

Implementing an ADT

**What is one area of strength that you identified as a
takeaway from completing the diagnostic?
(put your answers the chat)**



Roadmap

C++ basics

User/client

vectors + grids

stacks + queues

sets + maps

Core
Tools

testing

Object-Oriented Programming

Implementation

arrays

**dynamic memory
management**

linked data structures

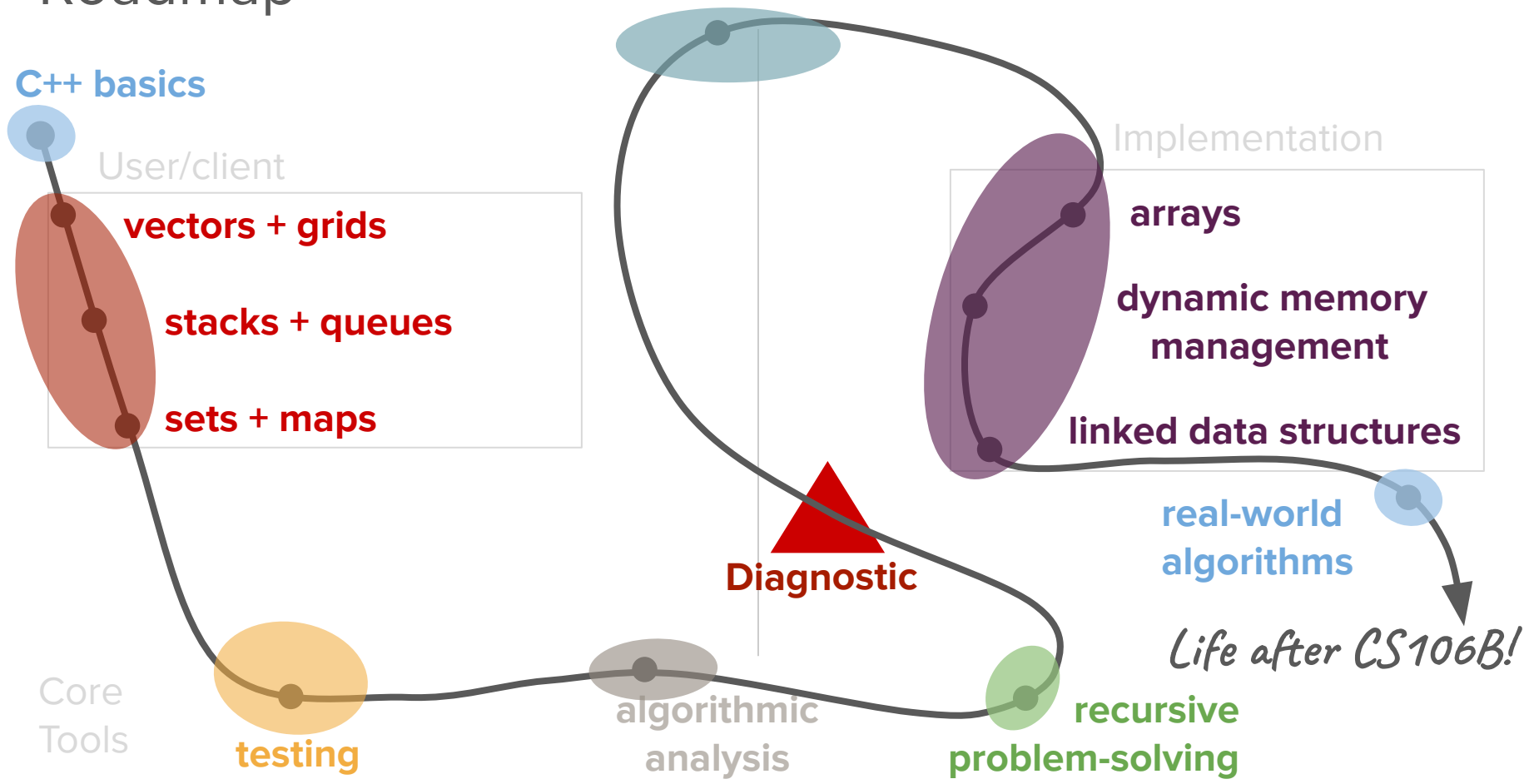
**real-world
algorithms**

Life after CS106B!

Diagnostic

**algorithmic
analysis**

**recursive
problem-solving**



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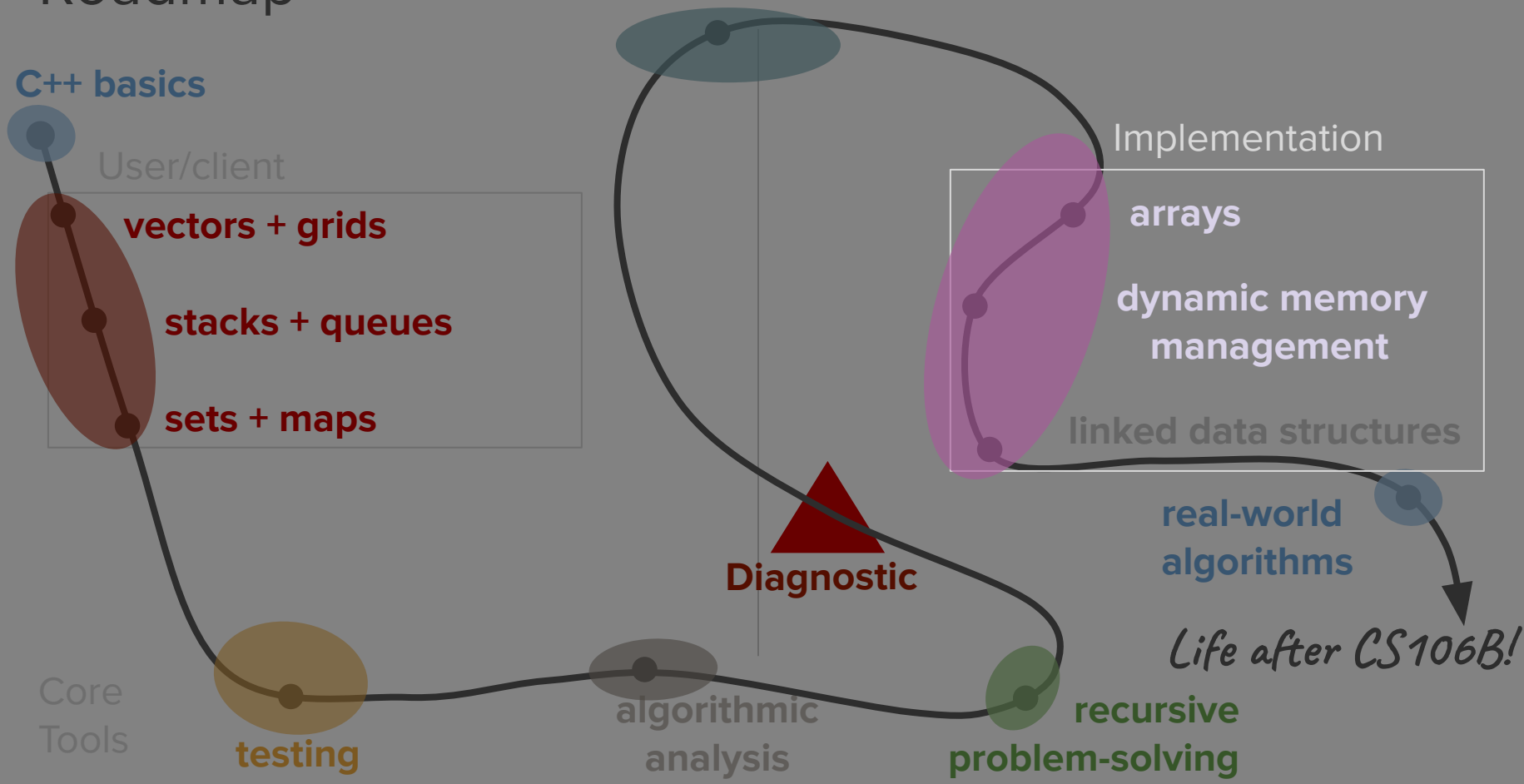
Diagnostic

Core
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Today's question

How can we use
fundamental data storage
capabilities in C++ to
implement an ADT class?



Today's topics

1. Review
2. Designing OurVector
3. Visualizing OurVector Operations
4. Implementing OurVector



Review

[arrays and dynamic memory management]



Acquiring and Using Storage Space

- Low-level storage space in C++ is acquired using **dynamic memory allocation**.
- Dynamic memory allocation normally has three steps:
 - You can, at runtime, ask for extra storage space, which C++ will give to you.
 - You can use that storage space however you'd like.
 - You have to explicitly tell the language when you're done using the memory.

Arrays

- Storage space on computers, which we often refer to as memory, is allocated in organized chunks called **arrays**
- An array is a contiguous chunk of space in the computer's memory, split into slots, each of which can contain one piece of information
 - Contiguous means that each slot is located directly next to the others. There are no "gaps".
 - All arrays have a specific type. Their type dictates what information can be held in each slot.
 - Each slot has an "index" by which we can refer to it.



Index: 0 1 2 3 4 5 6

Dynamically Allocating Arrays

- First, declare a variable that will point at the newly-allocated array. If the array elements have type **T**, the pointer will have type **T***.
 - e.g. `int*`, `string*`, `Vector<double>*`
- Then, create a new array with the **new** keyword and assign the pointer to point to it.
- In two separate steps:

```
T* arr;  
arr = new T[size];
```

- Or, in the same line:

```
T* arr = new T[size];
```



Pointers

- A pointer is a brand new data type that becomes very prominent when working with dynamically allocated memory.
- Just like all other data types, pointers take up space in memory and can store specific values.
- The meaning of these values is what's important. **A pointer always stores a memory address**, which is like the specific coordinates of where a piece of memory exists on the computer.
- Thus, they quite literally "point" to another location on your computer.

Properties of Dynamically Allocating Arrays

- The array you get from `new[]` is **fixed-size**: it can neither grow nor shrink once it's created.
 - The programmer's version of "conservation of mass."
- The array you get from `new[]` has **no bounds-checking**. Walking off the beginning or end of an array triggers *undefined behavior*.
 - Literally anything can happen: you read back garbage, you crash your program, you let a hacker take over your computer, etc...
- The array you get from the `new[]` keyword comes from an area of memory called the heap



Memory from the Stack vs. Heap

`Vector<string> varOnStack;`

- So far, all variables we've created get defined on the **stack**
- This is called static memory allocation
- Variables on the stack are stored directly to the memory and access to this memory is very fast
- We don't have to worry about memory management

`string* arr = new string[numValues];`

- We can now request memory from the **heap**
- This is called dynamic memory allocation
- We have more control over variables on the heap
- But this means that we also have to handle the memory we're using carefully and properly clean it up when done



Final Takeaways

- You can create arrays of a fixed size at runtime by using **new []**.
- C++ arrays don't know their lengths and have no bounds-checking. With great power comes great responsibility.
- You are responsible for freeing any memory you explicitly allocate by calling **delete []**. Otherwise your program will have memory leaks.
- Once you've deleted the memory pointed at by a pointer, you have a dangling pointer and shouldn't read or write from it.



How can we use fundamental data storage capabilities in C++ to implement an ADT class?

Arrays vs. Vectors

- Notice that we access the elements of an array just like we access them in a Vector, with square brackets.
- **BUT arrays are not objects** – they don't have any functions associated with them.
- So, you can't do this:

```
int* firstTen = new int[10];  
int len = firstTen.length(); // ERROR! No functions!  
firstTen.add(42); // ERROR! No functions!  
firstTen[10] = 42; // ERROR! Buffer overflow!
```



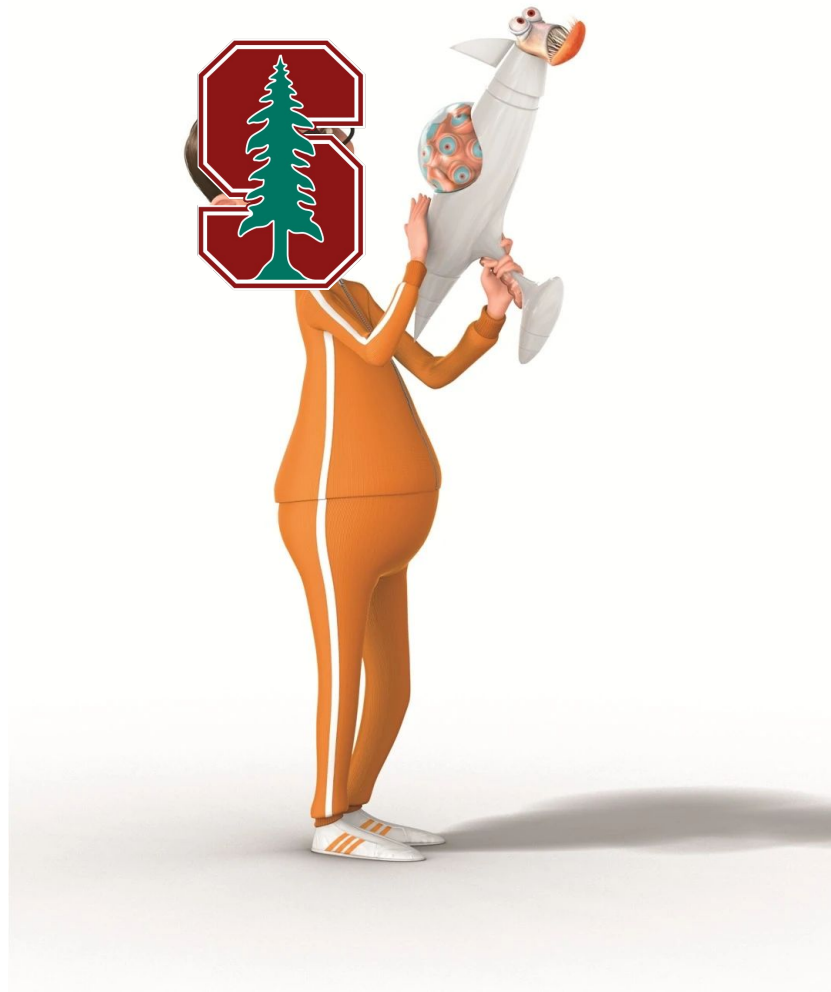
Arrays vs. Vectors

- Arrays are a very necessary tool to use if we want to actually store information in a structured way in a program.
- Vectors are a great abstraction, providing helpful methods and a clean interface that other programmers can use to solve interesting problems.
- **Idea:** Let's use a dynamically allocated array as the underlying method of data storage for a Vector class. Best of both worlds!



Designing OurVector







What is **OurVector**?

- Goal: Let's make our very own version of the Stanford C++ Vector that we've been using all quarter long.
 - It all will feel so much cooler when we've built it ourselves!
- Scope Constraints (aka "You've Gotta Start Somewhere"):
 - We will only implement a subset of the functionality that the Stanford Vector provides.
 - **OurVector** will **only store integers** and will not be configurable to store other types
 - 通用 Generic, or 模版类 "templated" class, that allow the client to specify the data type that is stored are possible in C++, but are beyond the scope of this class
 - At first, **OurVector** will be limited to **storing a fixed number of elements**, but we will 解除 lift this restriction by the end of class. For now, if we run out space we'll just throw an error.



How do we design a class?

We must specify the 3 parts:

1. Member functions: *What functions can you call on a variable of this type?*
2. Member variables: *What subvariables make up this new variable type?*
3. Constructor: *What happens when you make a new instance of this type?*



How do we design **OurVector**?

We must answer the following three questions:

1. Member functions: *What public interface should **OurVector** support? What functions might a client want to call?*
2. Member variables: *What private information will we need to store in order to keep track of the data stored in **OurVector**?*
3. Constructor: *How are the member variables initialized when a new instance of **OurVector** is created?*



How do we design **OurVector**?

We must answer the following three questions:

1. **Member functions:** *What public interface should **OurVector** support? What functions might a client want to call?*
2. **Member variables:** *What private information will we need to store in order to keep track of the data stored in **OurVector**?*
3. **Constructor:** *How are the member variables initialized when a new instance of **OurVector** is created?*

OurVector Public Interface

These methods should all look very familiar.
We've been using them all quarter long!

```
class OurVector {  
public:  
    OurVector();  
  
    void add(int value);  
    void insert(int index, int value);  
    int get(int index);  
    void remove(int index);  
    int size();  
    bool isEmpty();  
  
private:  
    /* To be defined soon! */  
};
```

We'll use the get method to
模仿 emulate the functionality of
the [] operator.



OurVector Public Interface

```
class OurVector {  
public:  
    OurVector();  
  
    void add(int value);  
    void insert(int index, int value);  
    int get(int index);  
    void remove(int index);  
    int size();  
    bool isEmpty();  
  
private:  
    /* To be defined soon! */  
};
```



*What should go
here?*

How do we design **OurVector**?

We must answer the following three questions:

1. Member functions: *What public interface should **OurVector** support? What functions might a client want to call?*
2. **Member variables: What private information will we need to store in order to keep track of the data stored in **OurVector**?**
3. Constructor: *How are the member variables initialized when a new instance of **OurVector** is created?*



Breakout Activity:

OurVector class design

OurVector Member Variables

- `int* elements;`
 - A pointer to an array of integers, which will act as our underlying data storage mechanism.
- `int allocatedCapacity;`
 - An integer that stores the size of the allocated elements array. Remember, arrays don't have any conception/knowledge of their own size, so we must manually track this!
- `int numItems;`
 - An integer that stores the number of elements currently stored in the vector.



OurVector Header File

```
class OurVector {
public:
    OurVector();

    void add(int value);
    void insert(int index, int value);
    int get(int index);
    void remove(int index);
    int size();
    bool isEmpty();
private:
    int* elements;
    int allocatedCapacity;
    int numItems;
};
```

How do we design **OurVector**?

We must answer the following three questions:

1. Member functions: *What public interface should **OurVector** support? What functions might a client want to call?*
2. Member variables: *What private information will we need to store in order to keep track of the data stored in **OurVector**?*
3. **Constructor: How are the member variables initialized when a new instance of **OurVector** is created?**


Review: Constructors

- A constructor is a special member function used to set up the class before it is used.
- The constructor is automatically called when the object is created.
- The constructor for a class named **ClassName** has signature **ClassName (args) ;**

```
class OurVector {  
public:  
    OurVector();  
  
    void add(int value);  
    void insert(int index, int value);  
    int get(int index);  
    void remove(int index);  
    int size();  
    bool isEmpty();  
private:  
    int* elements;  
    int allocatedCapacity;  
    int numItems;  
};
```

OurVector Constructor

- The constructor must initialize all the values of our member variables to be things that initially make sense
- The **allocatedCapacity** should be set to some small integer
- The **elements** array should be allocated using the **new[]** keyword
- The **numItems** counter should be initialized to 0.



*When does this
memory ever get
deallocated?*

Destructors

- A destructor is a special member function responsible for cleaning up an object's memory.
- It's automatically called whenever an object's lifetime ends (for example, if it's a local variable that goes out of scope.)
- The destructor for a class named **ClassName** has signature **~ClassName () ;**

```
class OurVector {  
public:  
    OurVector() ;  
    ~OurVector() ;  
    void add(int value) ;  
    void insert(int index, int value) ;  
    int get(int index) ;  
    void remove(int index) ;  
    int size() ;  
    bool isEmpty() ;  
private:  
    int* elements ;  
    int allocatedCapacity ;  
    int numItems ;  
};
```



OurVector Destructor

- The destructor must take responsibility for freeing any allocated memory currently in use by an instance of the class
- In particular, this means calling the **delete[]** operator on the elements array to officially give that memory back to the computer and avoid any memory leaks.
- The other member variables (**allocatedCapacity** and **numItems**) are both simple stack-allocated variables, so nothing special is needed to clean them up.



Let's Code It! (Part 1)

Member Variables, Constructor, and Destructor



Summary

- Member variables define the key data storage components of a class implementation
- The constructor is the special method that gets called when a new instance of a class is declared. In this method, we initialize all of our member variables to the appropriate values, including allocating any necessary memory.
- The destructor is a special method that gets called when an instance of a class goes out of scope and thus is destroyed. In this method, we most often are responsible for freeing any dynamically allocated memory used by the instance.



Announcements

Announcements

- Congratulations on finishing the diagnostic! Your section leaders will be hard at work grading this week – we're aiming to have grades back by **next Monday**.
- Assignment 4 will be released shortly after lecture and will be due next Monday, July 27 at 11:59pm PDT.
- Trip's Assignment 4 YEAH session will be **tomorrow evening (7/21) at 6pm PDT**. The Zoom info is posted on the course website.
- The final project guidelines will be posted on the website later today. Read them and start thinking about what you want to do your project on!



Final Project

For your capstone final project, you will:

- Pick a topic you have struggled with from the quarter and write your own problem on that topic (scoped for a section/diagnostic/exam)
- Write a project report including a problem description, possible solutions, the motivation behind developing the problem, and possible misconceptions that students might have when working on the problem. Due **Sunday, August 9.**
- Take on the role of a section leader and teach/present the problem to your section leader in a 30-minute, 1-on-1 session. **Takes place from August 13-16.**



Visualizing OurVector Operations

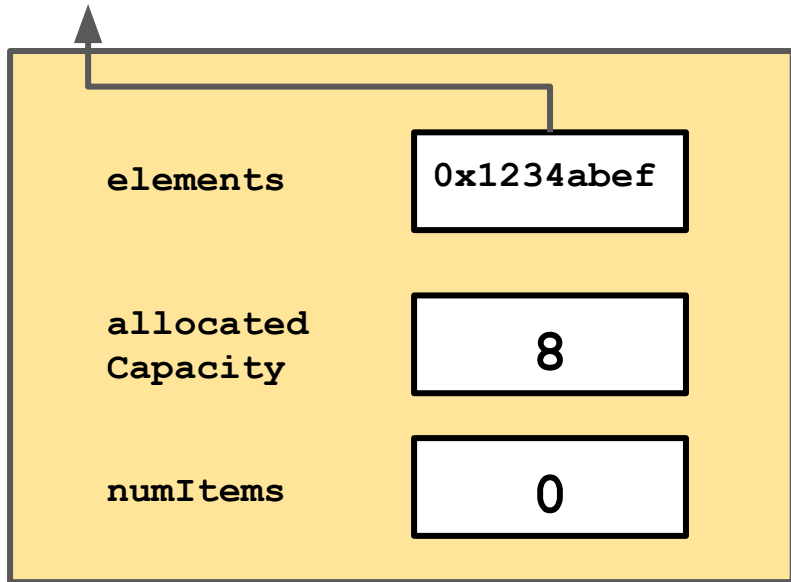
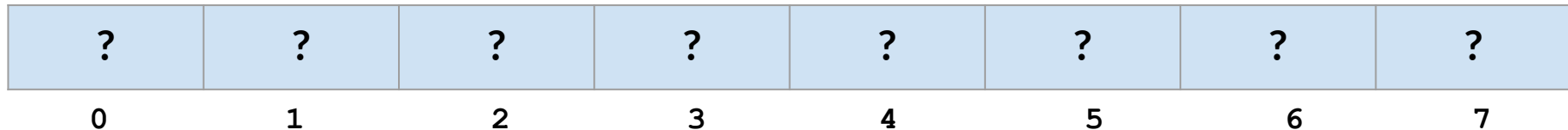


Initialization via the Constructor

```
// client code  
  
OurVector vec;
```

Initialization via the Constructor

*initially store random
(or garbage) values*



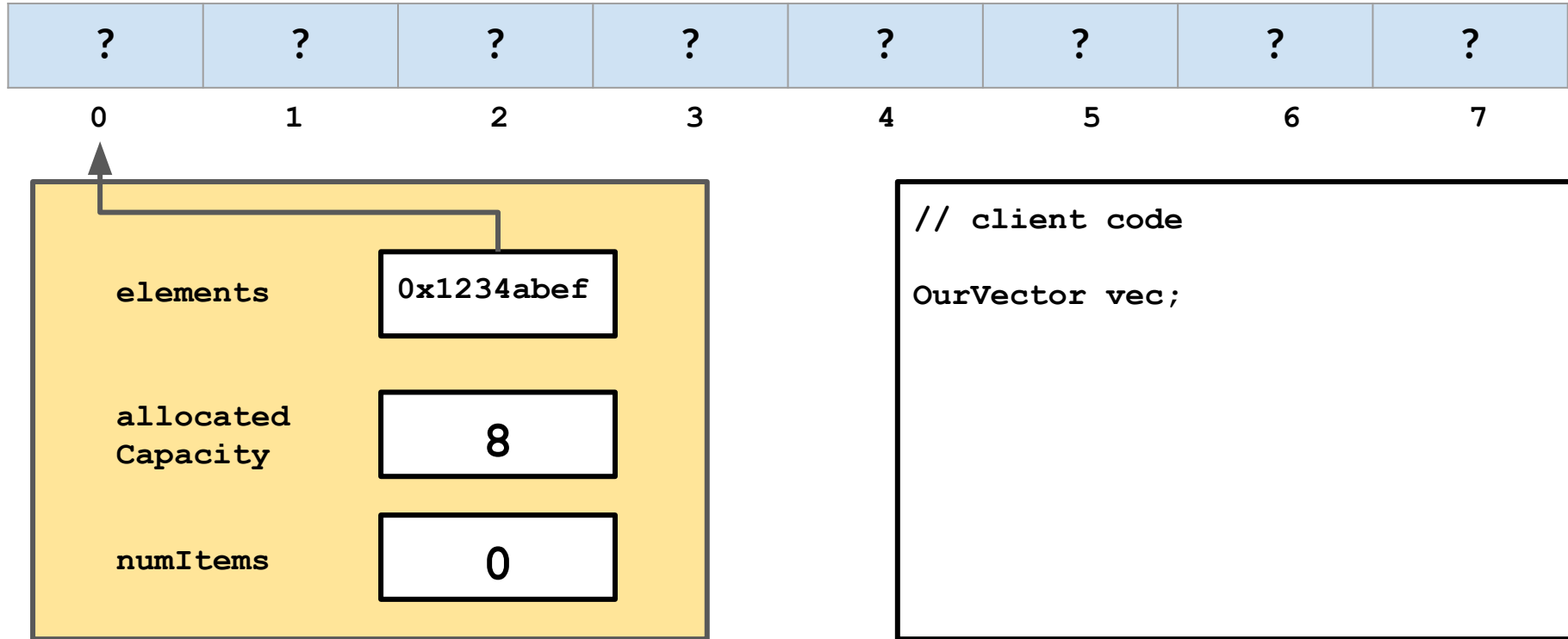
```
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```



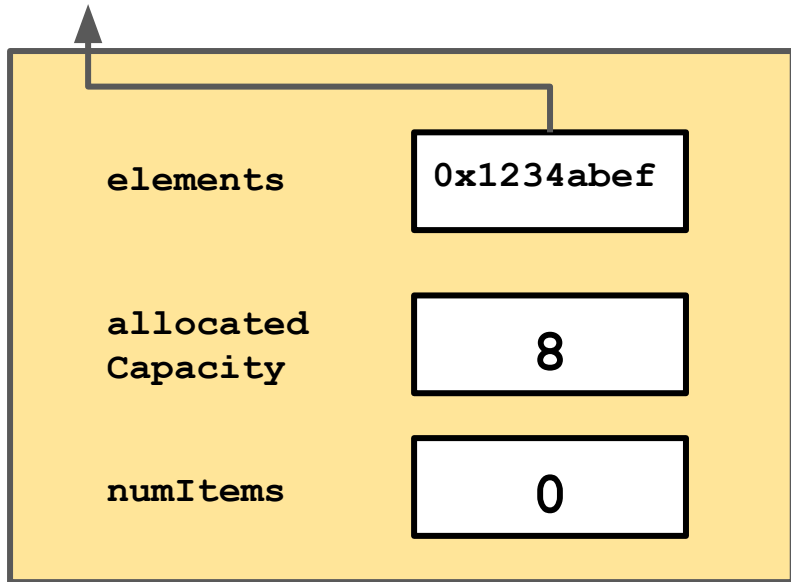
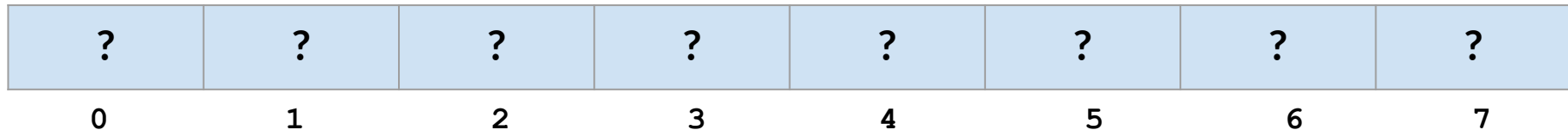
The **add()** operation

- The **add()** operation is responsible for taking a specified element and adding it to the first open spot at the end of the vector.

The `add()` operation



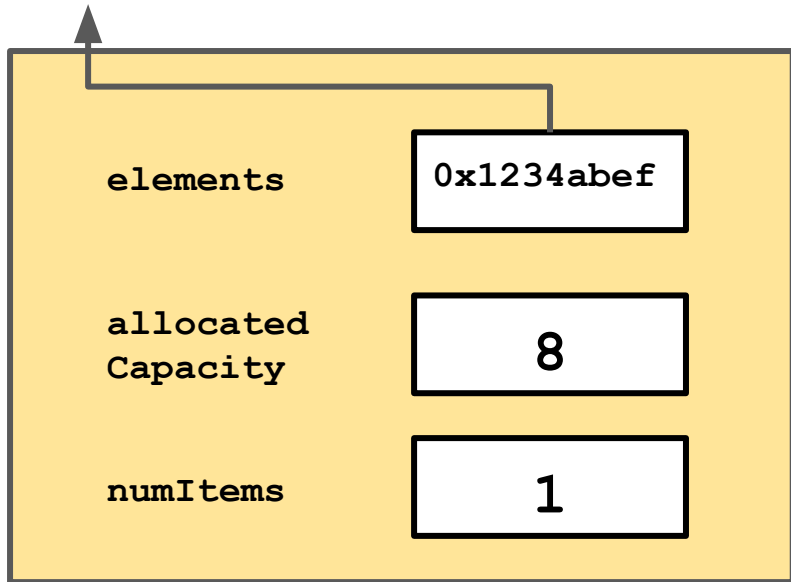
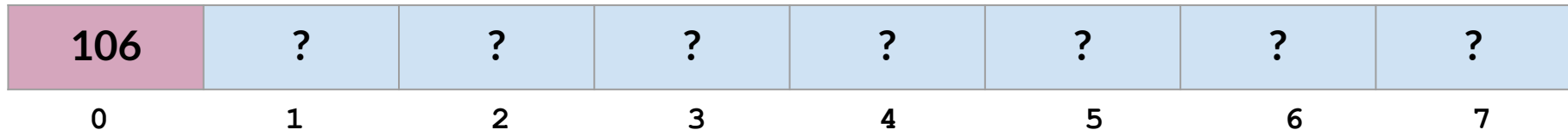
The `add()` operation



```
// client code
```

```
OurVector vec;  
vec.add(106);
```

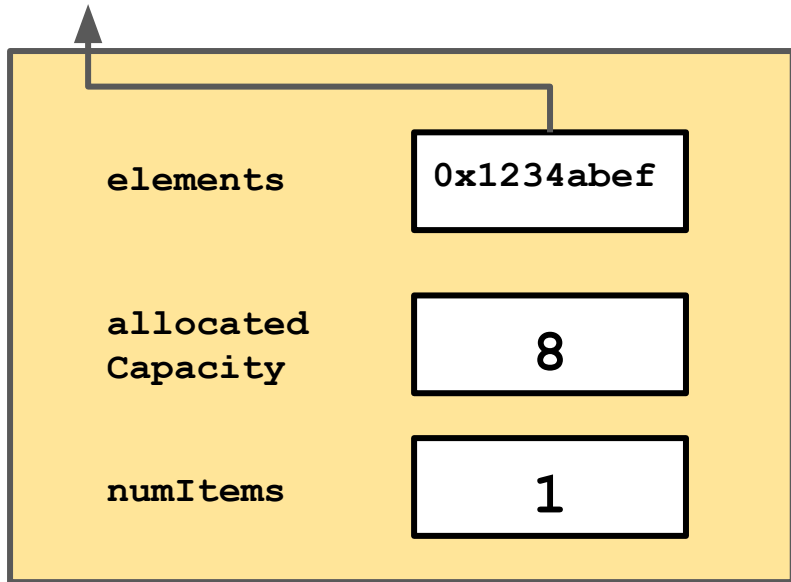
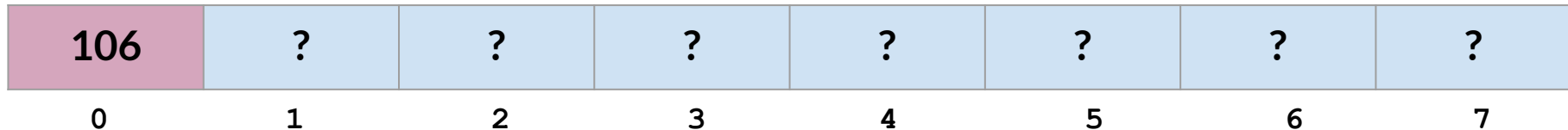
The `add()` operation



```
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vec.add(106);
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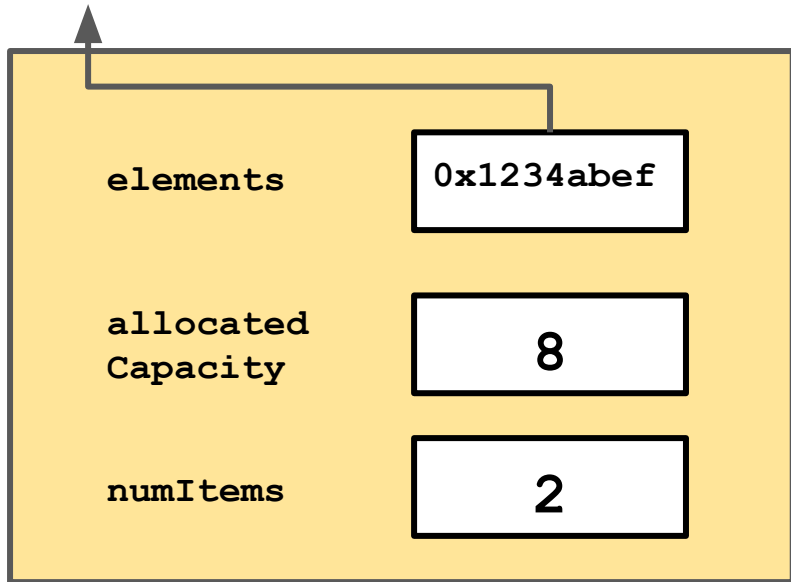
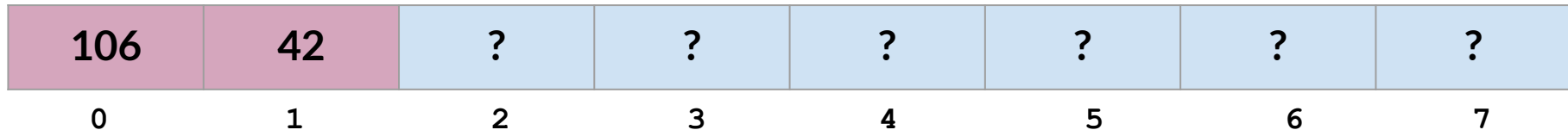
The `add()` operation



```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);
```

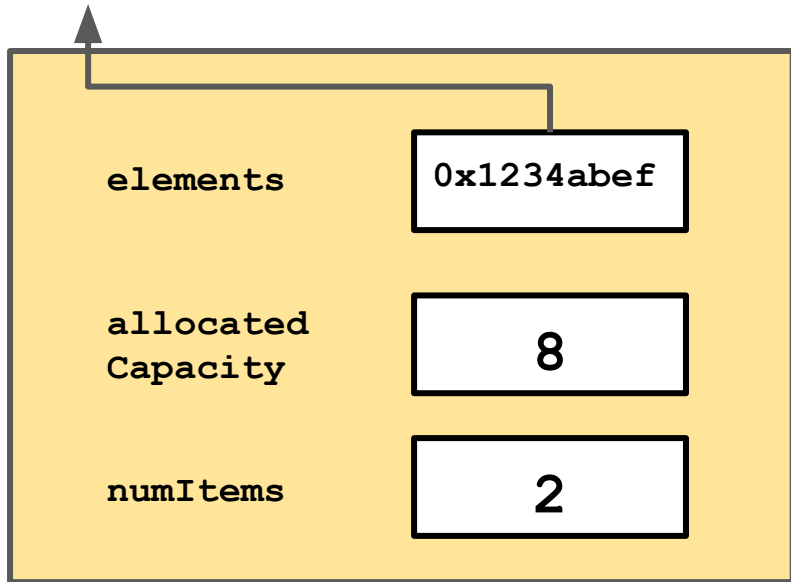
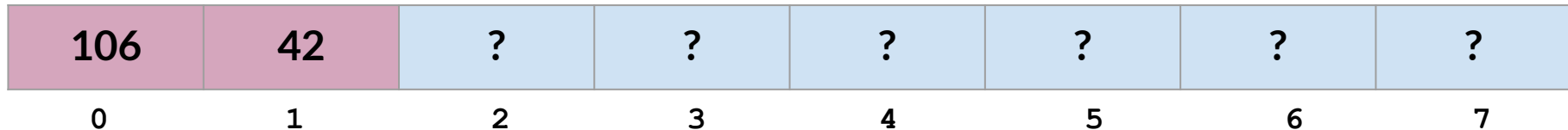
The `add()` operation



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OurVector vec;  
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The `add()` operation

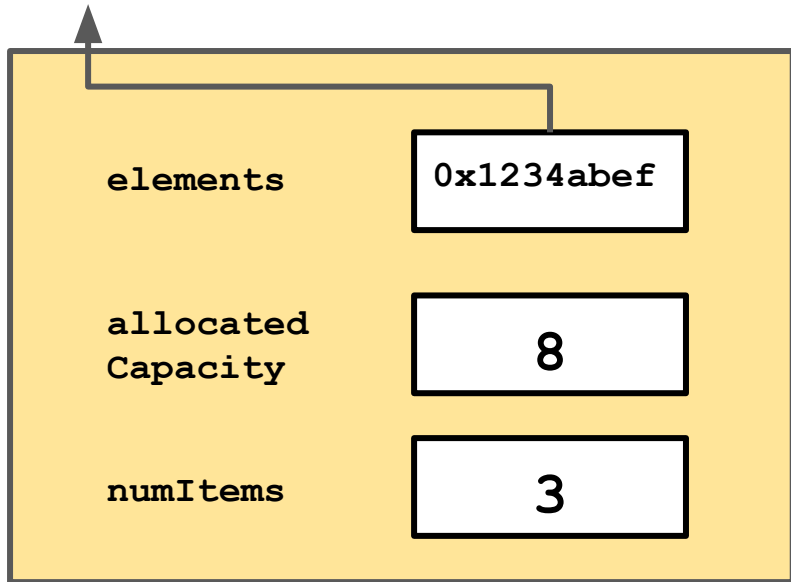


```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);  
vec.add(-3);
```

The `add()` operation

106	42	-3	?	?	?	?	?
0	1	2	3	4	5	6	7

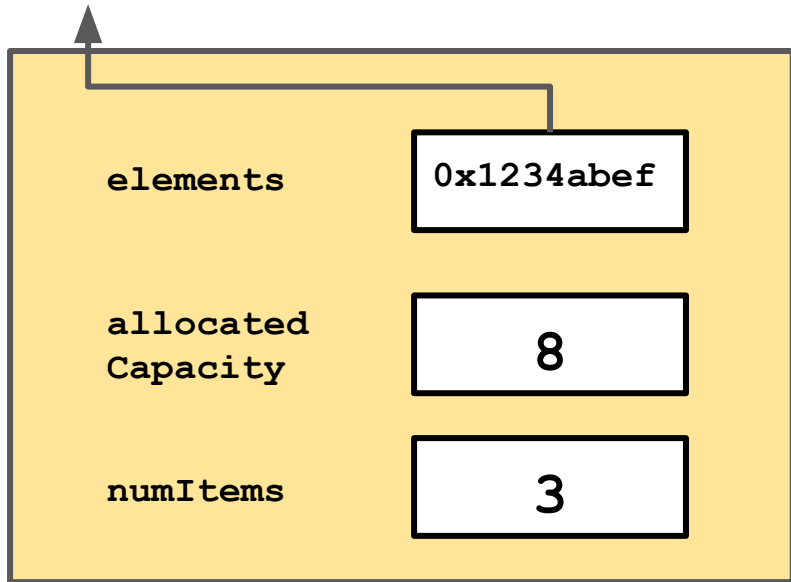


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The `add()` operation

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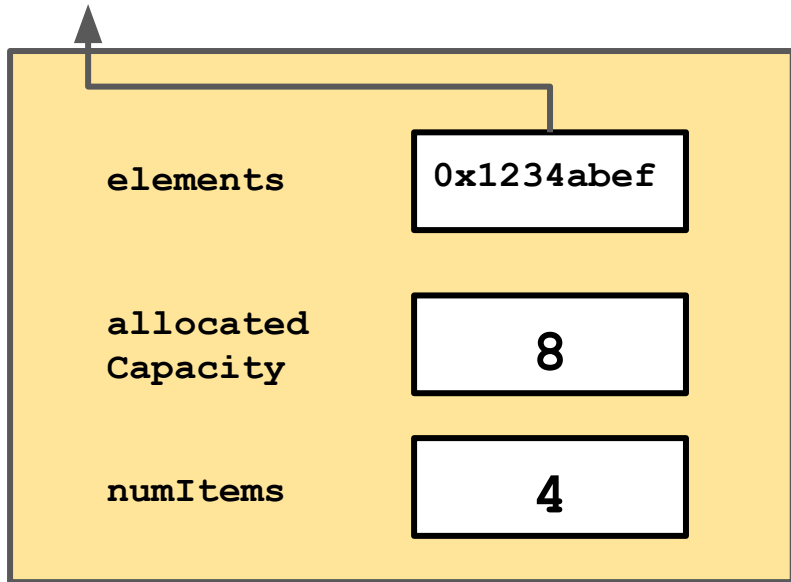


```
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```

```
OurVector vec;  
vec.add(106);  
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vec.add(-3);  
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```

The `add()` operation

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



```
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```

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OurVector vec;  
vec.add(106);  
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vec.add(-3);  
vec.add(27);
```

The **insert()** and **remove()** operations

- The **insert()** operation is similar to **add()**, but allows the client to specify which index they want the value to be inserted at.
- The **remove()** operation allows the client to specify an index at which to remove an element, and then removes the value at that index.

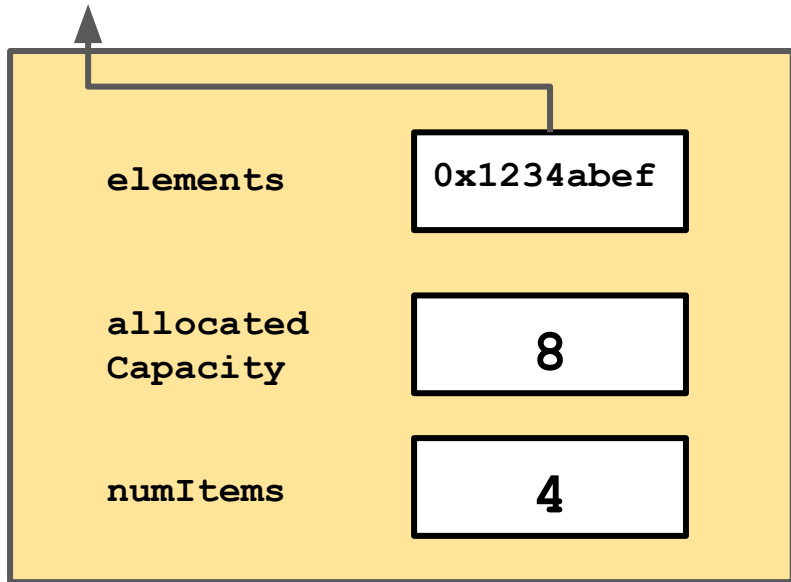


Breakout Activity:

OurVector operation tracing and design

The `remove()` operation

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7

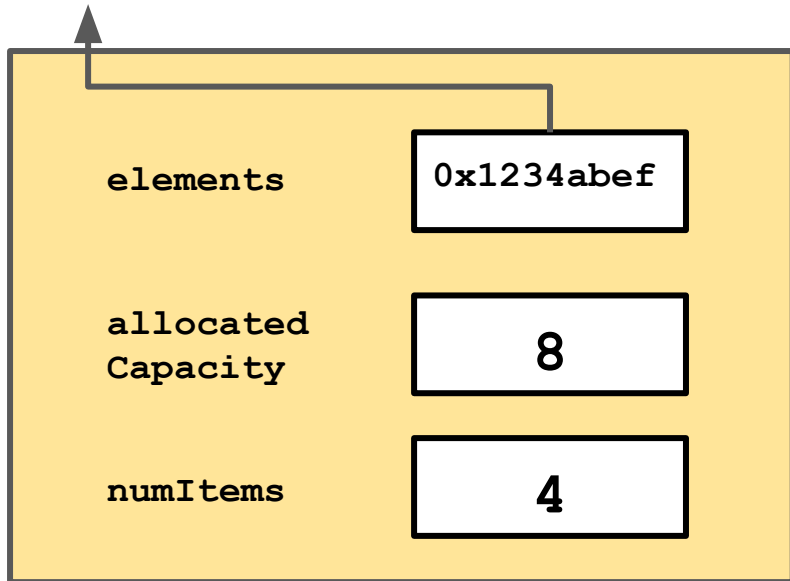


```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);  
vec.add(-3);  
vec.add(27);
```

The `remove()` operation

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7

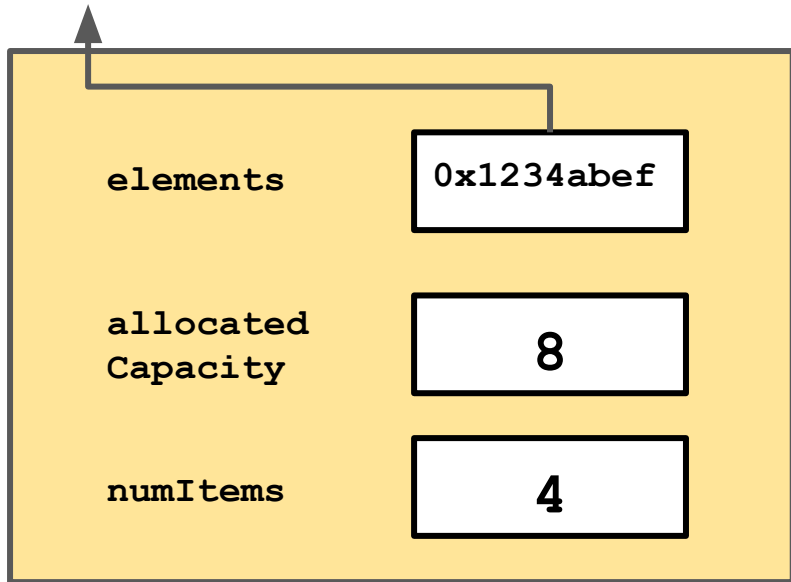
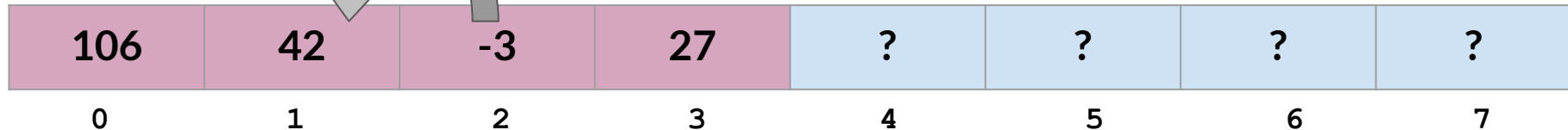


```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);  
vec.add(-3);  
vec.add(27);
```

```
vec.remove(1);
```


The `remove()` operation



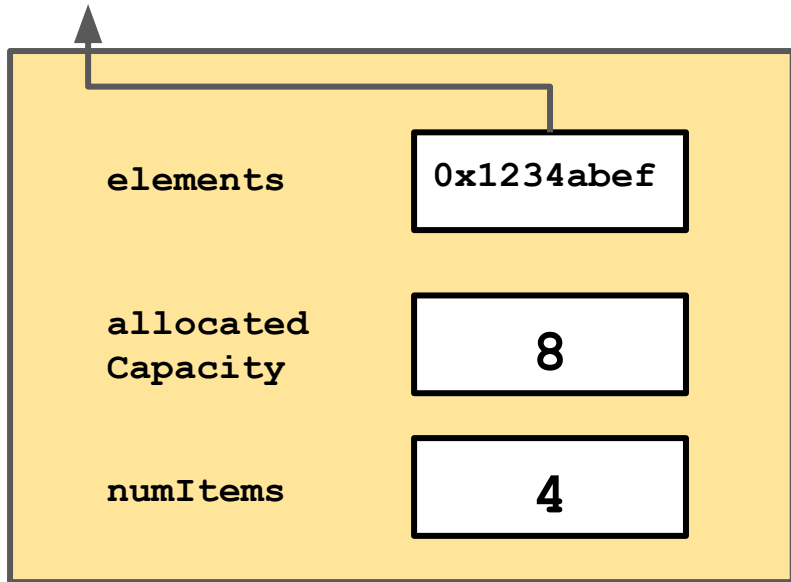
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The `remove()` operation

106	-3	-3	27	?	?	?	?
0	1	2	3	4	5	6	7

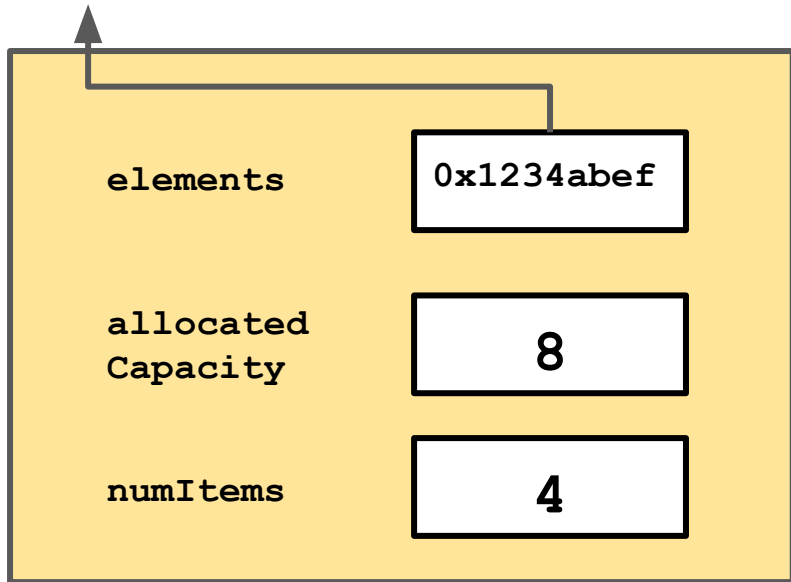
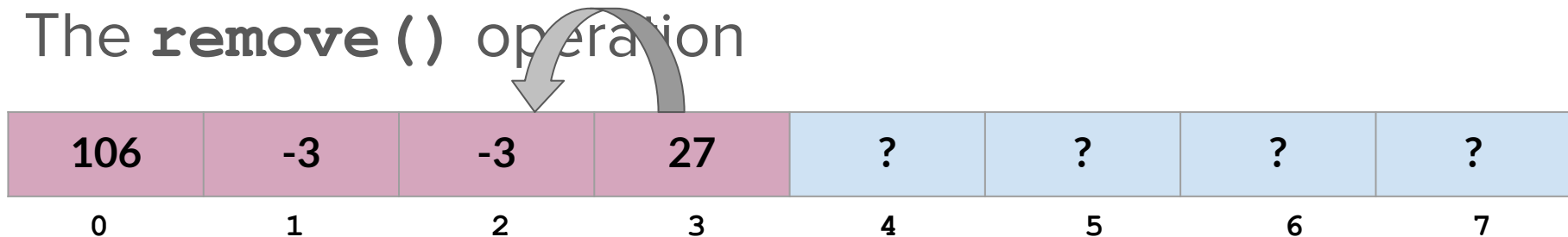


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The `remove()` operation



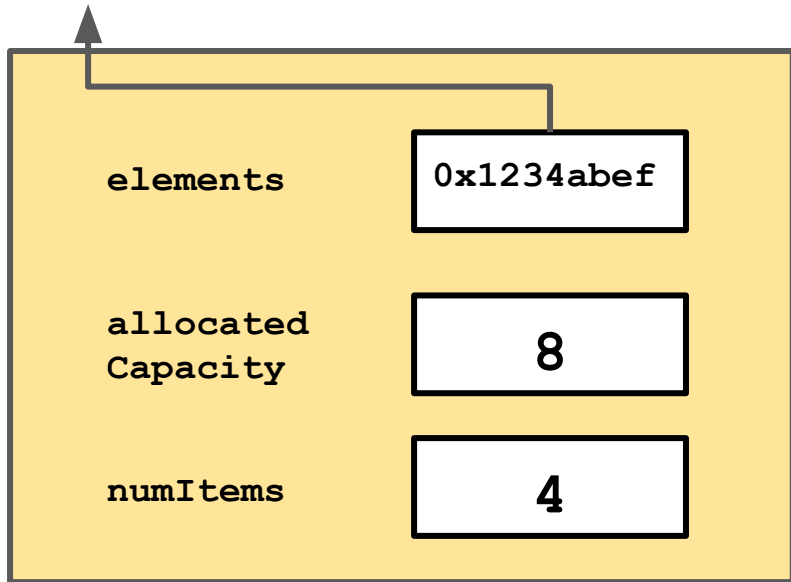
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The `remove()` operation

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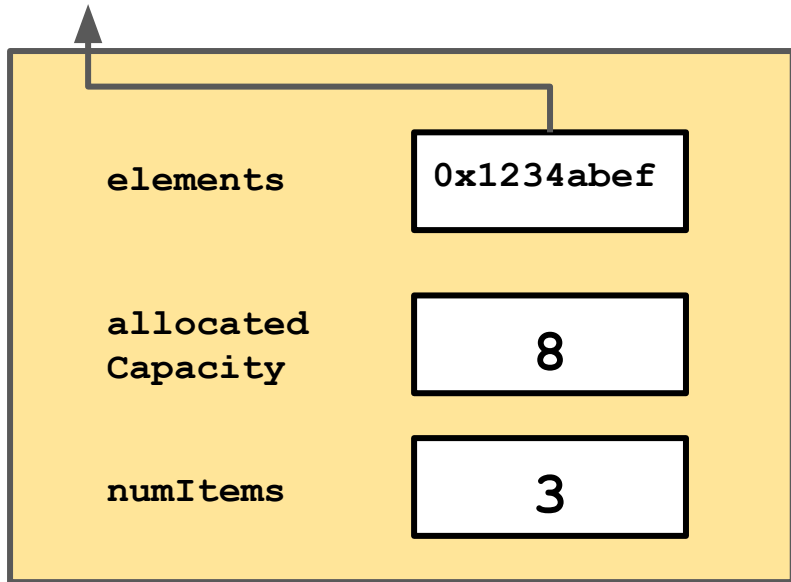
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```

```
vec.remove(1);
```

The `remove()` operation

106	-3	27	27	?	?	?	?
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// client code
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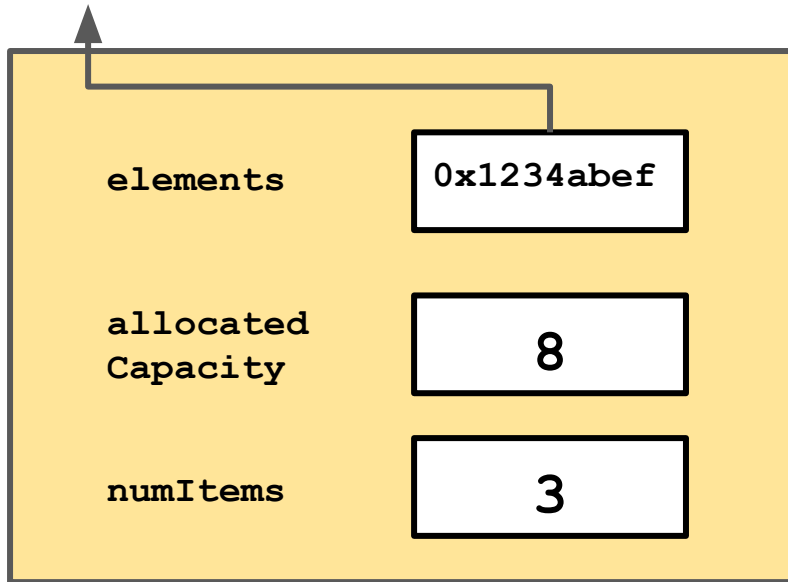
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vec.add(-3);  
vec.add(27);
```

```
vec.remove(1);
```

The `remove()` operation

Arrays cannot grow
value is still technically there in the array.
We're just going to pretend that it isn't!

106	-3	27	27	?	?	?	?
0	1	2	3	4	5	6	7



```
// client code
```

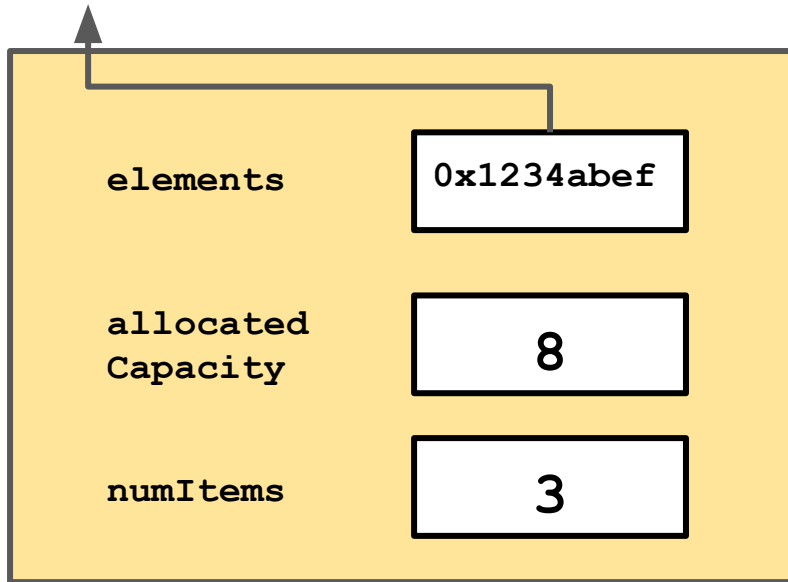
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The `remove()` operation

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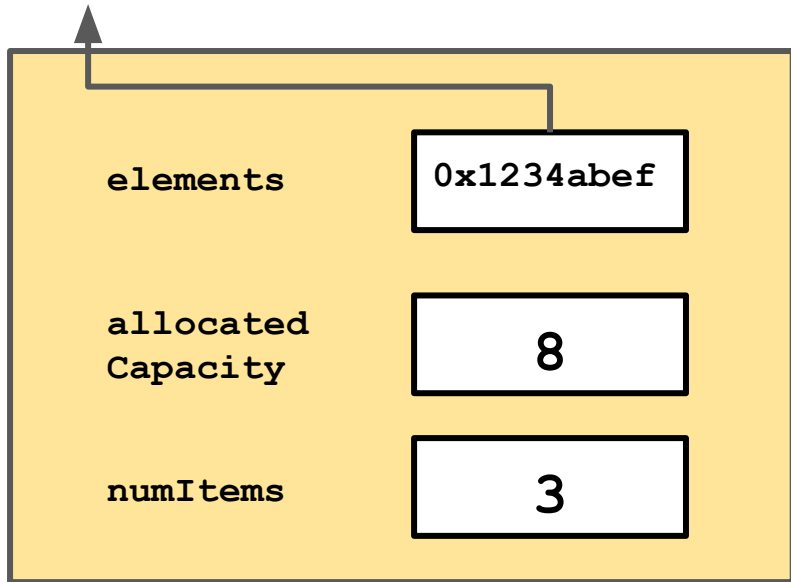


```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);  
vec.add(-3);  
vec.add(27);  
  
vec.remove(1);
```

The `insert()` operation

106	-3	27	?	?	?	?	?
0	1	2	3	4	5	6	7



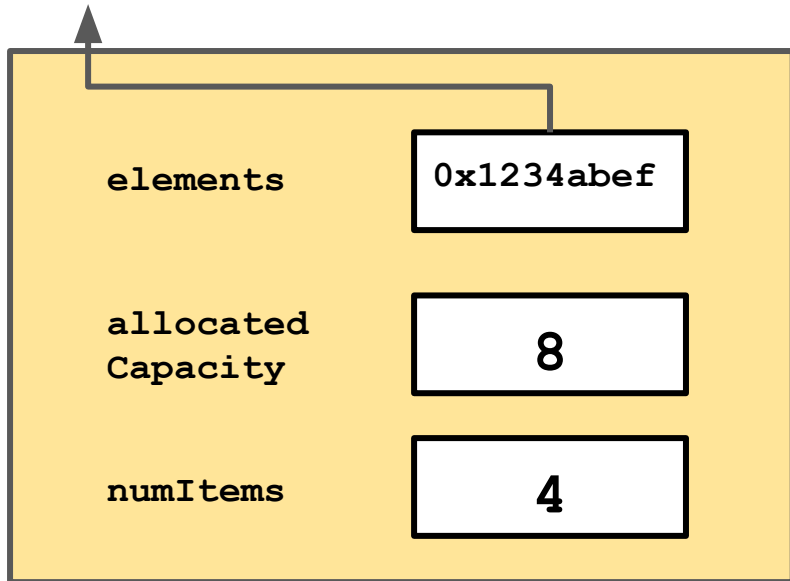
```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);  
vec.add(-3);  
vec.add(27);
```

```
vec.remove(1);  
vec.insert(0, 198);
```


The `insert()` operation

198	106	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



```
// client code
```

```
OurVector vec;  
vec.add(106);  
vec.add(42);  
vec.add(-3);  
vec.add(27);
```

```
vec.remove(1);  
vec.insert(0, 198);
```

The **get()** / **size()** / **isEmpty()** operations

- The remaining operations that we have left to implement should be relatively straightforward, given the member variables we have.
- The **get()** method can just return the array element at the specified index
- The **size()** method can just return the value of the **numItems** member variable
- The **isEmpty()** method can compare **numItems** to 0 and return the appropriate result



Implementing OurVector



Let's Code It! (Part 2)

`add(), remove(), insert(), get(), size(),
isEmpty()`



Summary

- Using an array as a backing store of data involves shifting elements around – this kind of code is ripe for off-by-one errors!
- With good member variable member choices, most public methods are relatively straightforward to implement.
- We've now gained an appreciation for *why* insertion/removal on Vectors is an "expensive" $O(n)$ operation



Running Out of Space

- Our current implementation very quickly runs out of space to store elements.
- What should we do when this happens?
 - Currently, we just throw an error. That doesn't seem quite right. What if all data structures we used were limited to hold only 8 items?
 - Instead, we need a way to **dynamically resize (grow)** our internal data storage mechanism.

Dynamic Array Growth



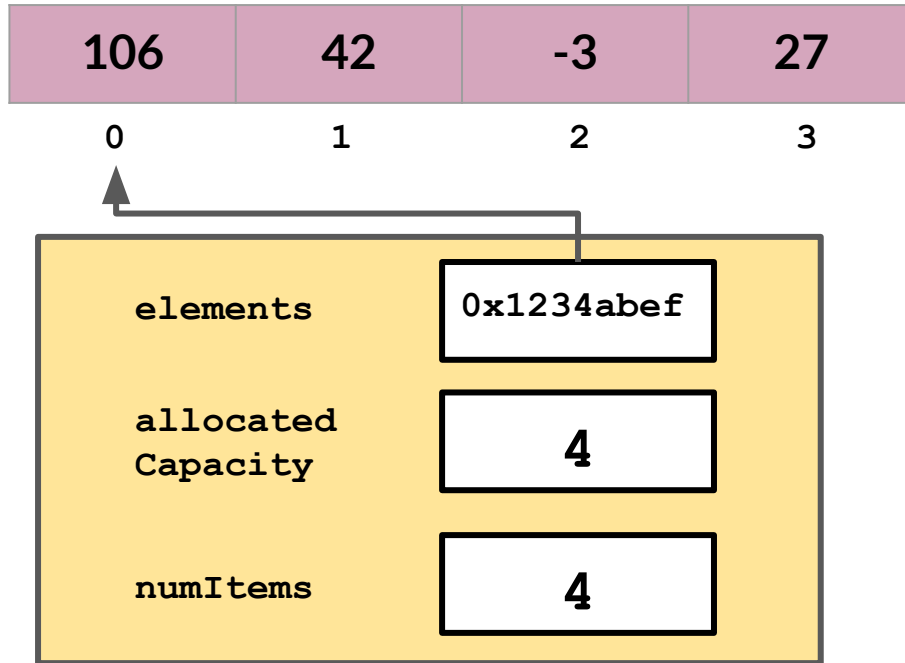


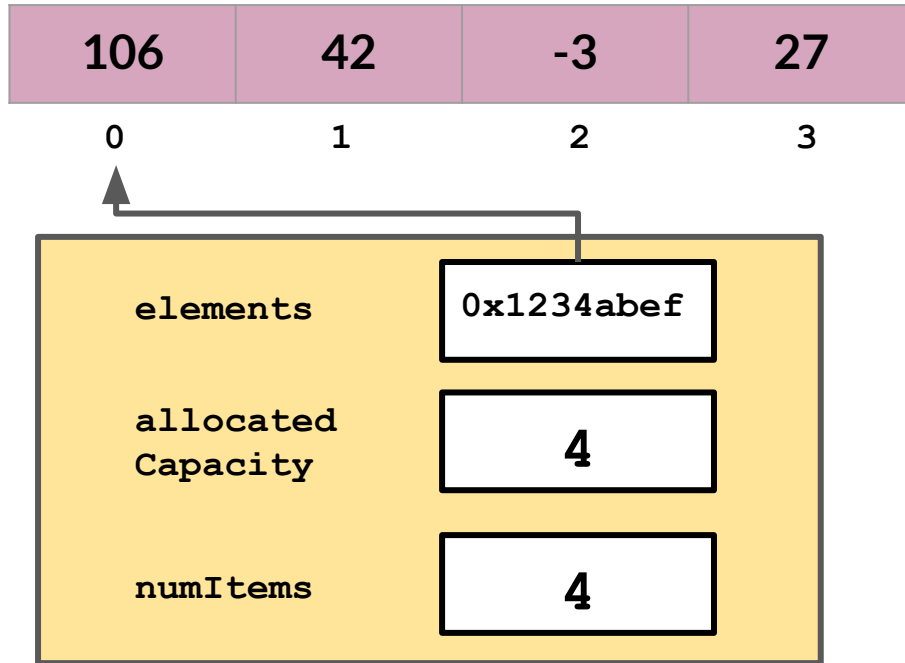
A Day in the Life of a Hermit Crab

- Hermit crabs are interesting animals. They live in scavenged shells that they find on the seafloor. Once in a shell, this is their lifestyle (with a bit of poetic license):
 - Grow until they have outgrown their current shell. Then, follow these 5 steps.
 - Find another, larger shell.
 - Move all their stuff into the new shell.
 - Leave the old shell on the seafloor.
 - Update their address with the Hermit Crab Postal Service.
 - Make note of their new shell's spacious capacity by posting on Hermit Crab Instagram.
- While this is purposefully a bit of a silly analogy, this process models almost exactly what we need to do in order to dynamically resize our internal data storage mechanism.

A Day in the Life of a Growable Array

- In essence, when we run out of space in our array, we want to allocate a new array that is bigger than our old array so we can store the new data and keep growing. These "growable arrays" follow a five-step expansion that mirrors the hermit crab model (with poetic license).
 - Grow the array until we run out of space (how can we tell if we've run out of space?)
 - Create a new, larger array. Usually we choose to **double** the current size.
 - Copy the old array elements to the new array.
 - Delete (free) the old array.
 - Point the old array variable to the new array.
 - Update the associated capacity variable for the array.

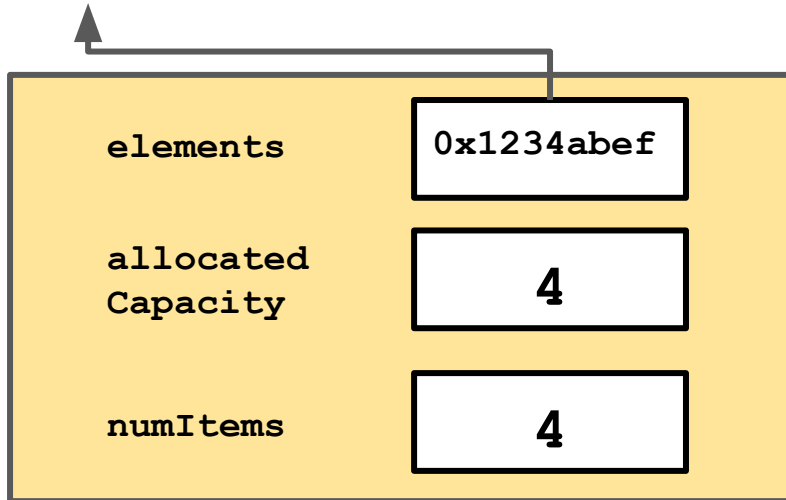




1. Create a new, larger array. Usually we choose to double the current size.

?	?	?	?	?	?	?	?
0	1	2	3	4	5	6	7

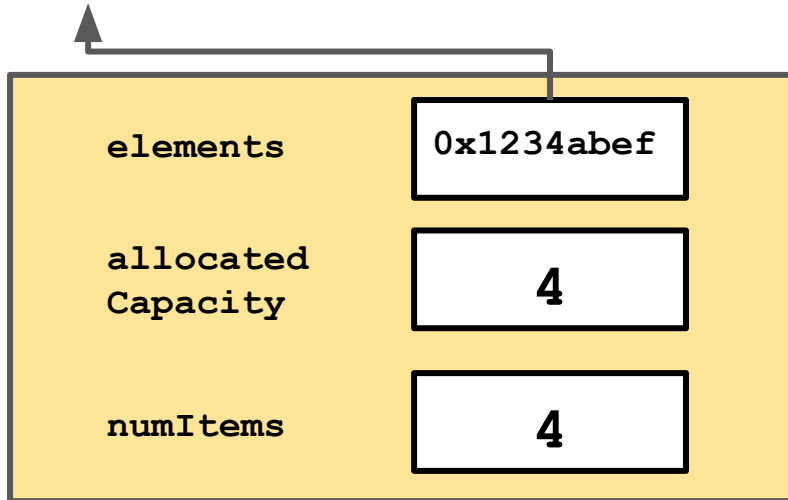
106	42	-3	27
0	1	2	3



1. Create a new, larger array. Usually we choose to double the current size.

?	?	?	?	?	?	?	?
0	1	2	3	4	5	6	7

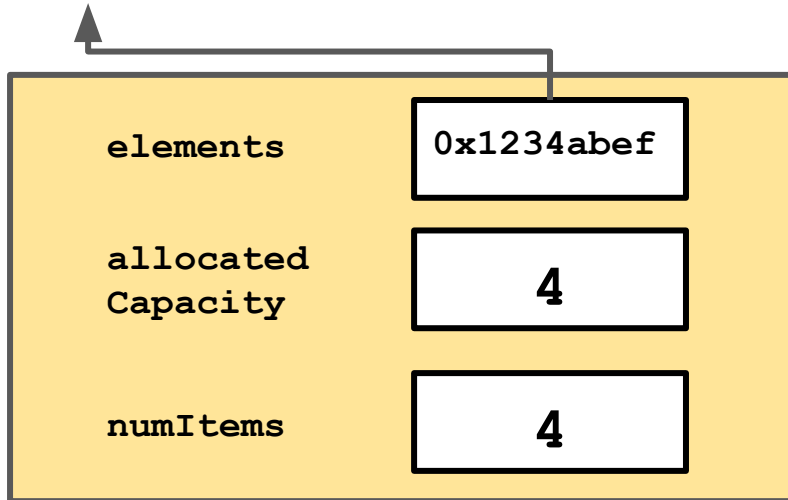
106	42	-3	27
0	1	2	3



1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7

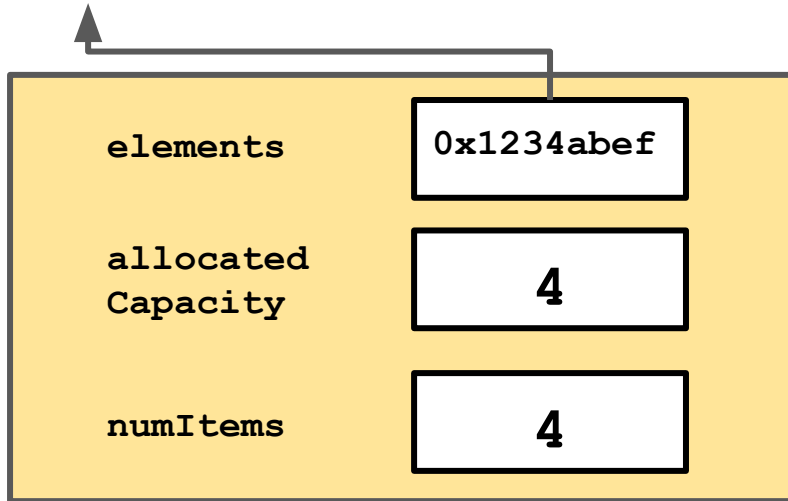
106	42	-3	27
0	1	2	3



1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7

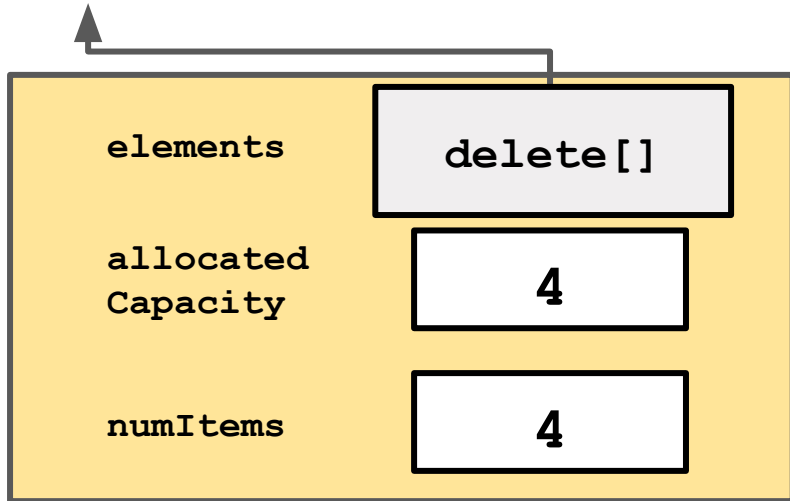
106	42	-3	27
0	1	2	3



1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
3. Delete (free) the old array.

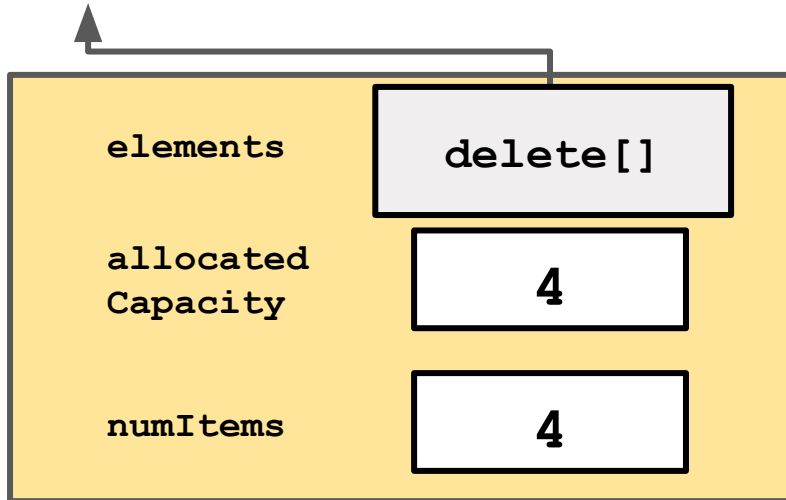
106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7

106	42	-3	27
0	1	2	3



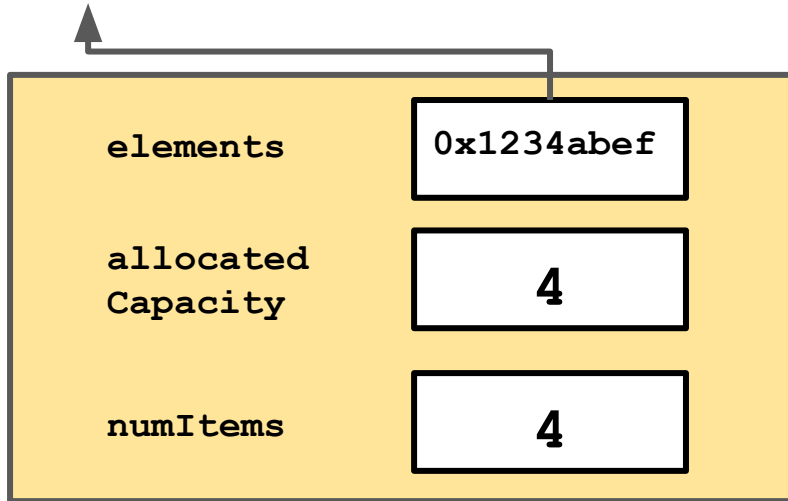
1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
3. Delete (free) the old array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



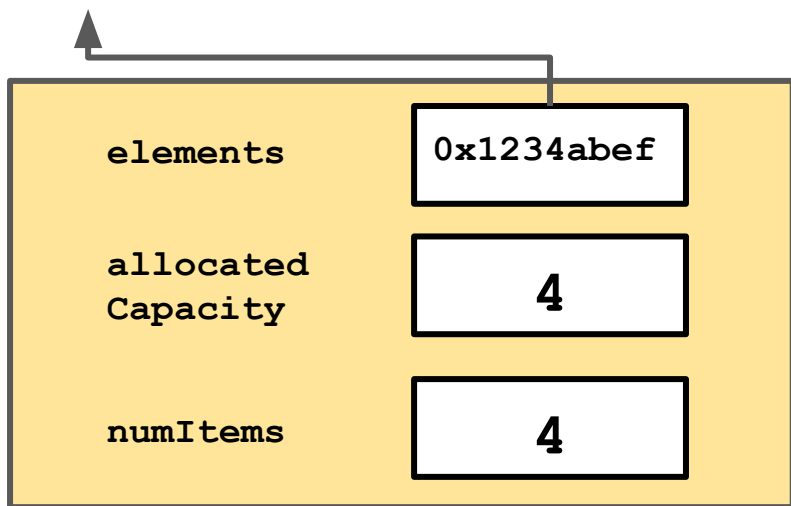
1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
3. Delete (free) the old array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



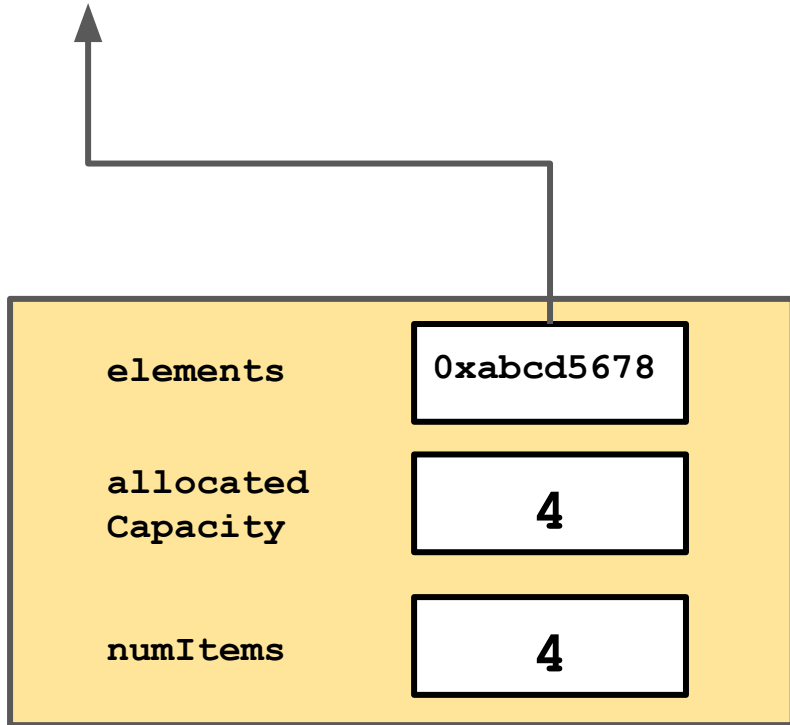
1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
3. Delete (free) the old array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



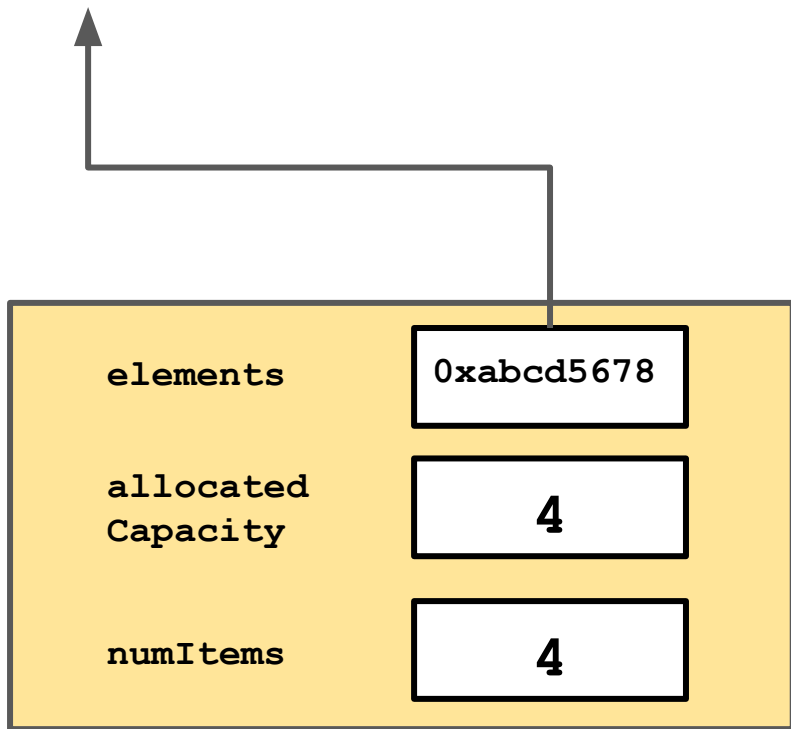
1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
3. Delete (free) the old array.
4. Point the old array variable to the new array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



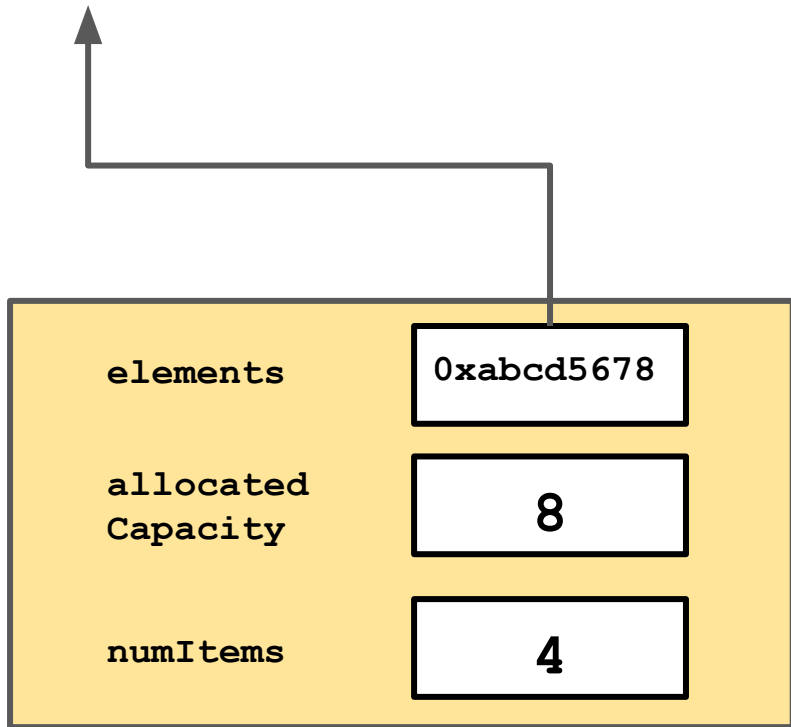
1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
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4. Point the old array variable to the new array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



1. Create a new, larger array. Usually we choose to double the current size.
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4. Point the old array variable to the new array.
5. Update the associated capacity variable for the array.

106	42	-3	27	?	?	?	?
0	1	2	3	4	5	6	7



1. Create a new, larger array. Usually we choose to double the current size.
2. Copy the old array elements to the new array.
3. Delete (free) the old array.
4. Point the old array variable to the new array.
5. Update the associated capacity variable for the array.



Let's Code It! (Part 3)

expand() private helper function



Summary



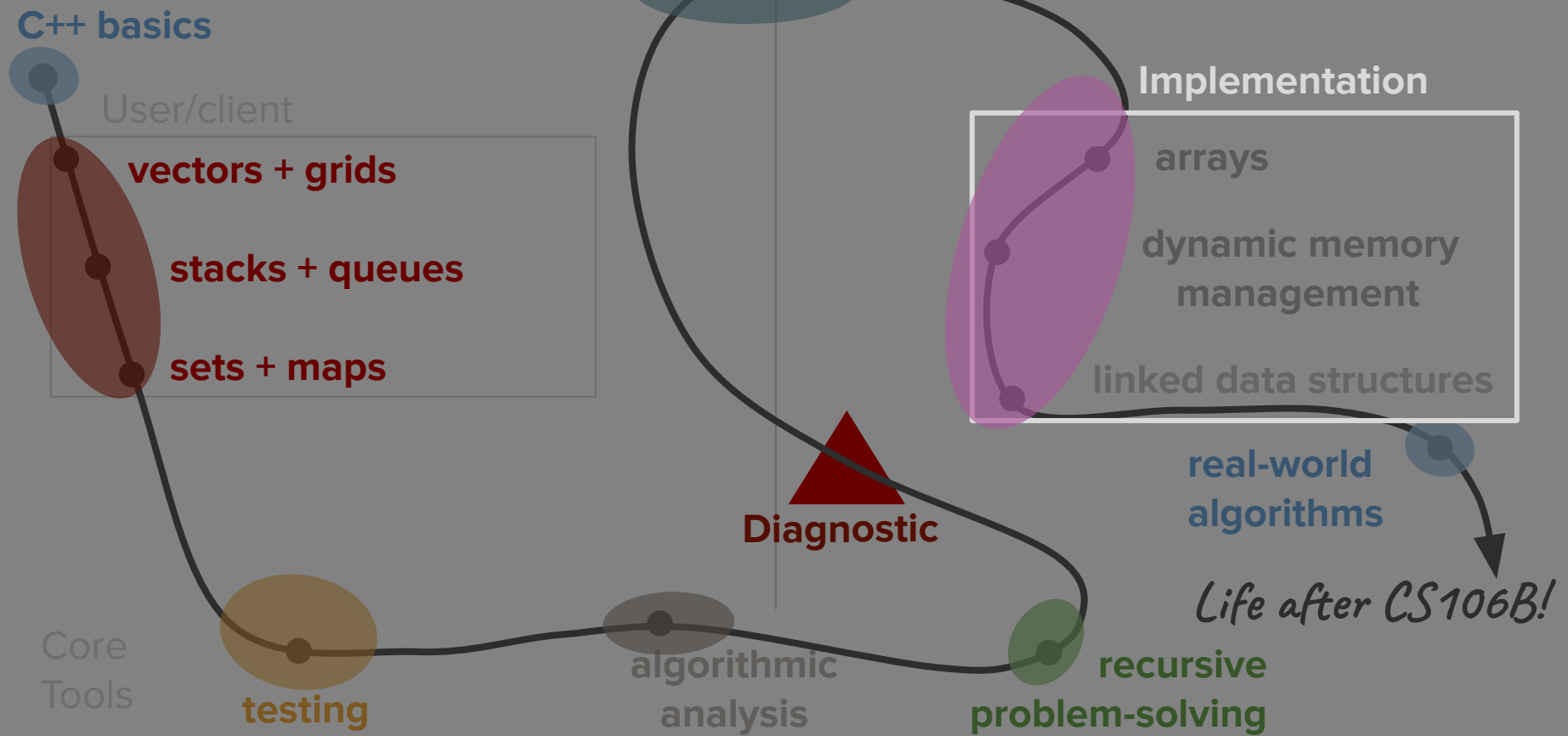
Implementing ADT Classes

- 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.



What's next?

Roadmap



Priority Queues and Heaps

