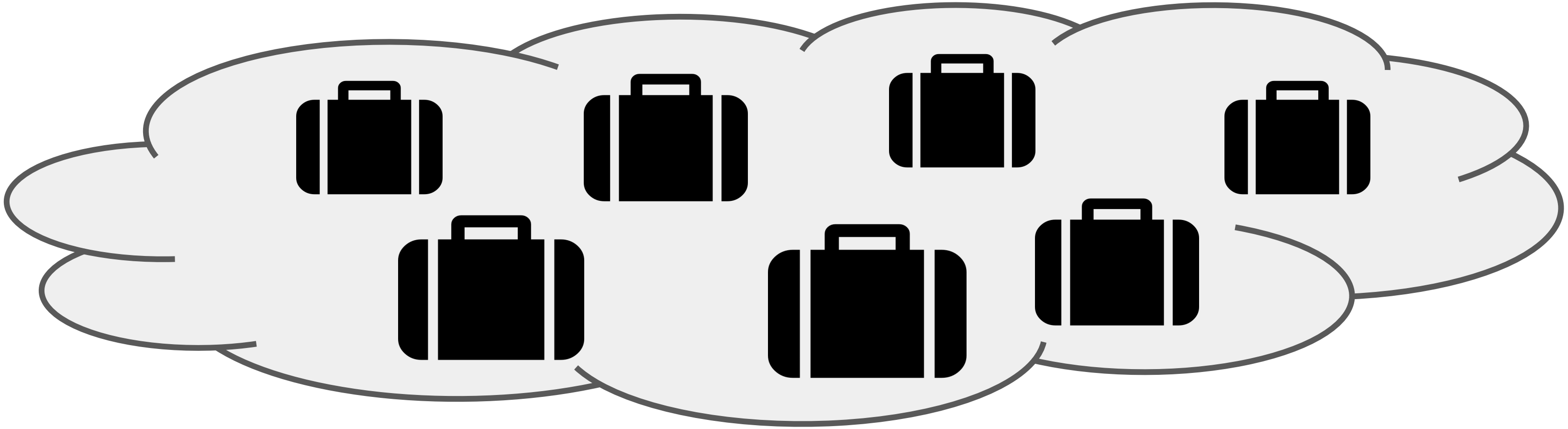

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  - **Key Idea:** Each box can be located using the computer's internal organization system, in which each box has an associated numerical location, called a **memory address**.
    - Just like a normal address, this value tells us where the box is located!

Memory Addresses

```
string pet = "cat";
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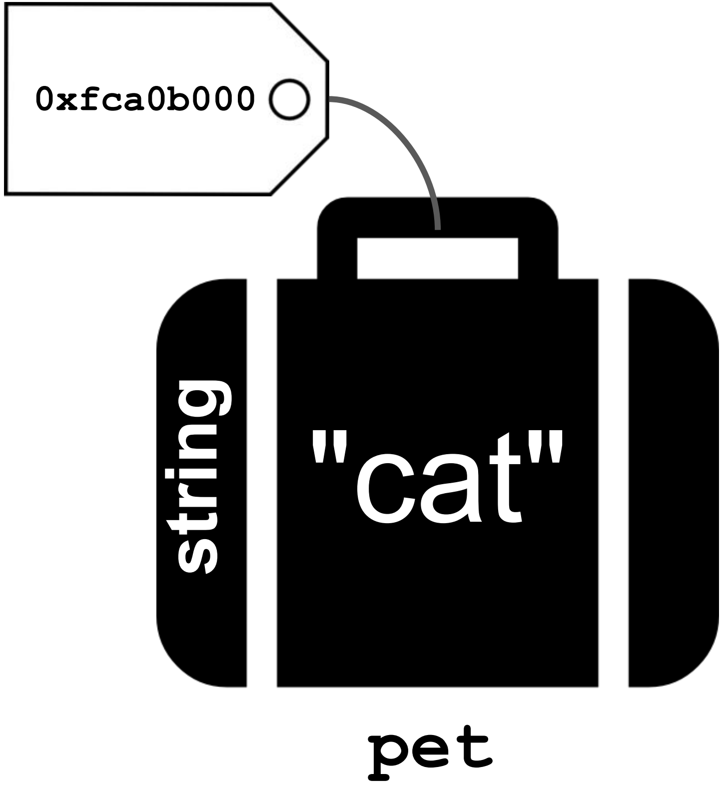

Memory Addresses

```
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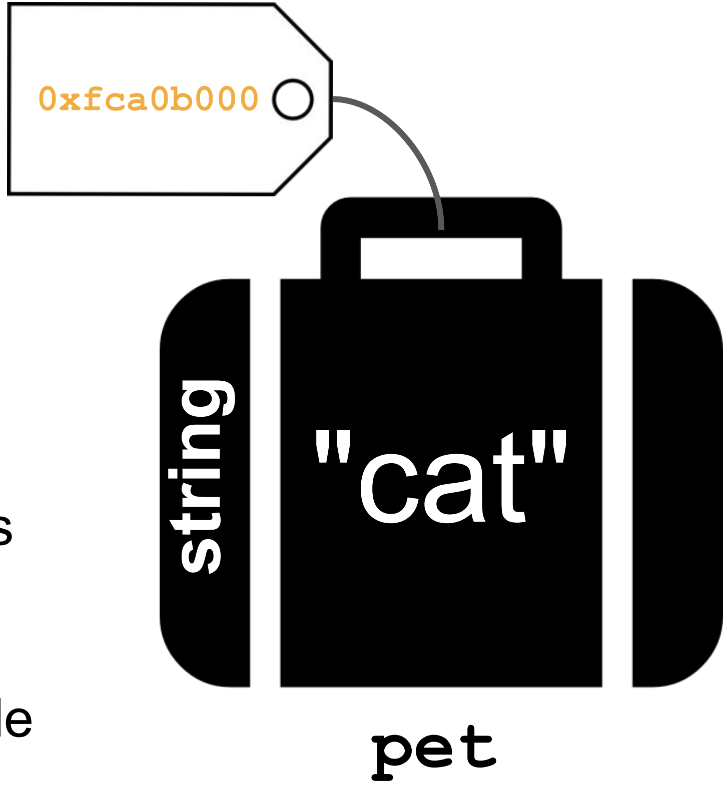
```

The **memory address** of `pet` is `0xfca0b000`. This special numerical value acts as the unique identifier for this variable across the entire pool of the computer's memory.



Memory Addresses

```
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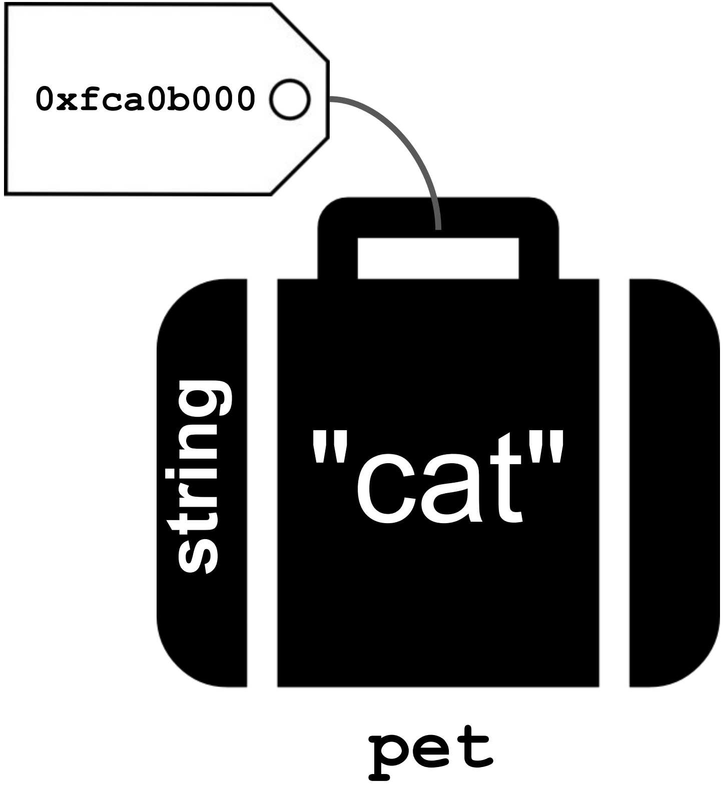
```

How is this value determined?

The computer (operating system) determines the address, not you!



Memory Addresses

```
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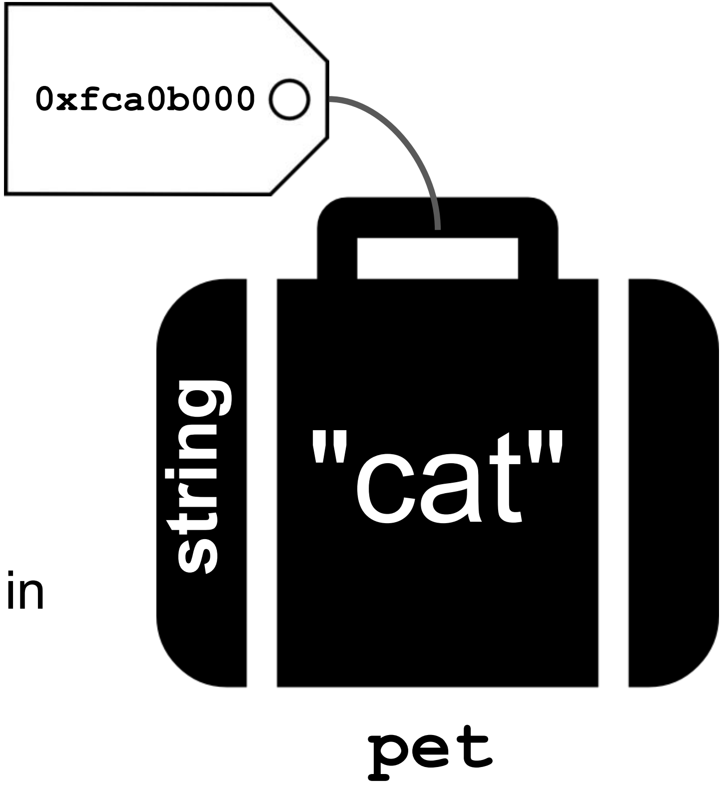
```

Is that really a number? Why is preceded by `0x` and have letters in it?

Let's talk (briefly) about **hexadecimal**!



The Hexadecimal Number System

- Normally, we represent numbers using the decimal (base-10) number system.
  - Each place value represents a factor of ten (ones, tens, hundreds, etc.) and there are 10 digits.

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- In computer systems, there a number of factors that make it more convenient to express numbers using the **hexadecimal (base-16) number system**.
  - Each place value represents a factor of 16 (16^0, 16^1, 16^2, etc.) and there are 16 "digits."
  - Since there are only 10 numerical digits (0-9), this system also uses the letters a to f as "digits."
  - `0 1 2 3 4 5 6 7 8 9 a(10) b(11) c(12) d(13) e(14) f(15)`

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The Hexadecimal Number System

- Normally, we represent numbers using the decimal (base-10) number system.
- In computer systems, there a number of factors that make it more convenient to express numbers using the **hexadecimal (base-16) number system**.
- The prefix `0x` is used to communicate that a number is being expressed in hexadecimal.
- In the end, remember that the specific address values have no special meaning to us, since they're always generated by the computer. This is mostly just a fun aside!

Memory Organization Summary

- Every location in memory, and therefore every variable, has an **address**.
- Every address corresponds to a **unique location in memory**.
- The computer generates/knows the address of every variable in your program.
- Given a memory address, the computer can find out what value is stored at that location.

How can we actually work with memory addresses in C++ to read and manipulate computer memory?

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How can we actually work with memory addresses in C++ to read and manipulate computer memory?

Pointers!

Announcements

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- Assignment 4 is due this upcoming **Tuesday, July 27 at 11:59pm PDT.**

- Diagnostic grades were released earlier today. Overall, we think people are meeting the learning goals of the class!
    - Common diagnostic questions: What letter grade did I get? Is it curved?
        - We don't want you to think about this as an exam! There won't be a curve so you can think of the 63 total points as making up the 15% of your overall grade. There will be a curve applied to your overall grade at the end of the quarter.
    - Regrade requests are now open through Gradescope and must be submitted by **Monday, July 26 at 11:59pm**.
        - These requests should only be submitted if you think the posted criteria has been misapplied to your submission, **not** if you think the criteria are unfair.

How can we navigate and directly manipulate computer memory in C++?

Pointers!

Pointers

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- Just like all other data types, pointers take up space in memory and store specific values.

- **A pointer always stores a memory address**, telling us where in the computer's memory to look for a certain value.

- In doing this, they quite literally "point" to another location on your computer.

What is a pointer?

A memory address!

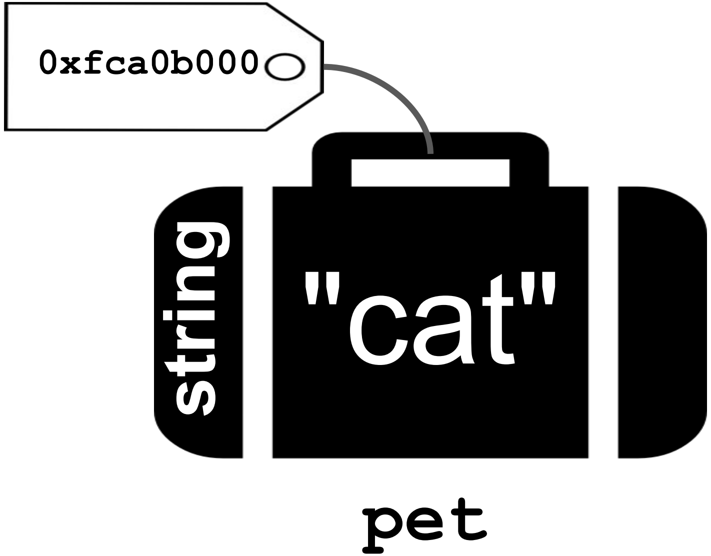
Moving Beyond Arrays

- We've already worked with pointers in the context of dynamically allocated arrays.

- However, pointers can be used to do so much more!

Introduction to Pointers

```
string pet = "cat";
```



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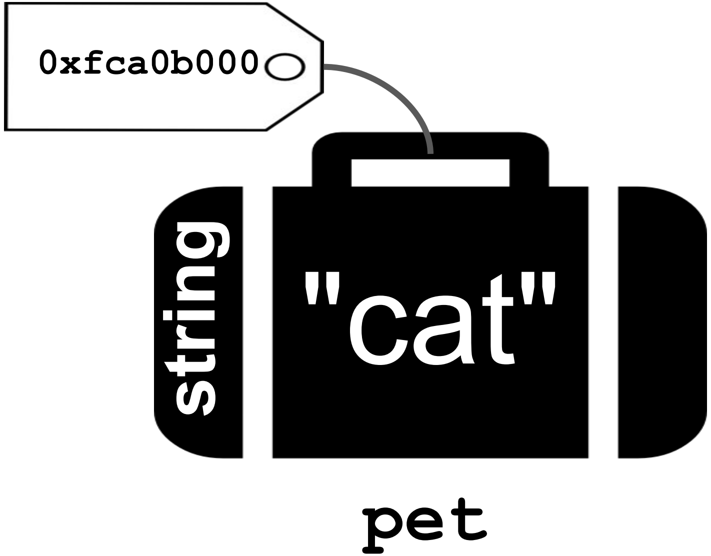
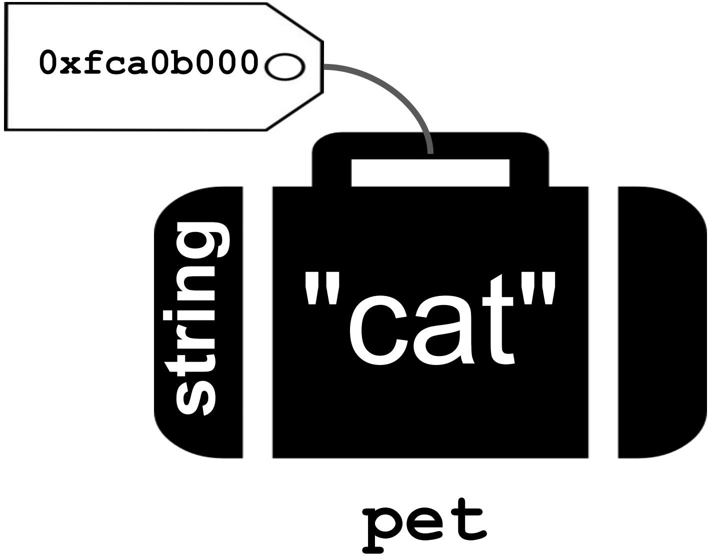



```
string pet = "cat";

string* petPointer = addressOf(pet);
```

Introduction to Pointers

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This “function" doesn't really exist but we'll resolve that soon enough!

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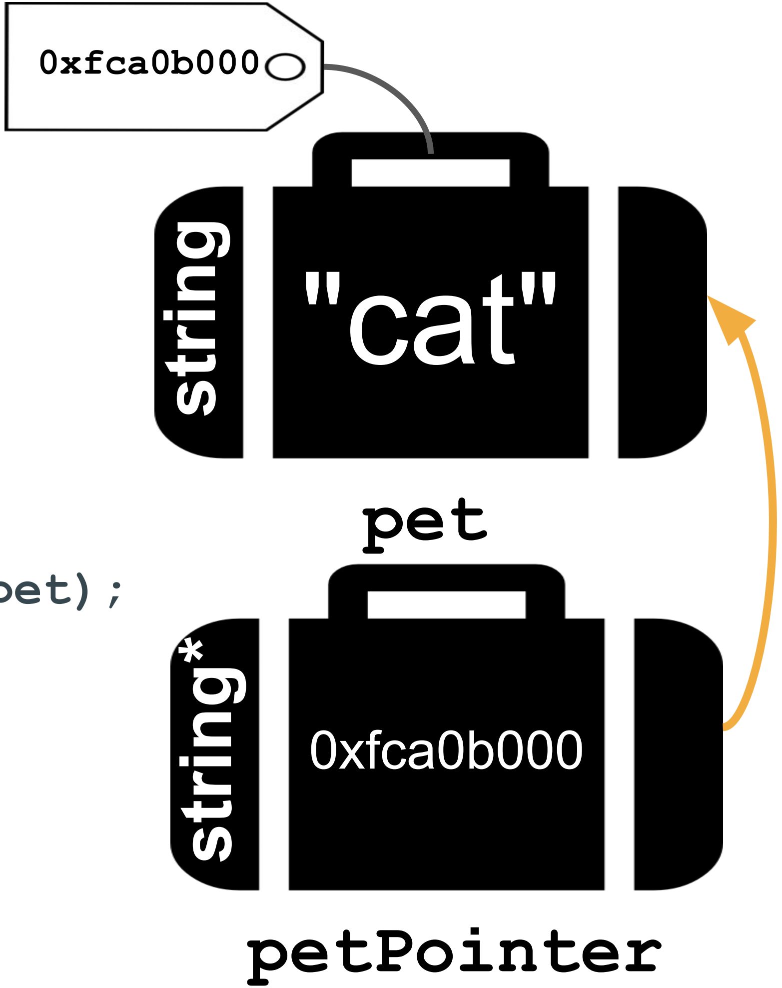

We generally use an arrow to “point" from a pointer to the variable it points to.

Introduction to Pointers

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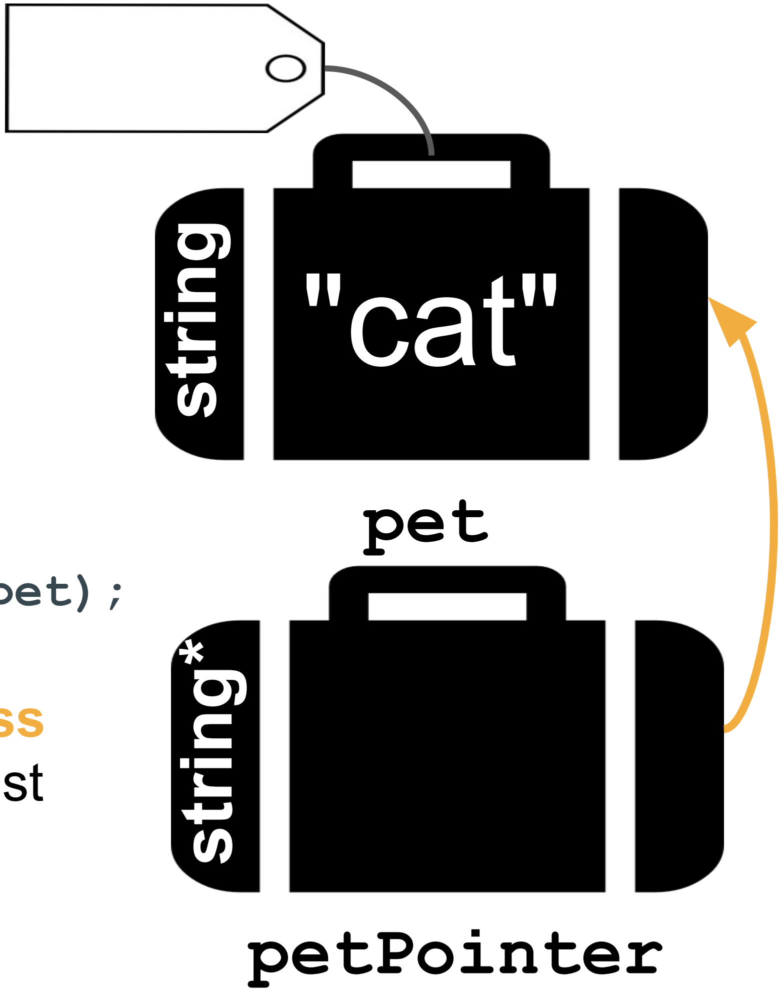
In fact, **the specific memory address values don't actually matter.** It is just the associated pointer/pointee relationship we care about.



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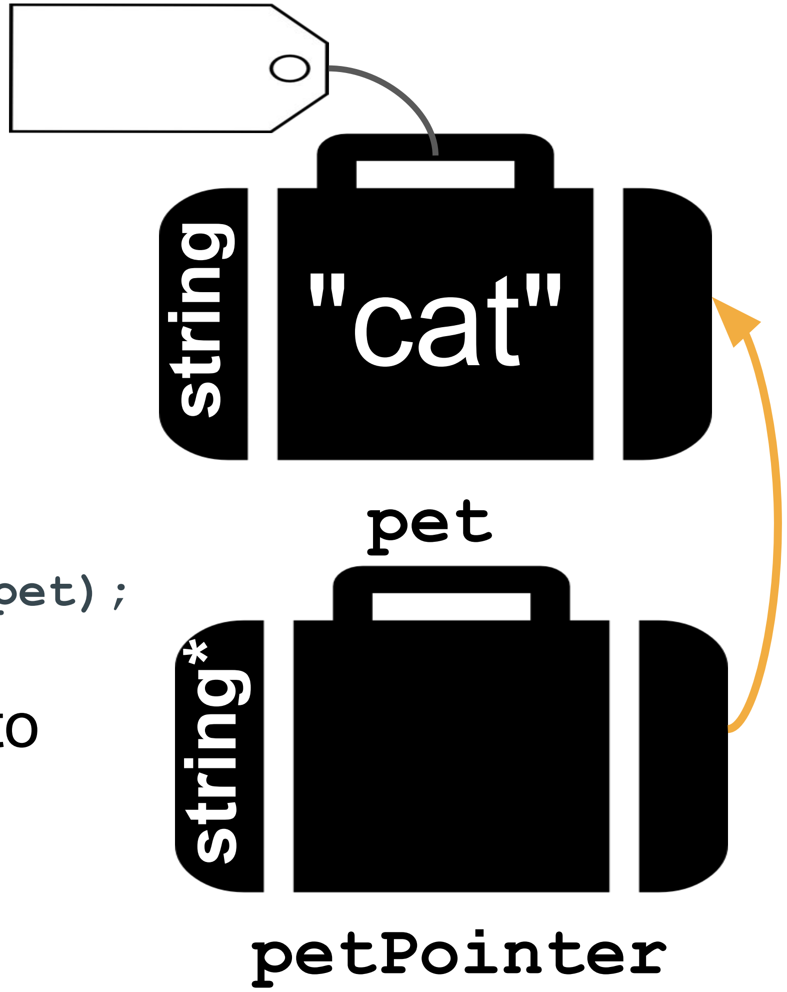
This visual relationship is key to understanding pointers. **The best way to learn pointers is to draw lots of pictures!**



Pointer Syntax

Pointer Syntax

- Pointer syntax can get really tricky! Our goal in this class is to give you a brief, holistic overview. To truly become a master of pointers, take a Computer Organization and Systems course.

- Let's talk about 4 main components of pointer syntax.

Pointer Syntax (Part 1)

- To declare a pointer of a particular type, use the * **(asterisk)** symbol:

```
string* petPtr;   // declare a pointer to a string
int* agePtr;      // declare a pointer to an int
char* letterPtr; // declare a pointer to a char
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- **Important Note:** The type for `petPtr` is `string*` and not `string`. **A pointer type is distinct from the pointee type.**

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- Note: This is **not** the same as using a reference parameter. Same symbol but very different meanings! Oh C++...

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- Note: This is **not** the same as using a reference parameter. Same symbol but very different meanings! Oh C++...
- By the way: **you should never need to do this in code you write in CS106B!** You'll use it more in a Computer Organization and Systems course, but if you find yourself using it in this class, reconsider your reason for using it.

Pointer Syntax (Part 3)

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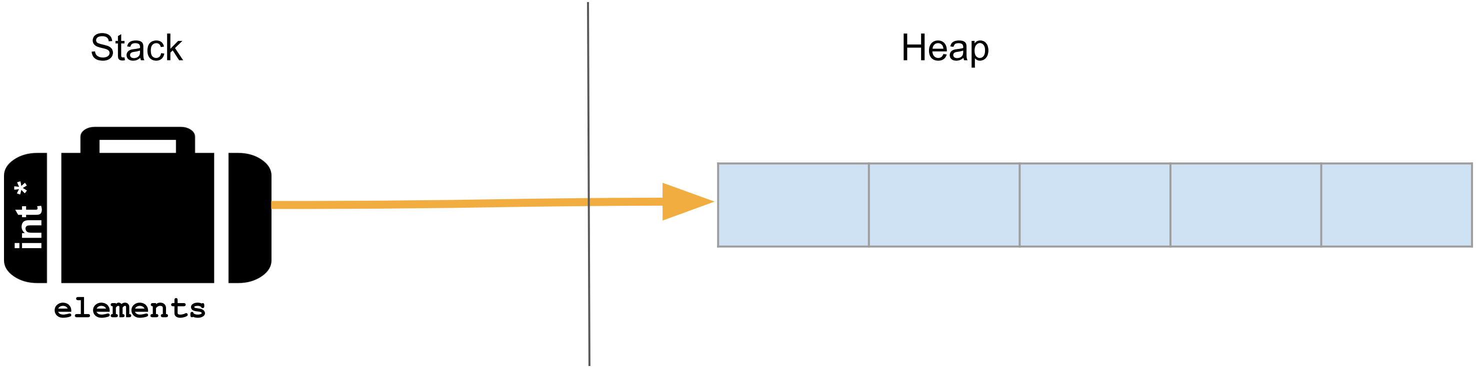

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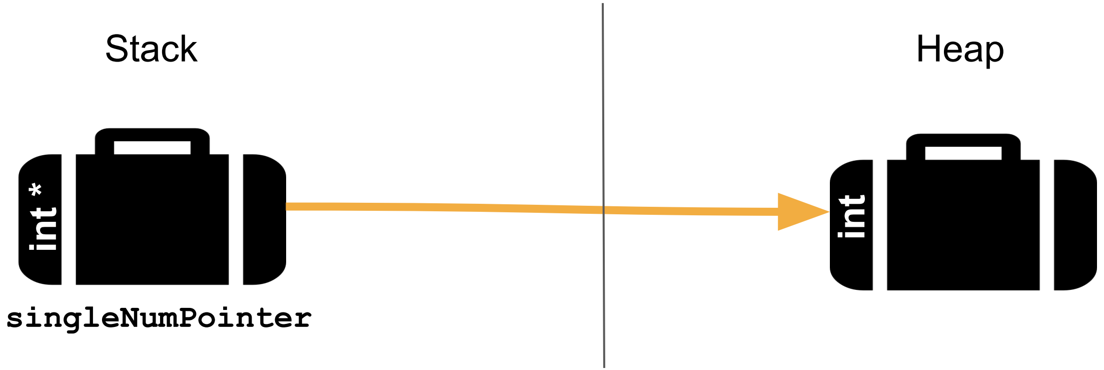

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```
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- The usefulness of this will become apparent starting tomorrow when we start our discussion of linked data structures.

2 Versions of **Delete**

- If you allocate memory using the `new[]` operator (e.g. `new int[137]`), you have to free it using the `delete[]` operator.

```
delete[] ptr;
```

- If you allocate memory using the `new` operator (e.g. `new int`), you have to free it using the `delete` operator.

```
delete ptr;
```

- **Make sure to use the proper deletion operation.** Mixing these up leads to bad, undefined behavior!

Pointer Syntax (Part 4)

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string* petPtr;
string pet = "cat";
petPtr = &pet;
cout << *petPtr << endl;
```

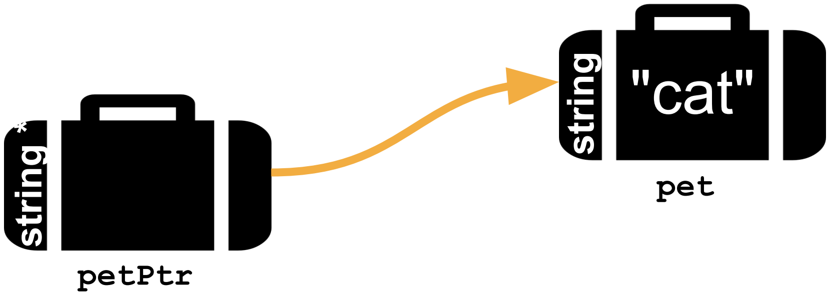

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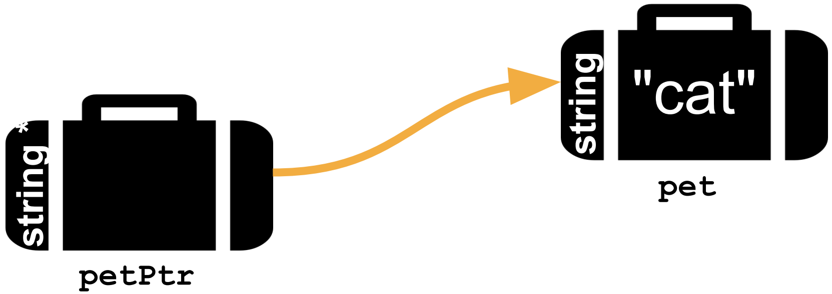
petPtr = &pet;
cout << *petPtr << endl;
*petPtr = "dog";
```



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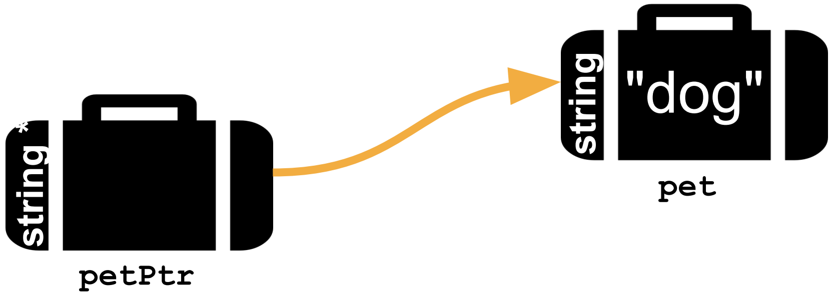

Pointer Tips

Pointer Tips

- Working with pointers and direct memory access can be very tricky!
- You must always be hyper-vigilant about what is pointing where and what pointers are valid before trying to dereference them.
- Here's a couple helpful tips to keep in mind when working with pointers...

Pointer Tips (Part 1)

- What do we do if we want to declare/initialize a pointer variable but we don't yet have anything to point it at?

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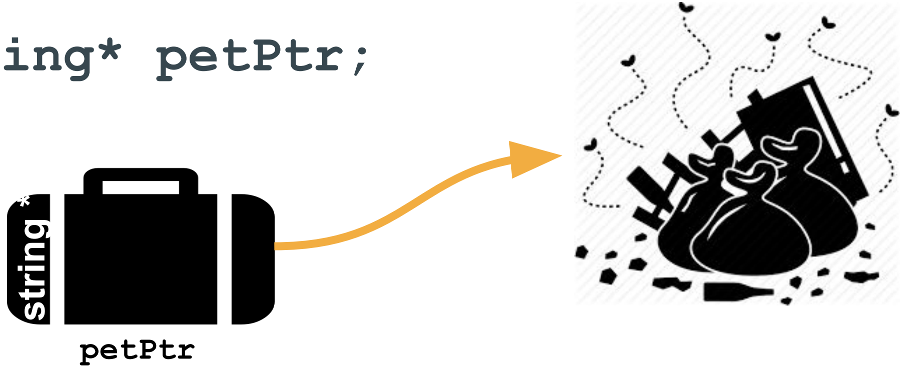

This is dangerous
and unpredictable!

Pointer Tips (Part 1)

- What do we do if we want to declare/initialize a pointer variable but we don't yet have anything to point it at?

- To ensure that we can tell if a pointer has a valid address or not, set your declared pointer equal to the special value **`nullptr`**, which means "no valid address."

Pointer Tips (Part 1)

- What do we do if we want to declare/initialize a pointer variable but we don't yet have anything to point it at?

- To ensure that we can tell if a pointer has a valid address or not, set your declared pointer equal to the special value **`nullptr`**, which means "no valid address."

```
string* petPtr = nullptr;
```

This allows for safe, consistent behavior. No arrow means no valid address.

Pointer Tips (Part 2)

- How can we tell if a pointer is safe to use (dereference)?

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- If you are unsure if your pointer holds a valid address, you should check for **`nullptr`**!

Pointer Tips (Part 2)

- How can we tell if a pointer is safe to use (dereference)?

- If you are unsure if your pointer holds a valid address, you should check for **`nullptr`**!

```
void printPetName(string* petPtr) {
    if (petPtr != nullptr) {
        cout << *petPtr << endl; // prints out the value pointed to by petPtr
                                 // if it is not nullptr
    } else {
        cout << "petPtr is not valid!" << endl;
    }
}
```

Positively Practical Pointer Practice

Getting Practice with Pointers

- The little boxes (suitcases) and arrows that we draw to show the state of the memory are so, so important to understanding what is happening.

- **Always draw box and arrow diagrams when working with pointers!**

- As with most things, the best way to build an understanding of pointers is to practice, practice, practice!
    - The published code project for today has a bunch of pointer examples. We strongly recommend reading the code, predicting the output, and then running the code to confirm your predictions!
    - To finish off lecture today, we'll work through a couple of the examples together, building up diagrams as we go.

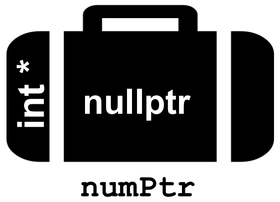
Pointer Practice (Part 1)

```
int* numPtr = nullptr;
```

Pointer Practice (Part 1)

```
int* numPtr = nullptr;

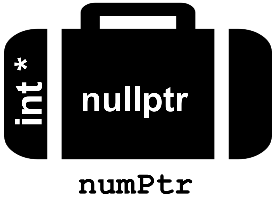
int num = 106;
```

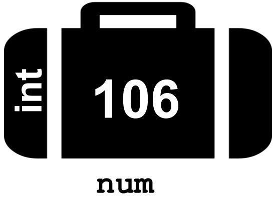


Pointer Practice (Part 1)

```
int* numPtr = nullptr;

int num = 106;
```



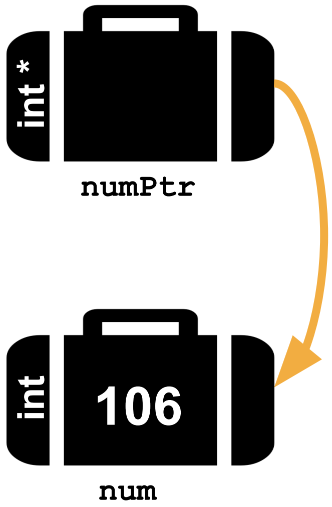


Pointer Practice (Part 1)

```
int* numPtr = nullptr;

int num = 106;

numPtr = &num;
```



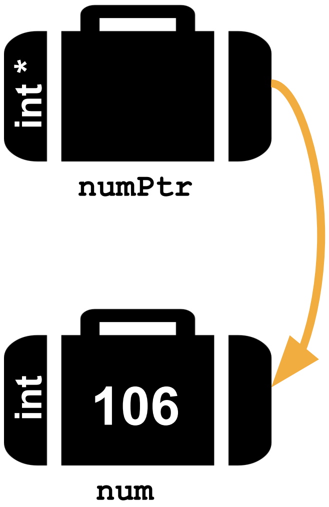
Pointer Practice (Part 1)

```
int* numPtr = nullptr;

int num = 106;

numPtr = &num;
```

At this point, we say that **`numPtr`** “points to" **`num`**



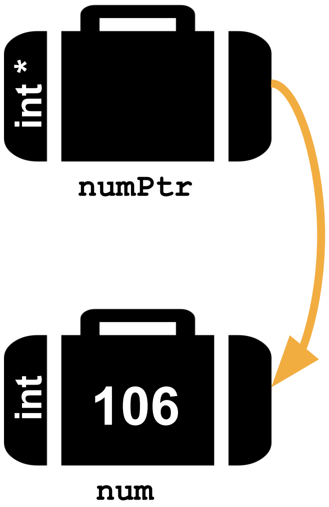
Pointer Practice (Part 1)

```
int* numPtr = nullptr;

int num = 106;

numPtr = &num;

cout << *numPtr << end;
```



Pointer Practice (Part 1)

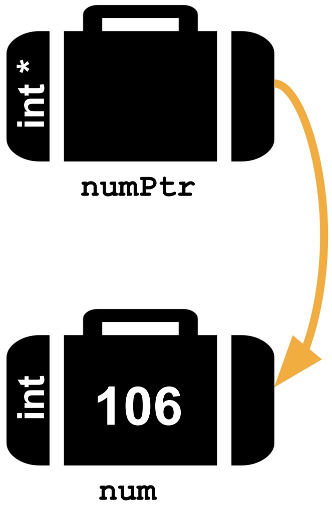
```
int* numPtr = nullptr;

int num = 106;

numPtr = &num;

cout << *numPtr << end;   // 106
```

By dereferencing `numPtr` we can print out the value of the variable that it points to.



Pointer Practice (Part 1)

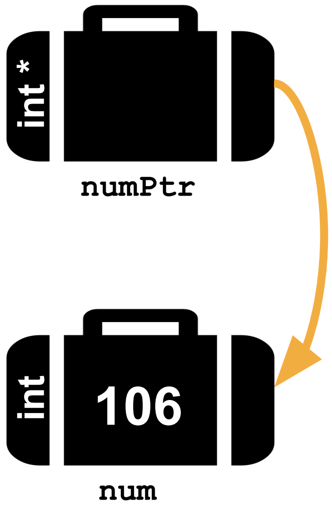
```
int* numPtr = nullptr;

int num = 106;

numPtr = &num;

cout << *numPtr << end;

*numPtr = 198;
```



Pointer Practice (Part 1)

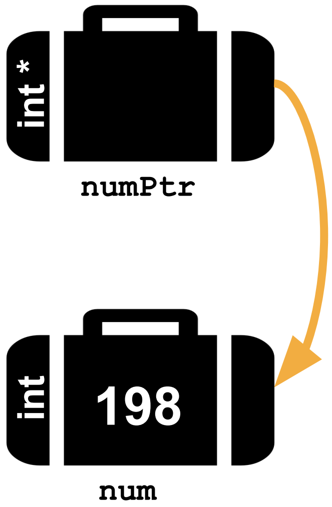
```
int* numPtr = nullptr;

int num = 106;

numPtr = &num;

cout << *numPtr << end;

*numPtr = 198;
```



Pointer Practice (Part 1)

```
int* numPtr = nullptr;

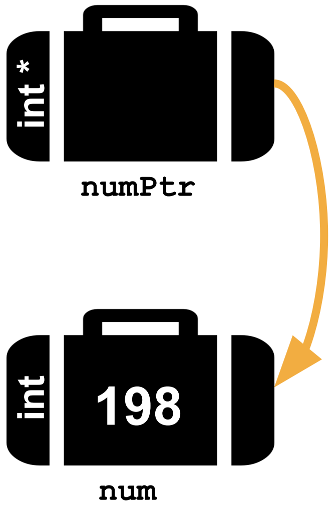
int num = 106;

numPtr = &num;

cout << *numPtr << end;

*numPtr = 198;
```

Dereferencing **numPtr** can also allow us to modify the value of the variable/memory it points to.



Pointer Practice (Part 2)

- What is the output of the following code snippet? (Zoom Poll)

```
string* stringPtr = nullptr;
string s = "hello";
cout << *stringPtr << endl;
```

Console

```
***
*** STANFORD C++ LIBRARY
*** A segmentation fault (SIGSEGV) occurred during program execution.
*** This typically happens when you try to dereference a pointer
*** that is NULL or invalid.
***
*** Stack trace (line numbers are approximate):
*** string:1500                 string::__get_pointer() const
*** string:1228                 string::data() const
*** ostream:1047                ostream& operator<<(ostream&, const string&)
*** pointers.cpp:33  main()
***
*** To learn more about the crash, we strongly
*** suggest running your program under the debugger.
```

Pointer Practice (Part 2)

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string* stringPtr = nullptr;
string s = "hello";
cout << *stringPtr << endl;
```

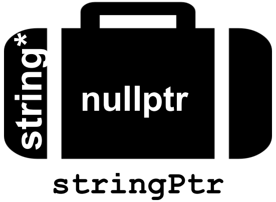

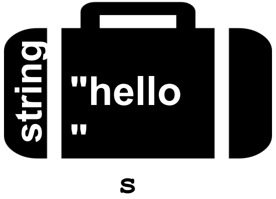

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When you dereference a `nullptr`, you encounter a **segmentation fault**, and the program crashes!

Pointer Practice (Part 2)

- What is the output of the following code snippet? (Zoom Poll)

```
string* stringPtr = nullptr;
string s = "hello";
cout << *stringPtr << endl;
```

Takeaway: Always use a nullptr check before dereferencing a pointer.

s

Pointer Practice (Part 3)

- What is the output of the following snippet of code? (Zoom Poll)

```
string* strPtr1 = nullptr;
string* strPtr2 = nullptr;

string s = "hello";
strPtr1 = &s;
strPtr2 = strPtr1;

*strPtr1 = "goodbye";

cout << *strPtr1 << " "
     << *strPtr2 << endl;
```

Pointer Practice (Part 3)

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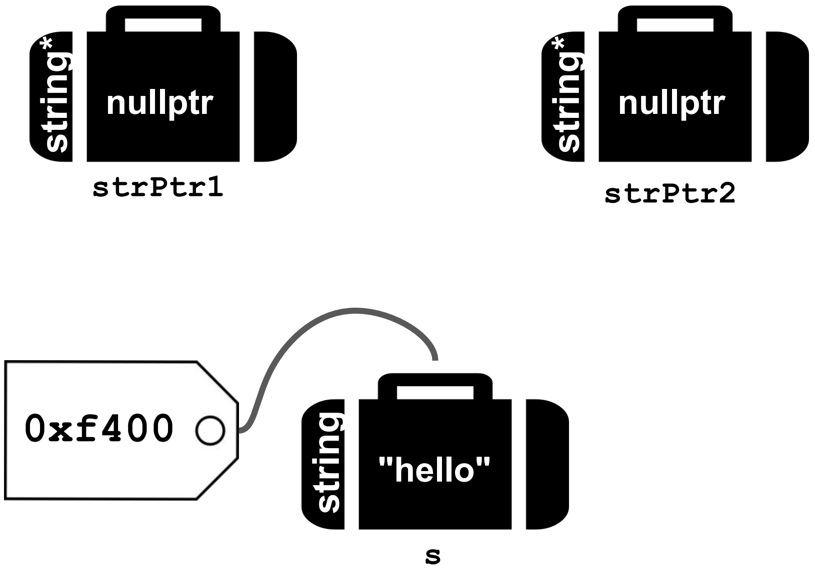

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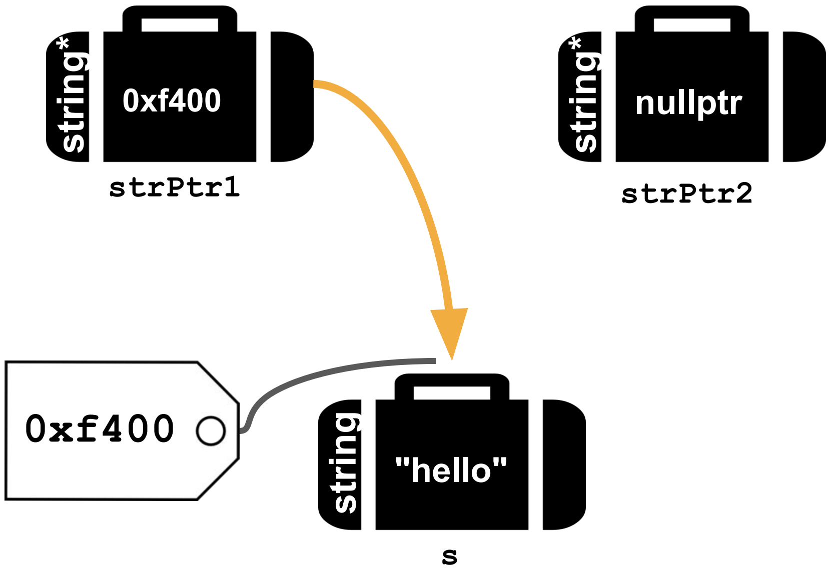

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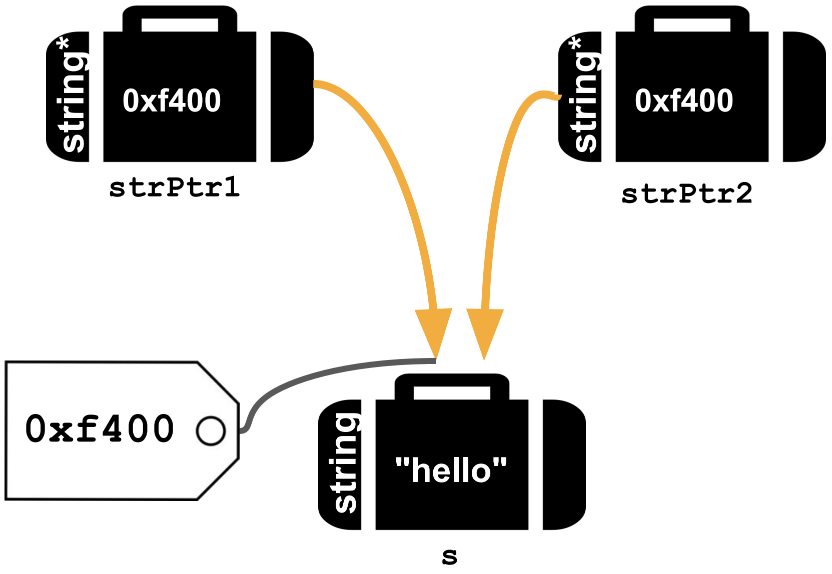

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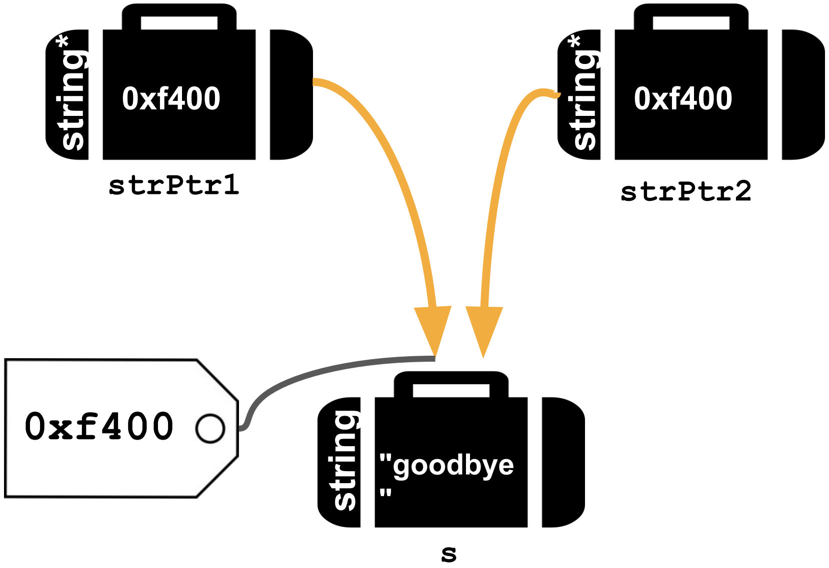

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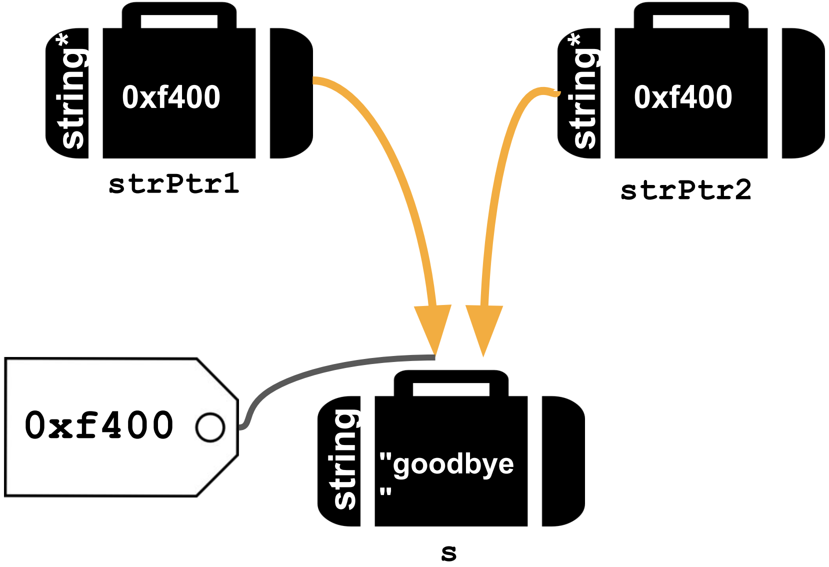



```
goodbye goodbye
```

Summary

Memory and Pointers

- All variables in a computer program are stored in **computer memory** and can each be uniquely identified by their numerical **memory address**.

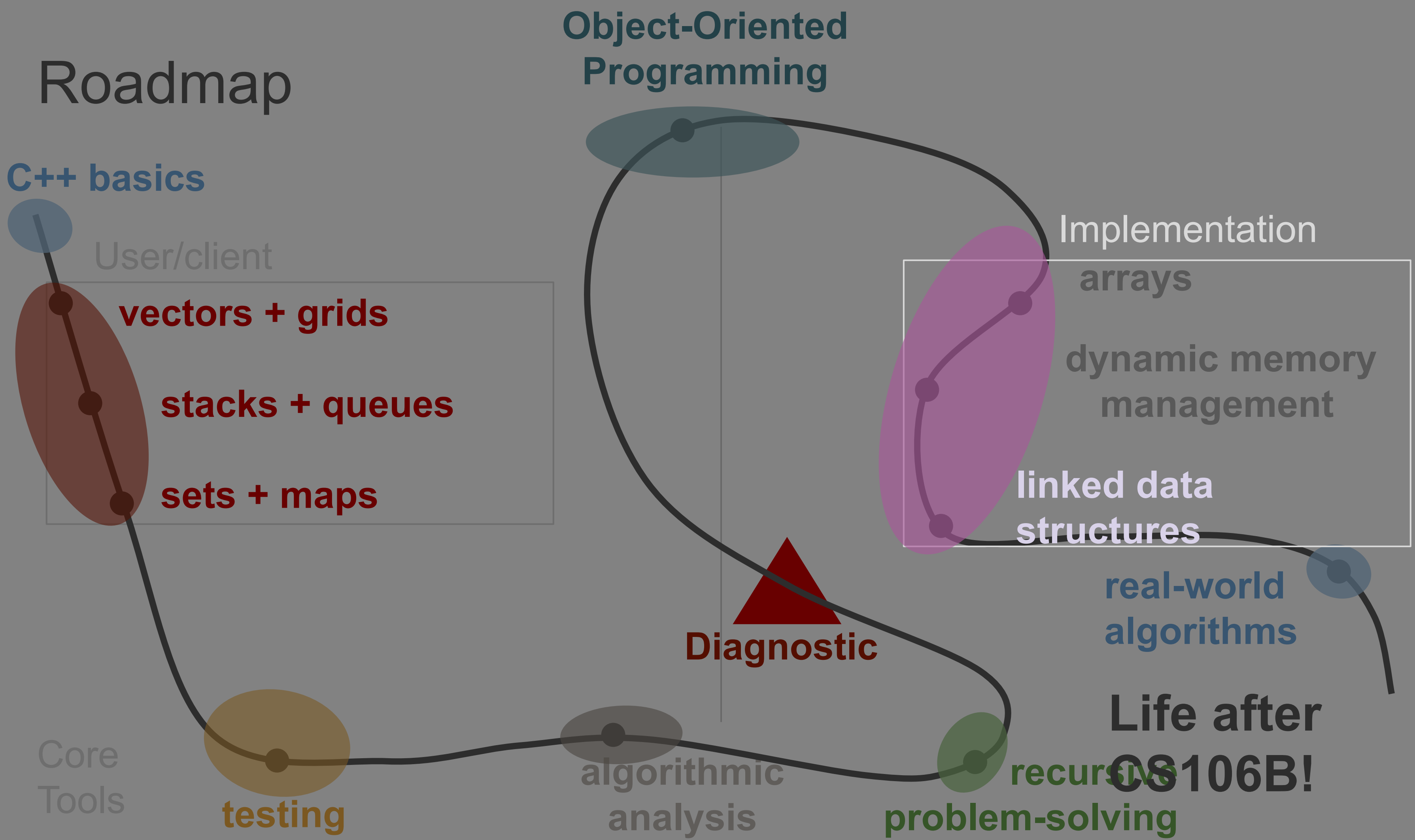
- **Pointers** are a special type of variable that store memory addresses.

- Pointers are especially useful as a tool to store the location of dynamically allocated memory (both arrays and individual elements) acquired with `new`

- The **dereference operator** allows us to access and modify the memory pointed to by a pointer.

What’s next?

Roadmap



Object-Oriented Programming
C++ basics
User/client
vectors + grids
stacks + queues
sets + maps
Implementation
arrays
dynamic memory management
linked data structures
real-world algorithms
Diagnostic
Life after CS106B!
Core Tools
testing
algorithmic analysis
recursive problem-solving

Introduction to Linked Lists