

Lecture 21: Template & Container

Template: Code reuse; polymorphism

Container of pointers: 1 invariant & 3 rules

- *At-most-once invariant*: any object can be linked to at most one container at any time through pointer.
1. *Existence*: An object must be dynamically allocated before a pointer to it is inserted.
 2. *Ownership*: Once a pointer to an object is inserted, that object becomes the property of the container. No one else may use or modify it in any way.
 3. *Conservation*: When a pointer is removed from a container, either the pointer must be inserted into some container, or its referent must be deleted.

```
template <class T>
class Set {
    T **elts; // An array of T *
    int numElts;
    int sizeElts;
public:
    bool isEmpty();
    void insert(T *vp);
    T *remove();
    Set(int sizeElts = MAXELTS);
    Set(const Set &s);
    Set &operator=(const Set &s);
    ~Set();
};

// where needs to put <T>
Set<T>::Set(){...}
Set<T>::Set(const Set<T> &s){...}
Set<T> &Set<T>::operator=(const Set<T> &s){...}
Set<T>::~~Set(){...}
```

Which invariant/rule is violated?

```
// 1
Set<T>::Set(const Set<T> &s){
    for(int i = 0; i < s.numElts; ++i){
        insert(s[i]);
    }
}

// 2
Set<T>::~~Set(){
```

```

        while(numElts > 0){
            remove();
        }
    }

    // -----
    Set<int> s1;
    Set<int> s2;

    int *v1;
    int *v2 = new int(5);
    int *v3 = new int(6);

    // 3
    s1.insert(v1);
    for(int i = 0; i < 3; ++i){
        s2.insert(&i);
    }

    // 4
    s1.insert(v2);
    delete v2;

    // 5
    int *v3 = new int(*(s1.remove()));
    s2.insert(v3);

```

Answer:

1. At-most-once invariant
2. Conservation rule
3. Existence rule
4. Ownership rule
5. Conservation rule

Polymorphic Container

```

class BigThing : public Object {
    ...
};

Set<Object> s;
BigThing *bp1 = new BigThing;
s.insert(bp1); // Legal due to substitution rule

Object *op;
BigThing *bp2;
op = s.remove();
bp2 = dynamic_cast<BigThing *>(op);
// if the actual type of `op` is either pointer to `BigThing` or some
pointer to derived class of `BigThing`, `bp2` will be assigned a pointer

```

```
to `BigThing`; Otherwise, `bp2` will be a null pointer
assert(bp2);
```

For more about dynamic cast, see [here](#). Notice that we should make sure the classes have one or more virtual methods.

Lecture 22: Operator Overload

For full explanations see [Operators](#).

C++ lets us redefine the meaning of the operators when applied to objects of class type. This is known as operator overloading.

Like any other function, an overloaded operator has a return type and a parameter list.

Unary operators

```
A A::operator-() const;
A& A::operator++();    // ++a
A A::operator++(int);  // a++
A& A::operator--();    // --a
A A::operator--(int);  // a--
```

Binary operators

```
A& A::operator= (const A& rhs);
A& A::operator+= (const A& rhs);
A& A::operator-= (const A& rhs);
A operator+ (const A& lhs, const A& rhs);
istream& operator>> (istream& is, A& rhs);
ostream& operator<< (ostream& os, const A& rhs);
bool operator== (const A& lhs, const A& rhs);
bool operator!= (const A& lhs, const A& rhs);
bool operator< (const A& lhs, const A& rhs);
bool operator<= (const A& lhs, const A& rhs);
bool operator> (const A& lhs, const A& rhs);
bool operator>= (const A& lhs, const A& rhs);

// Especially:
const T& A::operator[] (size_t pos) const;
T& A::operator[] (size_t pos);
```

Lecture 23: Linear List; Stack

1. Linear List

The main idea thing is that the operations are based by position. And if the position that you are going to access are invalid, you should throw `BoundsError` exception.

2. Stack

Property: last in, first out (*LIFO*).

Methods of Stack

- `size()`: number of elements in the stack.
- `isEmpty()`: check if stack has no elements.
- `push(Object o)`: add object o to the **top** of the stack.
- `pop()`: remove the **top** object if stack is not empty; otherwise, throw `stackEmpty`.
- `Object &top()`: returns a reference to the top element.

Implementation

Using Arrays

Need an `int size` to record the size of the stack.

- `size()`: return `size`;
- `isEmpty()`: return `(size == 0)`;
- `push(Object o)`: add object o to the **top** of the stack and increment `size`. Allocate more space if necessary.
- `pop()`: If `isEmpty()`, throw `stackEmpty`; otherwise, decrement `size`.
- `Object &top()`: returns a reference to the top element `Array[size-1]`.

Using Linked Lists

- `size()`: `LinkedList::size()`;
- `isEmpty()`: `LinkedList::isEmpty()`;
- `push(Object o)`: insert object at the beginning `LinkedList::insertFirst(Object o)`;
- `pop()`: remove the first node `LinkedList::removeFirst()`;
- `Object &top()`: returns a reference to the object stored in the first node.

Comparison: memory and time trade-off

1. Linked List:
 - memory efficient: a new item just needs extra constant amount of memory
 - time inefficient for `size()` operation because need to traverse the whole list
2. Array:
 - time efficient for `size()`.
 - memory inefficient: need to allocate a big enough array

Applications

1. Function calls in C++
2. Web browser's "back" feature

3. Parentheses Matching

Lecture 24: Queue

Very commonly used data structure. Basic principle: "First In First Out" (**FIFO**).

Methods of Queue

Most important methods (almost all kinds of queues has these methods):

- **enqueue(Object o)**: add object o to the rear of the queue. (Usually returns nothing.)
- **dequeue()**: remove the front object of the queue if not empty; otherwise, throw an exception. (Usually returns the object that is removed.)
- **size()**: returns number of elements in the queue.
- **isEmpty()**: check if queue has no elements.

Other possible methods:

- **Object &front()**: returns a reference to the front element of the queue.
- **Object &rear()**: returns a reference to the rear element of the queue.

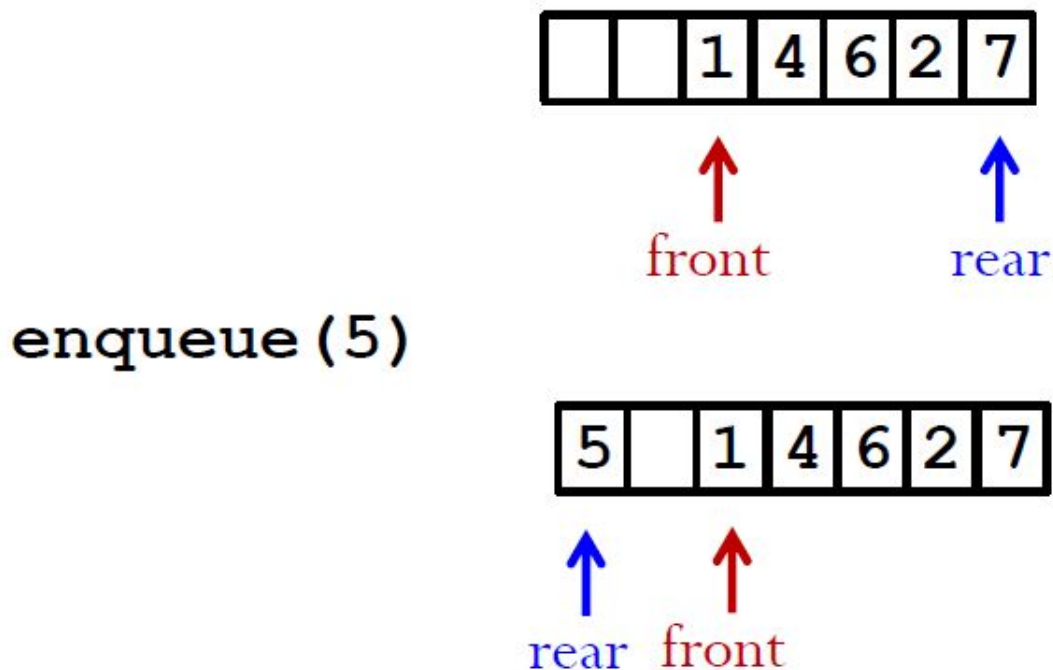
Queues Using Linked Lists

How to implement the methods using linked lists:

- **enqueue(Object o)**: add a node to the end of the linked list.
- **dequeue()**: remove a node from the head of the linked list.
- **size()**: can iterate through the linked list and count the number of nodes.
- **isEmpty()**: check if the pointer to the linked list is **NULL**.
- **Object &front()**: returns a reference to the node at the head of the linked list.
- **Object &rear()**: returns a reference to the node at the end of the linked list.

Queues Using Arrays

- Let the elements "drift" within the array.
- Maintain two integers to indicate the front and the rear of the queue (advance **front** when dequeuing; advance **rear** when inserting).
- Use a circular array (more space efficient):

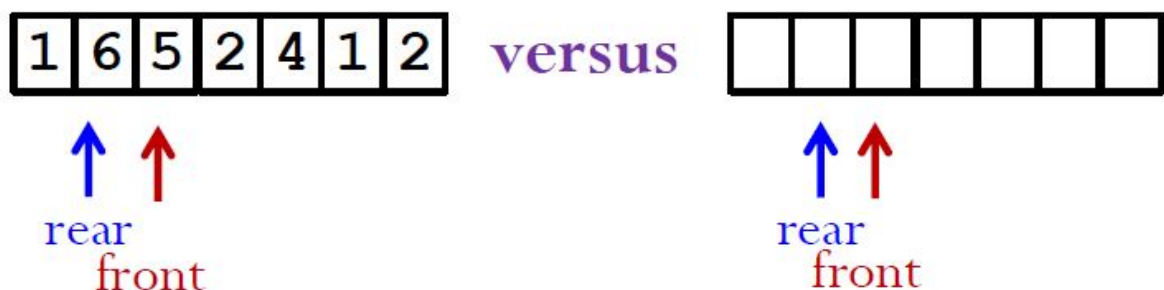


When inserting a new element, advance **rear** circularly; when popping out an element, advance **front** circularly.

Can be realized by

```
front = (front+1) % MAXSIZE;
rear = (rear+1) % MAXSIZE;
```

- Solve the problem of distinguishing an empty queue and full queue:



Maintain a **flag** indicating empty or full, or a **count** on the number of elements in the queue.

We can see that using array can be more complicated than linked list, and the size can be restricted by **MAXSIZE** of array. However, it can be easier to access the elements by index. For example, the index of the second element can be **front+1** (if not exceeding the capacity of array). Still, accessing elements by index is not very useful in queues.

Deque

Property: Items can be inserted and removed from both ends of the list.

Methods:

- `push_front(Object o)`
- `push_back(Object o)`
- `pop_front()`
- `pop_back()`

The implementation can be more complicated than queue. Only use it if inserting and removing from both ends are truly necessary.

Lecture 25, 26: STL

Three kinds of containers:

- **Sequential Containers:** let the programmer control the order in which the elements are stored and accessed. The order doesn't depend on the values of the elements.
- **Associative Containers:** store elements based on their *values*.
- **Container Adaptors:** take an existing container type and make it act like a different type

Sequential Containers:

1. **vector:** based on arrays.
 - fast random access
 - fast insert/delete at the back
 - inserting / deleting at other position is slow
2. **deque** (double-ended queue): based on arrays.
 - fast random access (`operator[]`)
 - fast insert/delete at front or back
3. **list:** based on doubly-linked lists.
 - only bidirectional sequential access (no `operator[]`)
 - fast insert/delete at any point in the list

I. Vector

1. How to use it

```
#include <vector>
using namespace std;

vector<int> ivec; // holds ints
vector<IntSet> isvec; // holds IntSets
```

1. **Initialization**

```
vector<T> v1; // empty vector v1
vector<T> v2(v1); // copy constructor
vector<T> v3(n,t); // construct v3 that has n elements with value t
```

1. Size

- `v.size()` returns a value of `size_type` corresponding to the vector type.
- `vector<int>::size_type`
 - a companion type of vector (why: to make the type machine-independent)
 - essentially an unsigned type
 - you can convert it into `unsigned int` but not `int`:

```
unsigned int s = v.size();
```

- not `vector::size_type`
- check whether empty: `v.empty()`

1. Add/Remove

- `v.push_back(t)`: add element `t` to the end of `v`
 - container elements are copies: no relationship between the element in the container and the value from which it was copied
- `v.pop_back()`: remove the last element in `v`. `v` must be non-empty

1. Subscripting Vector

```
vector<int>::size_type n;
v[n] = 0; //must ensure that the v.size() > n

for (n = 0; n != v.size(); ++n) {
    v[n] = 0;
}
```

1. other operations:

```
v1 = v2;
v.clear();
v.front(); //non-empty
v.back(); //non-empty
```


Iterator

All of the library containers define iterator types, but only a few of them support subscripting.

1. Declaratino: `vector<int>::iterator it;`
2.
 - `v.begin()` returns an iterator pointing to the first element of vector
 - `v.end()` returns an iterator positioning to **one-past-the-end** of the vector
 - usually used to indicate when we have processed all the elements in the vector
 - If the vector is empty, the iterator returned by `begin` is the same as the iterator returned by `end`, e.g.
3. Operations:
 - dereference: can read/write through `*iter` (cannot dereference the iterator returned by `end()`)
 - `++iter`, `iter++`: next item (cannot increment the iterator returned by `end()`);
`--iter`, `iter--` go back to the previous item
 - `iter == iter1` and `iter != iter1`: check whether two iterators point to the same data item

```
vector<int>::iterator begin = ivec.begin();
vector<int>::iterator end = ivec.end();
while (begin != end) {
    cout << *begin++ << " ";
    // 1. get the value of *begin
    // 2. cout << *begin << " ";
    // 3. begin++;
}
```

4. `const_iterator`: cannot change the value of the element it refers to.
 - Declaration: `vector<int>::const_iterator it;`
 - check `cbegin()` and `cend()`, which will return const iterator.

5. Iterator Arithmetic

Not all containers support! Check random access iterator [here](#) for example.

- `iter+n`, `iter-n`, where `n` is an integer
- example: go to the middle

```
vector<int>::iterator mid;
mid = v.begin() + v.size()/2;
```

6. Relational Operation: `>`, `>=`, `<`, `<=`

Not all containers support!

- To compare, iterators must refer to elements in the same container or one past the end of the container (`c.end()`)

7. More about initialization of vector `vector<T> v(b,e)`: create vector `v` with a copy of the elements from the range denoted by iterators `b` and `e`.

- `[b,e)`
- check the constructor of the containers, `vector` for example.

```
vector<int> front(v.begin(), mid);
```

- You can use deque to initialize vector, e.g.

```
deque<string> ds(10, "abc");
vector<string> vs(ds.begin(), ds.end());
```

- Use array to initialize vector:

```
int a[] = {1, 2, 3, 4};
unsigned int sz = sizeof(a) / sizeof(int);
vector<int> vi(a, a+sz);
```

8. `v.insert(p, t)`

- inserts element with value `t` **right before** the element referred to by iterator `p`.
- returns an iterator referring to the element that was added

9. `v.erase(p)`

- removes element referred to by iterator `p`.
- returns an iterator referring to the element after the one deleted, or an **off-the-end** iterator if `p` referred to the last element.

II. Deque

1. `#include <deque>`

2. Similarities with vector:

- **Initialization:**
 - `deque<T> d; deque<T> d(d1);`
 - `deque<T> d(n,t)`: create `d` with `n` elements, each with value `t`.
 - `deque<T> d(b,e)`: create `d` with a copy of the elements from the range denoted by iterators `b` and `e`.
- `size()`, `empty()`

- `push_back()`, `pop_back()`
- random access through `d[k]`
- `begin()`, `end()`, `insert(p,t)`, `erase(p)`
- operations on iterators: `*iter`, `++iter`, `--iter`, `iter != iter2`, `iter == iter2`.....

3. Difference with vector:

- `d.push_front(t)`
- `d.pop_front(t)`

III. List

1. `#include <list>`

2. only bidirectional sequential access

3. Similarities with vector:

- Initialization:
 - `list<T> l; list<T> l(l1);`
 - `list<T> l(n,t)`: create `l` with `n` elements, each with value `t`.
 - `list<T> l(b,e)`: create `l` with a copy of the elements from the range denoted by iterators `b` and `e`.
- `size()`, `empty()`
- `push_back()`, `pop_back()`
- `begin()`, `end()`, `insert(p,t)`, `erase(p)`
- operations on iterators: `*iter`, `++iter`, `--iter`, `iter != iter2`, `iter == iter2`.....

4. Difference with vectors

- not support subscripting
- not support iterator arithmetic, i.e. cannot do `it+3`, you can only use `++/--`
- no relational operation `<`, `<=`, `>`, `>=`, you can only use `==` and `!=` to compare
- `l.push_front(t)`
- `l.pop_front(t)`

Choose appropriate containers

1. Use vector, unless have other good reasons
2. require random access: vector or deque
3. insert or delete elements in the middle: list
4. insert or delete elements at the front and the back: deque
5. others: check the predominant operations

Container Adaptors

e.g. `stack`, `queue`, `priority_queue` (will be learned in 281)

1. `#include <stack>` and `#include <queue>`
2. By default, there are implemented using deque. So if you initialize it in this way: `stack<int> stk(deq);`, `deq` must be a deque. But you can also use vector or list to build stack:

```
// Assume ivec is vector<int>
stack<int, vector<int> > stk(ivec);
//                ^ theres is a space here
```

1. Notice that for queue, you can use deque and list to build it (no vector here). Check the link.
2. Be aware that the names of the operations are different with previous ones. Check the link.

stack	queue
s.empty()	q.empty()
s.size()	q.size()
s.pop()	q.pop()
s.push(item)	q.push(item)
s.top()	q.front()

Associative Container

ADT: Dictionary

1. quickly add (key, value) pair and retrieve value by key
2. Methods
 - Value find(Key K): return the value whose key is K. Return Null if none.
 - void insert(Key K, Value V): Insert a pair (K, V) into the dictionary. If the pair with key as K already exists, **update** the value.
 - Value remove(Key K): Remove the pair with key as K from the dictionary and return its value. Return Null if none.
 - int size(): return number of pairs in the dictionary.
3. Implementation: array or linked list.

Applications:

1. map: dictionary, elements are (key, value) pairs
2. set: contains only a key and supports efficient queries to whether a given key is present.

Map: associative array

Important: key cannot be duplicate

1. `#include <map>`
2. **Constructors:**
 - `map<k, v> m;` // create an empty map named m
 - `map<k, v> m(m1);` // create m as a copy of m1, the two maps must have the same key and value types

- `map<k, v> m(b, e)` // create m as a copy of the elements from the range denoted by iterators b and e

3. Elements are sorted by keys, so the key type should have: strict weak ordering (<)

4. iterators: `map<string, int>::iterator it = word_count.begin()`, then `*it` is a reference to a `pair<const string, int>`.

- Please notice that `it->first` is const, so we cannot write `it->first = "new key";`.
- To access the value, use `it->second`, you can assign new value to it.
- Note that here we are using arrows (->) to access its key or value.

5. Adding elements to a map

- use subscript operator (different with `vector`)
 - if the key is already there in the map, then there is nothing new. You can read or update the value using `m[k]=v`.
 - if the key is not there, `m[k] = v` will
 1. search the key `k` and don't find it.
 2. insert (k, default_v) to the map. If `v` is `int`, it will insert (k, 0).
 3. update (k, default_v) to (k, v)
- use `insert` member:
 - `m.insert(e)`, where `e` is a (key, value) pair. If the key is not in m, then insert the pair. Otherwise, does nothing.
 - returns a **pair** of (map iterator, bool)
 - map iterator refers to the element with key
 - bool indicates whether the element was inserted or not

```
#include <iostream>
#include <map>

int main (){
    std::map<char,int> mymap;

    // first insert function version (single parameter):
    mymap.insert ( std::pair<char,int>('a',100) );
    // can also use mymap.insert(std::make_pair('a', 100))
    // remember to #include <utility> if you use make_pair
    mymap.insert ( std::pair<char,int>('z',200) );

    std::pair<std::map<char,int>::iterator,bool> ret;
    ret = mymap.insert ( std::pair<char,int>('z',500) );
    if (ret.second==false) {
        std::cout << "element 'z' already existed";
        std::cout << " with a value of " << ret.first->second <<
'\n';
    }
}
```

6. find elements: `m.find(k)`

- returns an iterator to the element indexed by key `k` if there is one
- else, returns an off-the-end iterator: compare with `end()` to check whether the key is there

```
int occurs = 0;
map<string, int>::iterator it = world_count.find("abc");
if (it != world_count.end()) occurs = it->second;
```

7. remove elements:

- `m.erase(iter)`
 - removes element referred to by the iterator `iter` from `m`. `iter` must refer to an actual element in `m`; it must not be `m.end()`
 - returns void
- `m.erase(k)`
 - removes the element with key `k` from `m` if it exists
 - otherwise, do nothing
 - returns the number of elements removed, either 0 or 1 for map.

8. iterate across a map: When we use a niterator to traverse a map, the iterators yield elements in ascending key order.

```
map<string, int>::iterator it;
for(it = word_count.begin(); it != word_count.end(); ++it) {
    cout << it->first << " occurs" << it->second << " times";
}
```

For the STL part, please search the thing you need in www.cplusplus.com/reference/ or en.cppreference.com/w/ often