CSC 212: Data Structures and Abstractions

08: Queues

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THINK BIG WE DO℠

Solution to lab problem

```
int eval(const std::string& exp) {
    std::stack<int> operands;
    std::stack<char> operators;

    for (size_t i = 0 ; i < exp.length() ; ++i) {
        if (exp[i] == ' ' || exp[i] == '(') {
            continue;
        } else if (isdigit(exp[i])) {
            operands.push(exp[i] - '0');
        } else if (exp[i] == '+' || exp[i] == '-' || exp[i] == '*' || exp[i] == '/') {
            operators.push(exp[i]);
        } else if (exp[i] == ')') {
            int right = operands.top();
            operands.pop();
            int left = operands.top();
            operands.pop();
            char op = operators.top();
            operators.pop();
            switch (op) {
                case '+': operands.push(left + right); break;
                case '-': operands.push(left - right); break;
                case '*': operands.push(left * right); break;
                case '/': operands.push(left / right); break;
            }
        }
    }
    return operands.top();
}
```

Stacks

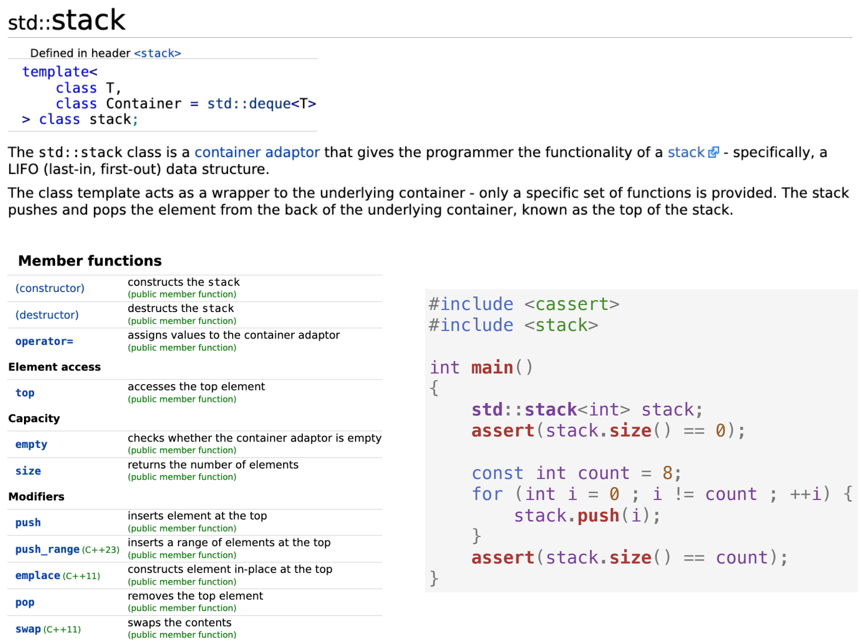
- Consider a stack implemented by a dynamic array (insertion and deletion at the end)
  - ✓ what is the computational cost?

Push	O(1) amortized
Pop	O(1)

- Consider a stack implemented by a dynamic array (insertion and deletion at the beginning)
  - ✓ what is the computational cost?

both operations require shifting elements

Push	O(n)
Pop	O(n)



std::stack

Defined in header `<stack>`

```
template<
    class T,
    class Container = std::deque<T>
> class stack;
```

The `std::stack` class is a container adaptor that gives the programmer the functionality of a stack - specifically, a LIFO (last-in, first-out) data structure.

The class template acts as a wrapper to the underlying container - only a specific set of functions is provided. The stack pushes and pops the element from the back of the underlying container, known as the top of the stack.

Member functions

(constructor)	constructs the stack (public member function)
(destructor)	destructs the stack (public member function)
`operator=`	assigns values to the container adaptor (public member function)
Element access	
`top`	accesses the top element (public member function)
Capacity	
`empty`	checks whether the container adaptor is empty (public member function)
`size`	returns the number of elements (public member function)
Modifiers	
`push`	inserts element at the top (public member function)
`push_range` (C++23)	inserts a range of elements at the top (public member function)
`emplace` (C++11)	constructs element in-place at the top (public member function)
`pop`	removes the top element (public member function)
`swap` (C++11)	swaps the contents (public member function)

```
#include <cassert>
#include <stack>

int main()
{
    std::stack<int> stack;
    assert(stack.size() == 0);

    const int count = 8;
    for (int i = 0 ; i != count ; ++i) {
        stack.push(i);
    }
    assert(stack.size() == count);
}
```

https://en.cppreference.com/w/cpp/container/stack

Queues

Queues

- First-in-first-out
  - ✓ a **queue** is a linear data structure that follows the (FIFO) principle
  - ✓ the first element added to the queue is the first one to be removed
    - analogous to a real-world queue, such as a line of people waiting for service
- Main operations
  - ✓ **Enqueue**: add an element to the end of the queue
  - ✓ **Dequeue**: remove an element from the front of the queue
- Applications
  - ✓ scheduling tasks in operating systems, managing requests in web servers, implementing breadth-first search (BFS) in graph algorithms, etc.

Practice

- What is the output of this code?

```
Queue<int> s1, s2;

s1.enqueue(100);
s2.enqueue(s1.dequeue());
s1.enqueue(200);
s1.enqueue(300);
s2.enqueue(s1.dequeue());
s2.enqueue(s1.dequeue());

s1.enqueue(s2.dequeue());
s1.enqueue(s2.dequeue());

while (!s1.empty()) {
    std::cout << s1.dequeue() << std::endl;
}

while (!s2.empty()) {
    std::cout << s2.dequeue() << std::endl;
}
```

Practice

- Write a function that modifies a queue of elements by replacing every element with two copies of itself
  - ✓ for example: [a, b, c] becomes [a, a, b, b, c, c]

Practice

- Design an algorithm to:
  - ✓ load a number of audio files (songs)
  - ✓ play them in a continuous loop

Practice

- Write an algorithm to reverse the order of elements of a queue (hint: can use a separate stack)

- Write an algorithm that accepts a queue of elements and appends the queue's contents to itself in reverse order (hint: can use a separate stack)
  - ✓ for example: [a, b, c] becomes [a, b, c, c, b, a]

Implementation

- Using arrays
  - ✓ ensure **enqueue** and **dequeue** work at <u>different ends</u> of the array
  - ✓ array can be fixed-length or a dynamic array (additional cost)

- Considerations
  - ✓ underflow: throw an error when calling dequeue on an empty queue
  - ✓ overflow: throw an error when calling enqueue on a full queue

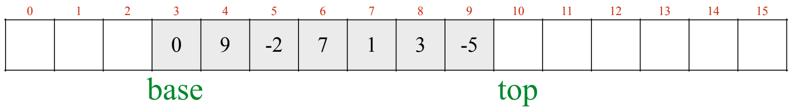
Implementation

- Array-based (standard)
  - ✓ enqueue at the end — $O(1)$ cost (amortized cost if using a dynamic array)
  - ✓ dequeue from the beginning — $O(n)$ cost
    - requires shifting elements

- Array-based (alternative)
  - ✓ enqueue at the beginning — $O(n)$ cost
    - requires shifting elements
  - ✓ dequeue from the end — $O(1)$ cost

- Circular array
  - ✓ enqueue at the end — $O(1)$ cost (amortized cost if using a dynamic array)
  - ✓ dequeue from the beginning — $O(1)$ cost
  - ✓ more efficient approach, as it eliminates the need for shifting elements
  - ✓ requires handling wrap-around at array boundaries

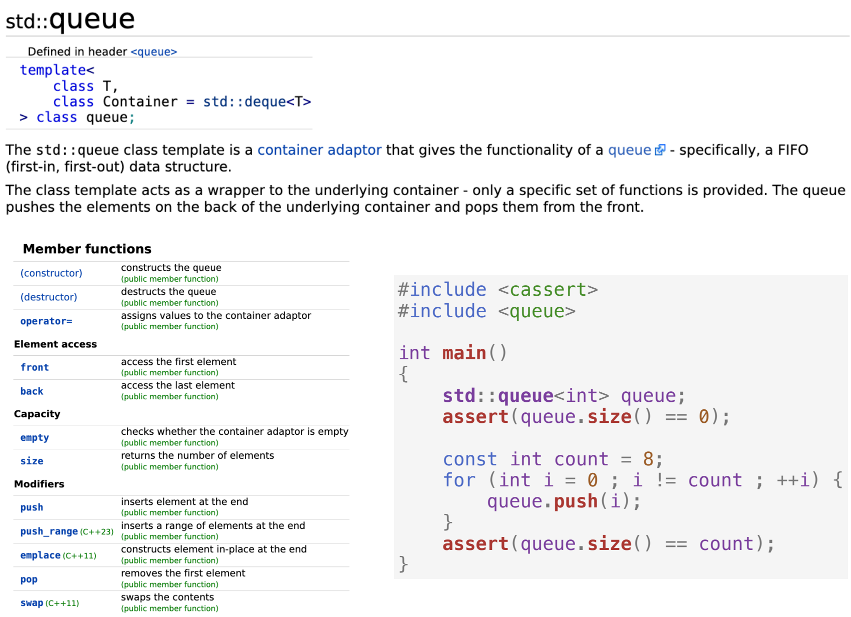
Circular array



0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			0	9	-2	7	1	3	-5						

https://www.cs.usfca.edu/~galles/visualization/QueueArray.html

```
// implements a (circular) queue using a fixed-size array
class Queue {
    private:
        // array to store queue elements
        int *array;
        // maximum number of elements queue can hold
        int length;
        // index of the first element in the queue
        int base;
        // index of the last element in the queue
        int top;

    public:

        Queue(int);
        ~Queue();

        // adds an element to the end of the queue
        void enqueue(int);
        // removes the first element from the queue
        int dequeue();
};
```



std::queue

Defined in header <queue>

```
template<
    class T,
    class Container = std::deque<T>
> class queue;
```

The std::queue class template is a container adaptor that gives the functionality of a queue - specifically, a FIFO (first-in, first-out) data structure.

The class template acts as a wrapper to the underlying container - only a specific set of functions is provided. The queue pushes the elements on the back of the underlying container and pops them from the front.

Member functions

(constructor)	constructs the queue (public member function)
(destructor)	destructs the queue (public member function)
operator=	assigns values to the container adaptor (public member function)
Element access	
front	access the first element (public member function)
back	access the last element (public member function)
Capacity	
empty	checks whether the container adaptor is empty (public member function)
size	returns the number of elements (public member function)
Modifiers	
push	inserts element at the end (public member function)
push_range (C++23)	inserts a range of elements at the end (public member function)
emplace (C++11)	constructs element in-place at the end (public member function)
pop	removes the first element (public member function)
swap (C++11)	swaps the contents (public member function)

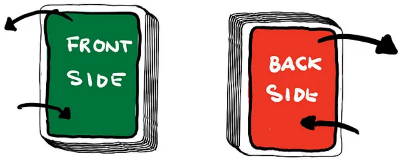
```
#include <cassert>
#include <queue>

int main()
{
    std::queue<int> queue;
    assert(queue.size() == 0);

    const int count = 8;
    for (int i = 0 ; i != count ; ++i) {
        queue.push(i);
    }
    assert(queue.size() == count);
}
```

https://en.cppreference.com/w/cpp/container/queue

Deques

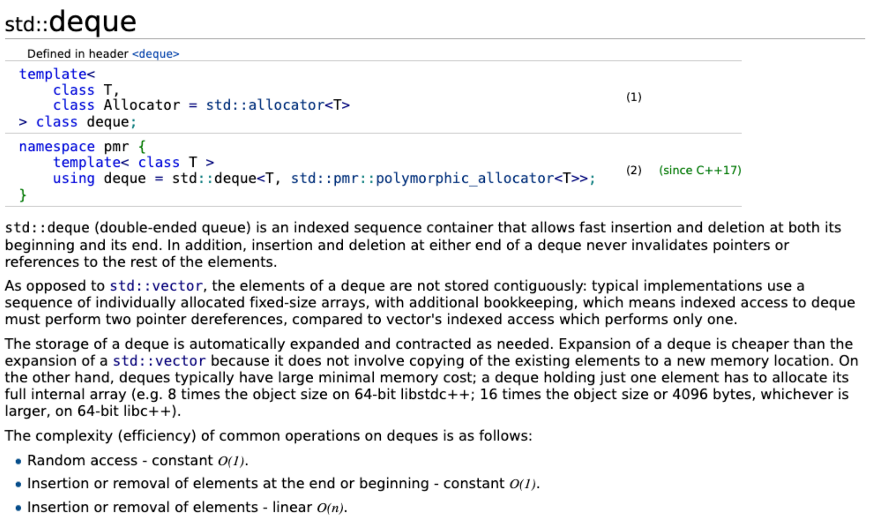
Deques

- Double-ended queue
  - ✓ a **deque** (pronounced "deck") is a linear data structure that allows insertion and removal of elements from both ends
  - ✓ combines the capabilities of stacks and queues
- Main operations
  - ✓ **InsertFront, InsertEnd**: add an element to the front or to the end of the queue respectively
  - ✓ **DeleteFront, DeleteEnd**: remove an element from the front or from the end of the queue respectively
- Applications
  - ✓ task scheduling, undo/redo functionality, web browser history (forward/backward), sliding window problems, palindrome checking, etc.



Implementation

- Using arrays
  - ✓ array can be fixed-length or a dynamic array (additional cost)
- Considerations
  - ✓ underflow: throw an error when calling "remove" on an empty queue
  - ✓ overflow: throw an error when calling "insert" on a full queue
- Circular array
  - ✓ use a circular array to allow efficient operations at both ends
  - ✓ $O(1)$ cost for all operations
    - "InsertEnd" has an amortized constant time if using a dynamic array



std::**deque**

Defined in header <deque>

```
template<
    class T,
    class Allocator = std::allocator<T>
> class deque;                                                    (1)
```

```
namespace pmr {
    template< class T >
    using deque = std::deque<T, std::pmr::polymorphic_allocator<T>>;   (2)  (since C++17)
}
```

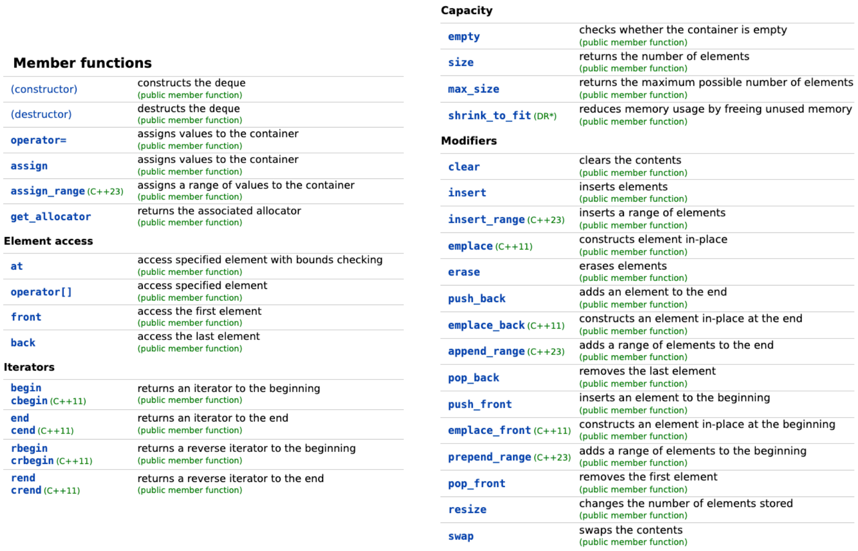
std::deque (double-ended queue) is an indexed sequence container that allows fast insertion and deletion at both its beginning and its end. In addition, insertion and deletion at either end of a deque never invalidates pointers or references to the rest of the elements.

As opposed to std::vector, the elements of a deque are not stored contiguously: typical implementations use a sequence of individually allocated fixed-size arrays, with additional bookkeeping, which means indexed access to deque must perform two pointer dereferences, compared to vector's indexed access which performs only one.

The storage of a deque is automatically expanded and contracted as needed. Expansion of a deque is cheaper than the expansion of a std::vector because it does not involve copying of the existing elements to a new memory location. On the other hand, deques typically have large minimal memory cost; a deque holding just one element has to allocate its full internal array (e.g. 8 times the object size on 64-bit libstdc++; 16 times the object size or 4096 bytes, whichever is larger, on 64-bit libc++).

The complexity (efficiency) of common operations on deques is as follows:

- Random access - constant $O(1)$.
- Insertion or removal of elements at the end or beginning - constant $O(1)$.
- Insertion or removal of elements - linear $O(n)$.



Member functions

(constructor)	constructs the deque (public member function)
(destructor)	destructs the deque (public member function)
`operator=`	assigns values to the container (public member function)
`assign`	assigns values to the container (public member function)
`assign_range` (C++23)	assigns a range of values to the container (public member function)
`get_allocator`	returns the associated allocator (public member function)
Element access	
`at`	access specified element with bounds checking (public member function)
`operator[]`	access specified element (public member function)
`front`	access the first element (public member function)
`back`	access the last element (public member function)
Iterators	
`begin` `cbegin` (C++11)	returns an iterator to the beginning (public member function)
`end` `cend` (C++11)	returns an iterator to the end (public member function)
`rbegin` `crbegin` (C++11)	returns a reverse iterator to the beginning (public member function)
`rend` `crend` (C++11)	returns a reverse iterator to the end (public member function)

Capacity

`empty`	checks whether the container is empty (public member function)
`size`	returns the number of elements (public member function)
`max_size`	returns the maximum possible number of elements (public member function)
`shrink_to_fit` (DR*)	reduces memory usage by freeing unused memory (public member function)
Modifiers	
`clear`	clears the contents (public member function)
`insert`	inserts elements (public member function)
`insert_range` (C++23)	inserts a range of elements (public member function)
`emplace` (C++11)	constructs element in-place (public member function)
`erase`	erases elements (public member function)
`push_back`	adds an element to the end (public member function)
`emplace_back` (C++11)	constructs an element in-place at the end (public member function)
`append_range` (C++23)	adds a range of elements to the end (public member function)
`pop_back`	removes the last element (public member function)
`push_front`	inserts an element to the beginning (public member function)
`emplace_front` (C++11)	constructs an element in-place at the beginning (public member function)
`prepend_range` (C++23)	adds a range of elements to the beginning (public member function)
`pop_front`	removes the first element (public member function)
`resize`	changes the number of elements stored (public member function)
`swap`	swaps the contents (public member function)

```cpp
#include <deque>
#include <iostream>

int main()
{
    // create a deque containing integers
    std::deque<int> d = {7, 5, 16, 8};

    // add an integer to the beginning and end of the deque
    d.push_front(13);
    d.push_back(25);

    // iterate and print values of deque
    for (int n : d) {
        std::cout << n << ' ';
    }
    std::cout << '\n';
}
```