

Data Structures

Stacks and Queues

CS 225

September 10, 2025

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ILLINOIS
URBANA - CHAMPAIGN

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Autograded MC and one coding question

Manually graded short answer prompt

Practice exam will be released on PL

Topics covered can be found on website

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<https://courses.engr.illinois.edu/cs225/fa2025/exams/>

Preparing for Exams

Make sure you understand the coding assignments

Review lecture slides — especially review slides!



Take a look at 'staff notes' — added to website for past lectures

Do the practice exam before watching practice exam solution video

Learning Objectives

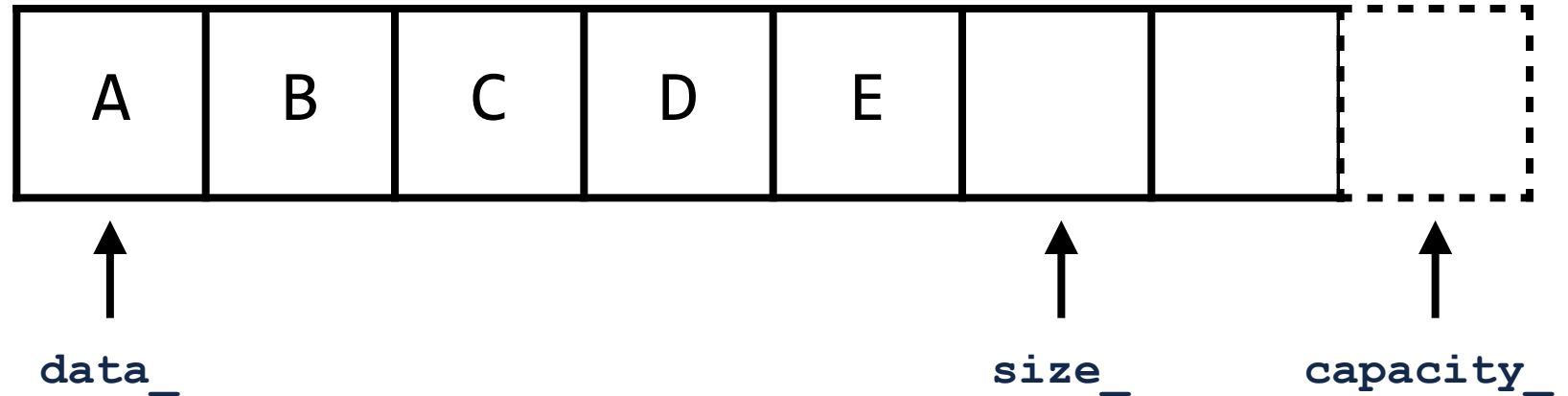
Discuss amortized analysis

Consider extensions to lists (data structure tradeoffs)

Introduce the stack and the queue data structure

Introduce and explore iterators

Array List



In C++, vector is implemented as:

- 1) **Data:** Stored as a pointer to array start
- 2) **Size:** Stored as a pointer to the next available space
- 3) **Capacity:** Stored as a pointer past the end of the array

Array List: Not at capacity

c	s	2	2	5					
---	---	---	---	---	--	--	--	--	--

	@Front	@Back	@Index
Insert	$O(n)$	$O(1)$	$O(n)$
Delete	$O(n)$	$O(1)$	$O(n)$

Resize Strategy: +2 elements every time



Resize Strategy: +2 elements every time

Total copies for N inserts: $\frac{N^2 + 2N}{4}$

Amortized:

Precise total work over N calls

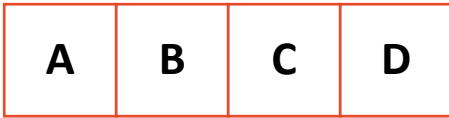
Big O:

Upperbound on worst case

Resize Strategy: x2 elements every time



Resize Strategy: x2 elements every time



1) How many copy calls per reallocation?

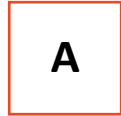
For reallocation i , 2^i copy calls are made

2) Total reallocations for N objects?

$k = \text{final realloc needed} = \lceil \log_2 n \rceil$

Total number of copy calls:

Resize Strategy: x2 elements every time



1) How many copy calls per reallocation?

For reallocation i , 2^i copy calls are made

2) Total reallocations for N objects?

$k = \text{final realloc needed} = \lceil \log_2 n \rceil$

Total number of copy calls:

$$\sum_{i=0}^k 2^i = 2^{k+1} - 1$$

... For N objects: $2n - 1$

Resize Strategy: x2 elements every time

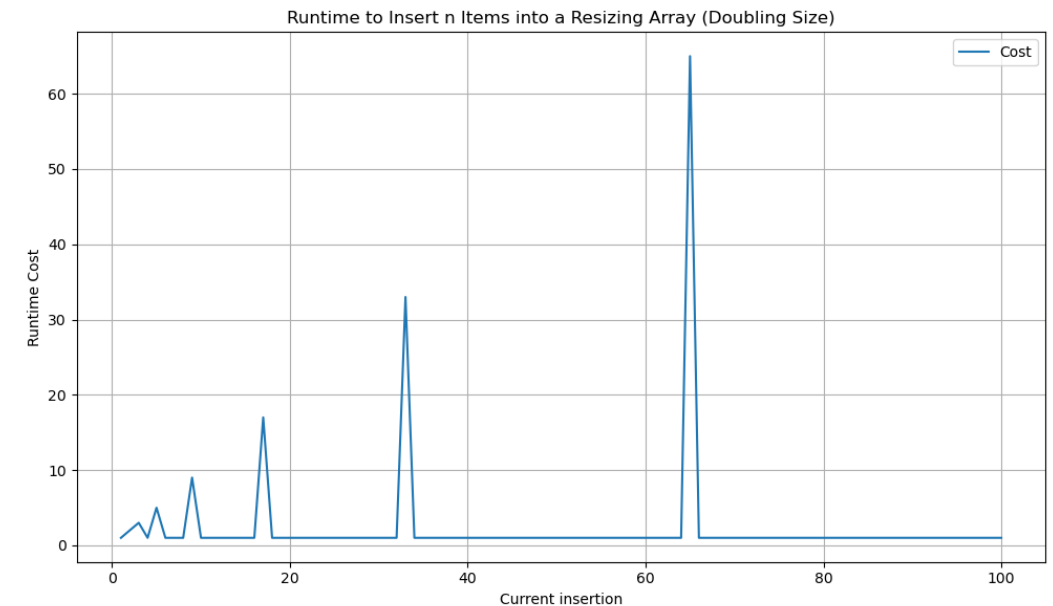
Total copies for n inserts: $2n - 1$

Amortized:

Precise total work over N calls

Big O:

Upperbound on worst case



List Implementation



	Singly Linked List	Array
Look up arbitrary location		
Insert after given element		
Remove after given element		
Insert at arbitrary location		
Remove at arbitrary location		
Search for an input value		

Thinking critically about lists: tradeoffs

The implementations shown are foundational (simple).

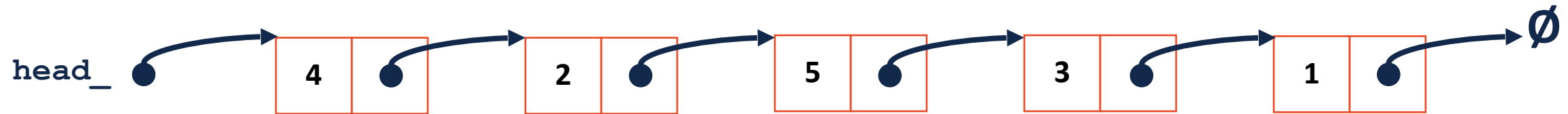
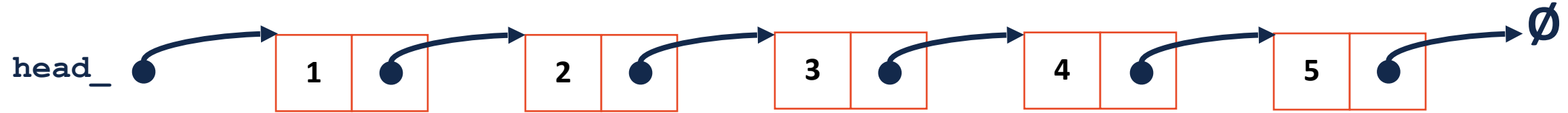
Can we make our lists better at some things? What is the cost?

Thinking critically about lists: tradeoffs

Getting the size of a linked list has a Big O of:



Thinking critically about lists: tradeoffs

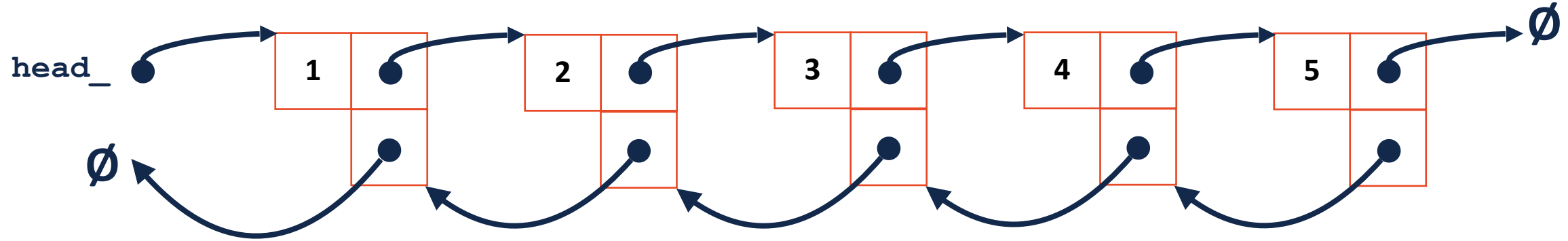


Thinking critically about lists: tradeoffs

2	7	5	9	7	14	1	0	8	3
---	---	---	---	---	----	---	---	---	---

0	1	2	3	5	7	7	8	9	14
---	---	---	---	---	---	---	---	---	----

Thinking critically about lists: tradeoffs



Thinking critically about lists: tradeoffs

As we progress in the class, we will see that $O(n)$ isn't very good.

Take searching for a specific list value:

2	7	5	9	7	14	1	0	8	3
---	---	---	---	---	----	---	---	---	---

0	1	2	3	5	7	7	8	9	14
---	---	---	---	---	---	---	---	---	----

Thinking critically about lists: tradeoffs

Can we make a 'list' that is $O(1)$ to insert and remove?

Stack Data Structure

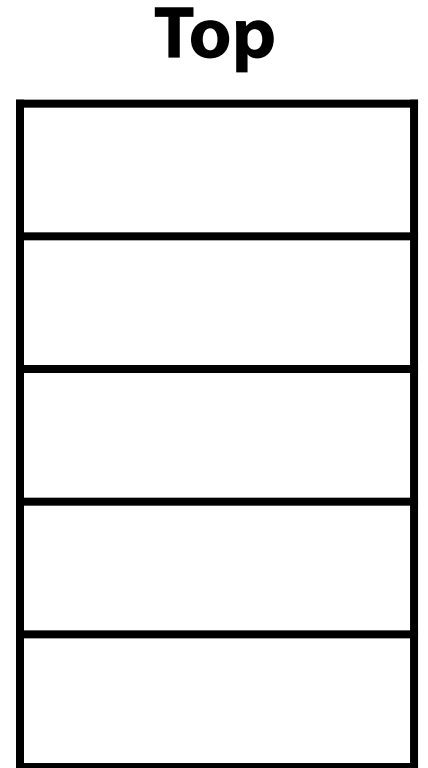
A **stack** stores an ordered collection of objects (like a list)

However you can only do two* operations:

Push: Put an item on top of the stack

Pop: Remove the top item of the stack (and return it)

```
push (3) ; push (5) ; pop () ; push (2)
```

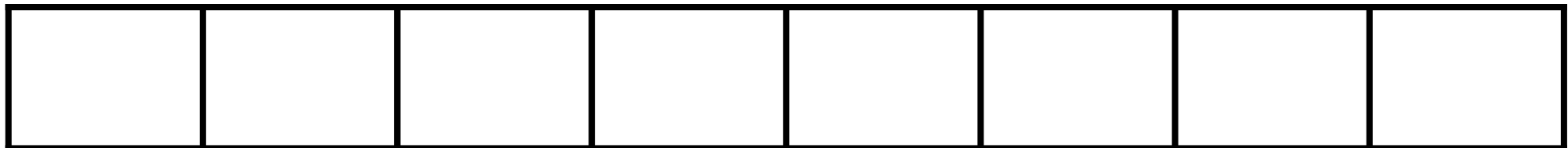


Stack Data Structure

C++ has a built-in stack

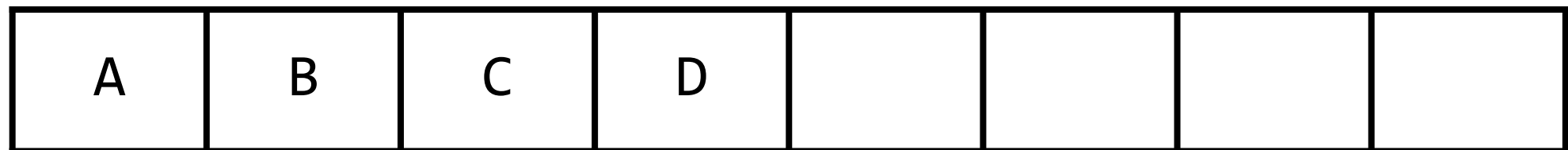
Underlying implementation is vector or deque

```
1 #include <stack>
2 int main() {
3     stack<int> stack;
4     stack.push(3);
5     stack.push(8);
6     stack.push(4);
7     stack.pop();
8     stack.push(7);
9     stack.pop();
10    stack.pop();
11 }
```



Stack Data Structure

Push(X) is equivalent to ...

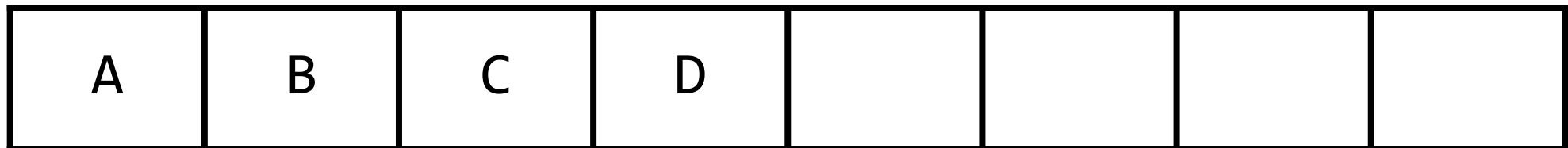


Stack Data Structure

Push(X) is equivalent to insertBack(X)

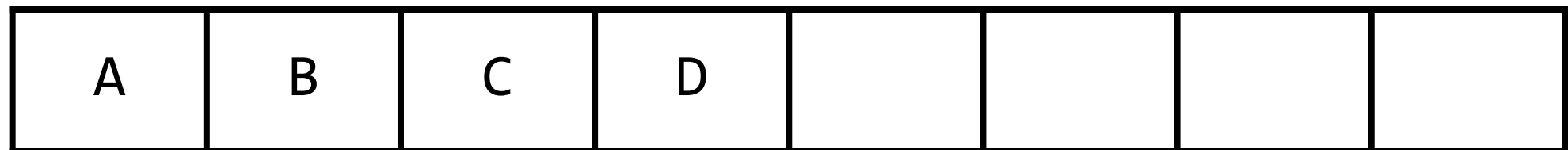
```
*size = X;
```

```
size++;
```



Stack Data Structure

Pop() is equivalent to...



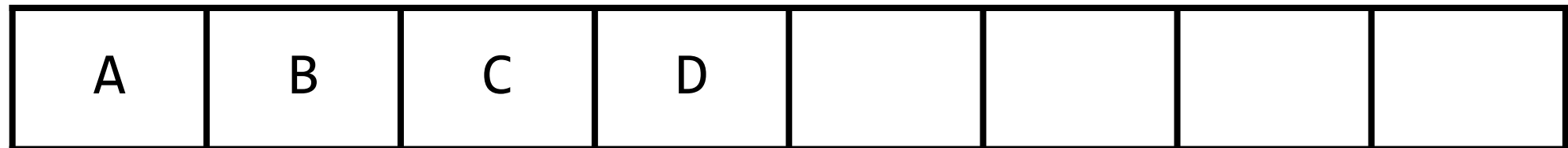
Stack Data Structure

Pop() is equivalent to removeBack()

size--;

T tmp = *size;

return tmp;



Stack ADT

- [Order]:
- [Implementation]:
- [Runtime]:



Queue Data Structure

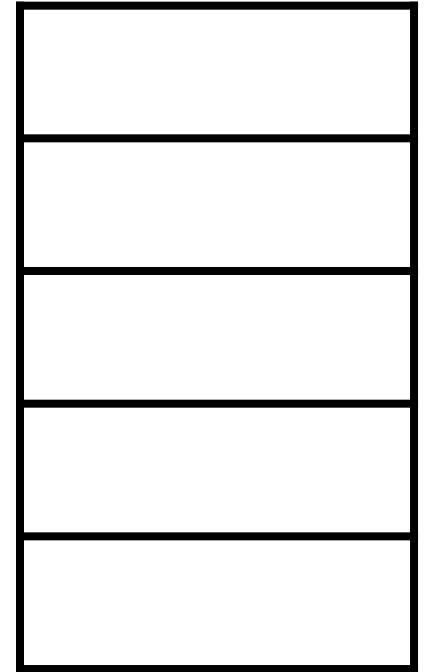
A **queue** stores an ordered collection of objects (like a list)

However you can only do two* operations:

Enqueue: Put an item at the back of the queue

Dequeue: Remove and return the front item of the queue

Front



```
enqueue (3) ; enqueue (5) ; dequeue () ; enqueue (2)
```

Queue Data Structure

The queue is a **first in — first out** data structure (FIFO)

What data structure excels at removing from the front?

Can we make that same data structure good at inserting at the end?

Queue Data Structure

The C++ implementation of a queue is also a vector or deque — why?

Engineering vs Theory Efficiency

	Time x1 billion	Like
L1 cache reference	0.5 seconds	Heartbeat 💖
Branch mispredict	5 seconds	Yawn 🥱
L2 cache reference	7 seconds	Long yawn 🥱 🥱 🥱
Mutex lock/unlock	25 seconds	Make coffee ☕
Main memory reference	100 seconds	Brush teeth
Compress 1K bytes	50 minutes	TV show 📺
Send 2K bytes over 1 Gbps network	5.5 hours	(Brief) Night's sleep 🛌
SSD random read	1.7 days	Weekend
Read 1 MB sequentially from memory	2.9 days	Long weekend
Read 1 MB sequentially from SSD	11.6 days	2 weeks for delivery 📦
Disk seek	16.5 weeks	Semester
Read 1 MB sequentially from disk	7.8 months	Human gestation 🐣
Above two together	1 year	🌍 ☀️
Send packet CA->Netherlands->CA	4.8 years	Ph.D. 🎓

(Care of <https://gist.github.com/hellerbarde/2843375>)

Engineering vs Theory Efficiency

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Send packet CA->Netherlands->CA	4.8 years	Ph.D. 🎓

(Care of <https://gist.github.com/hellerbarde/2843375>)

Queue Data Structure

```
q.enqueue(8);  
q.enqueue(4);  
q.dequeue();
```

What do we need to track to maintain a queue with an array list?

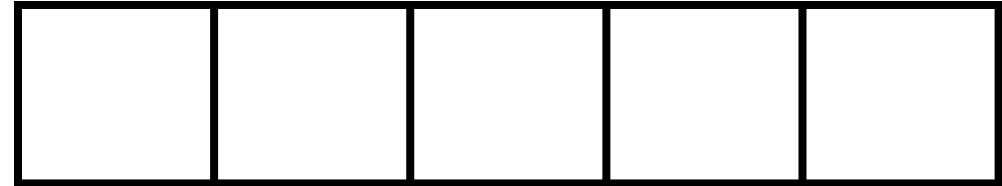


Queue Data Structure

Unlike the array list, it is easier to implement a Queue using unsigned ints

Queue.h

```
1  #pragma once
2
3  template <typename T>
4  class Queue {
5      public:
6          void enqueue(T e);
7          T dequeue();
8          bool isEmpty();
9
10     private:
11         T *data_;
12         unsigned size_;
13         unsigned capacity_;
14         unsigned front_;
15 };
```

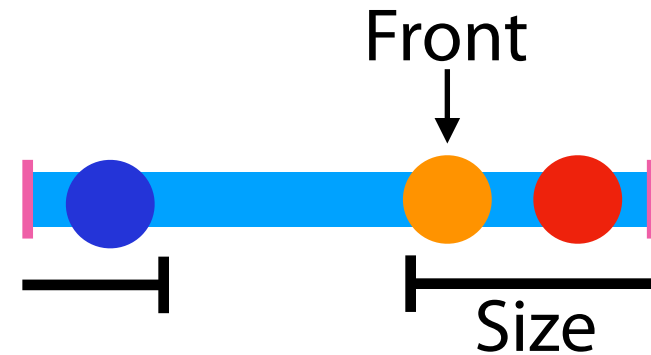
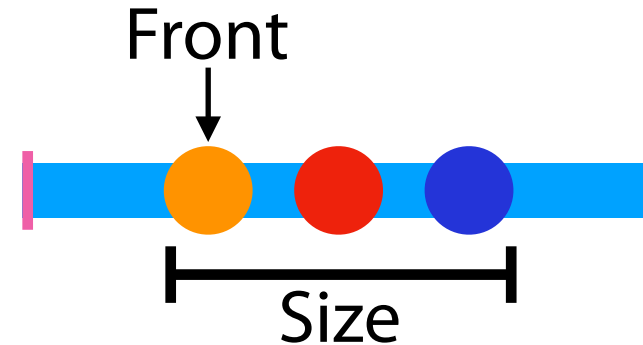


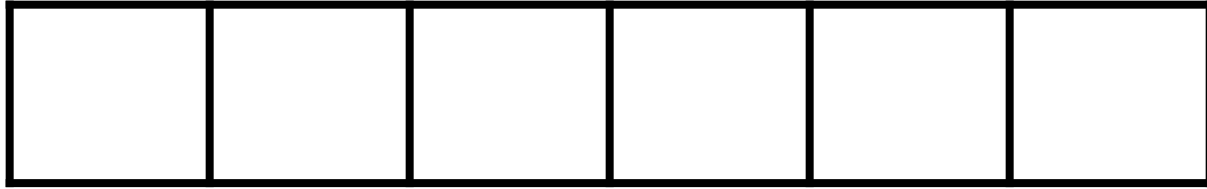
(Circular) Queue Data Structure



Queue.h

```
1 #pragma once
2
3 template <typename T>
4 class Queue {
5     public:
6         void enqueue(T e);
7         T dequeue();
8         bool isEmpty();
9
10    private:
11        T *data_;
12        unsigned capacity_;
13        unsigned size_;
14        unsigned front_;
15 };
```





Enqueue(D) :

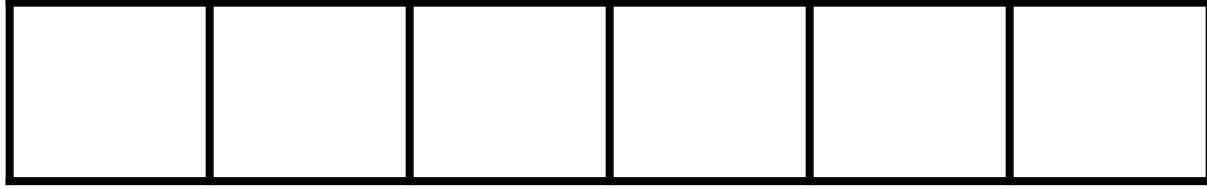
Dequeue() :

Size:

Front:

```
Queue<int> q;  
q.enqueue(3);  
q.enqueue(8);  
q.enqueue(4);  
q.dequeue();  
q.enqueue(7);  
q.dequeue();  
q.dequeue();  
q.enqueue(2);  
q.enqueue(1);  
q.enqueue(3);  
q.enqueue(5);  
q.dequeue();  
q.enqueue(9);
```

Capacity:



Enqueue(D): Insert @ $(\text{size} + \text{front}) \% \text{capacity}$
size++ until size == capacity

Dequeue(): Remove @front
 $\text{front} = (\text{front} + 1) \% \text{capacity}$
size--

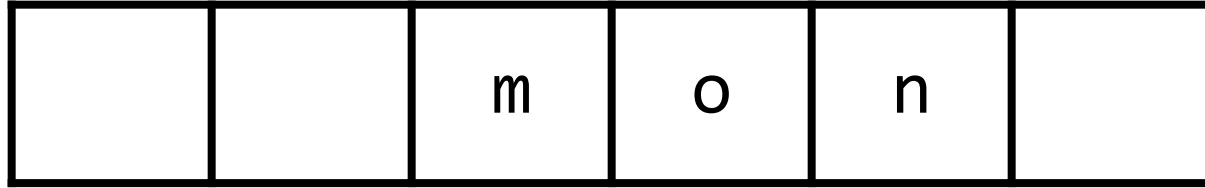
Size:

Front:

Capacity:

```
Queue<int> q;  
q.enqueue(3);  
q.enqueue(8);  
q.enqueue(4);  
q.dequeue();  
q.enqueue(7);  
q.dequeue();  
q.dequeue();  
q.enqueue(2);  
q.enqueue(1);  
q.enqueue(3);  
q.enqueue(5);  
q.dequeue();  
q.enqueue(9);
```

Queue Data Structure: Resizing



```
Queue<char> q;
```

```
...
```

```
q.enqueue(d);
```

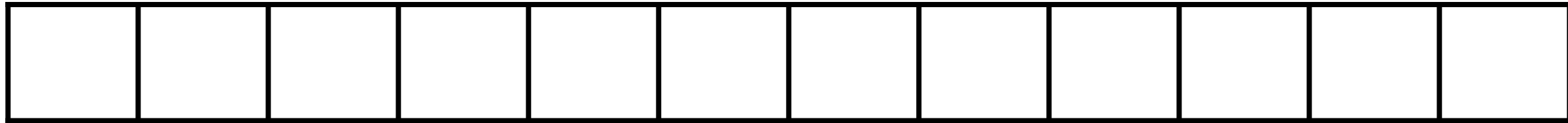
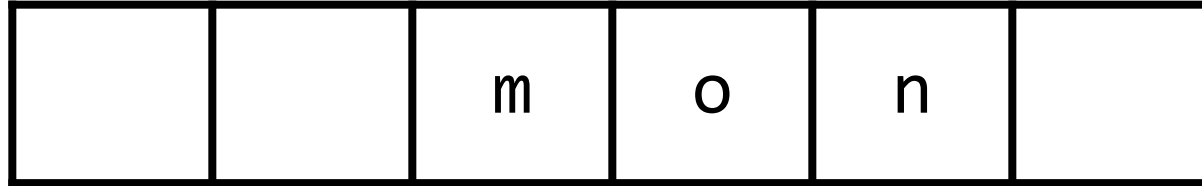
```
q.enqueue(a);
```

```
q.enqueue(y);
```

```
q.enqueue(i);
```

```
q.enqueue(s);
```

Queue Data Structure: Resizing



```
Queue<char> q;
```

```
...
```

```
q.enqueue(d);
```

```
q.enqueue(a);
```

```
q.enqueue(y);
```

```
q.enqueue(i);
```

```
q.enqueue(s);
```

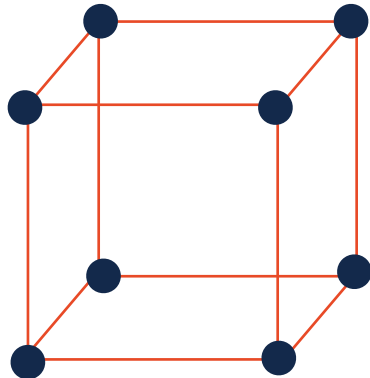

Queue ADT

- [Order]:
- [Implementation]:
- [Runtime]:



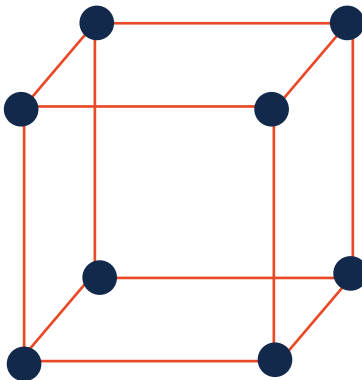
Iterators

We want to be able to loop through all elements for any underlying implementation in a systematic way



Iterators

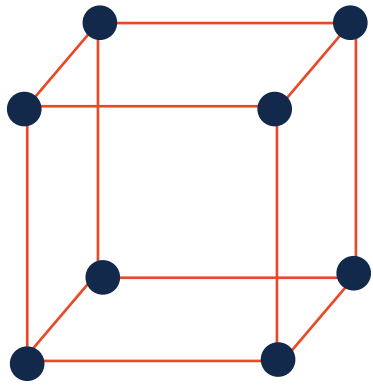
We want to be able to loop through all elements for any underlying implementation in a systematic way



Cur. Location	Cur. Data	Next
ListNode * curr		
unsigned index		
Some form of (x, y, z)		

Iterators

Iterators provide a way to access items in a container without exposing the underlying structure of the container



```
1 Cube::Iterator start = myCube.begin();  
2  
3 while (it != myCube.end()) {  
4     std::cout << *it << " ";  
5     it++;  
6 }  
7
```

Iterators

For a class to implement an iterator, it needs two functions:

Iterator begin()

Iterator end()

Iterators

The actual iterator is defined as a class **inside** the outer class:

1. It must be of base class **std::iterator**

2. It must implement at least the following operations:

Iterator& operator ++()

const T & operator *()

bool operator !=(const Iterator &)

Iterators



Here is a (truncated) example of an iterator:

```
1  template <class T>
2  class List {
3
4      class ListIterator : public
5  std::iterator<std::bidirectional_iterator_tag, T> {
6      public:
7
8          ListIterator& operator++();
9
10         ListIterator& operator--();
11
12         bool operator!=(const ListIterator& rhs);
13
14         const T& operator*();
15     };
16
17     ListIterator begin() const;
18
19     ListIterator end() const;
20 };
```

```
1  #include <list>
2  #include <string>
3  #include <iostream>
4
5  struct Animal {
6      std::string name, food;
7      bool big;
8      Animal(std::string name = "blob", std::string food = "you", bool big = true) :
9          name(name), food(food), big(big) { /* nothing */ }
10 };
11
12 int main() {
13     Animal g("giraffe", "leaves", true), p("penguin", "fish", false), b("bear");
14     std::vector<Animal> zoo;
15
16     zoo.push_back(g);
17     zoo.push_back(p);    // std::vector's insertAtEnd
18     zoo.push_back(b);
19
20     for ( std::vector<Animal>::iterator it = zoo.begin(); it != zoo.end(); ++it ) {
21         std::cout << (*it).name << " " << (*it).food << std::endl;
22     }
23
24     return 0;
25 }
```



```
1
2 std::vector<Animal> zoo;
3
4
5 /* Full text snippet */
6
7     for ( std::vector<Animal>::iterator it = zoo.begin(); it != zoo.end(); ++it ) {
8         std::cout << (*it).name << " " << (*it).food << std::endl;
9     }
10
11
12 /* Auto Snippet */
13
14     for ( auto it = zoo.begin(); it != zoo.end; ++it ) {
15         std::cout << animal.name << " " << animal.food << std::endl;
16     }
17
18 /* For Each Snippet */
19
20     for ( const Animal & animal : zoo ) {
21         std::cout << animal.name << " " << animal.food << std::endl;
22     }
23
24
25
```

Trees

“The most important non-linear data structure in computer science.”

- David Knuth, The Art of Programming, Vol. 1

A tree is:

-
-

