

C++ Programming II

Introduction to Standard Template Library
Overview STL Containers

C++ Programming II
September 16, 2018

Prof. Dr. P. Arnold
Bern University of Applied Sciences

► Standard Template Library



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

Agenda

- ▶ **Standard Template Library**
- ▶ **Containers**

Lecture 2

Prof. Dr. P. Arnold



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

Agenda

► Standard Template Library

► Containers

► Sequential Containers

- Vector
- Deque
- List
- Array

Lecture 2

Prof. Dr. P. Arnold



Bern University
of Applied Sciences

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

Agenda

▶ Standard Template Library

▶ Containers

▶ Sequential Containers

- ▶ Vector
- ▶ Deque
- ▶ List
- ▶ Array

▶ Associative Containers

- ▶ Set / Multiset
- ▶ Map / Multimaps

Lecture 2

Prof. Dr. P. Arnold



Bern University
of Applied Sciences

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ **Standard Template Library**
- ▶ **Containers**
- ▶ **Sequential Containers**
 - ▶ Vector
 - ▶ Deque
 - ▶ List
 - ▶ Array
- ▶ **Associative Containers**
 - ▶ Set / Multiset
 - ▶ Map / Multimap
- ▶ **Unordered Containers**
 - ▶ Unordered Set / Unordered Multiset



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ **Standard Template Library**
- ▶ **Containers**
- ▶ **Sequential Containers**
 - ▶ Vector
 - ▶ Deque
 - ▶ List
 - ▶ Array
- ▶ **Associative Containers**
 - ▶ Set / Multiset
 - ▶ Map / Multimap
- ▶ **Unordered Containers**
 - ▶ Unordered Set / Unordered Multiset
- ▶ **Container Adapters**



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ **Standard Template Library**
- ▶ **Containers**
- ▶ **Sequential Containers**
 - ▶ Vector
 - ▶ Deque
 - ▶ List
 - ▶ Array
- ▶ **Associative Containers**
 - ▶ Set / Multiset
 - ▶ Map / Multimap
- ▶ **Unordered Containers**
 - ▶ Unordered Set / Unordered Multiset
- ▶ **Container Adapters**
- ▶ **Algorithms**



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

Standard Template Library

Standard Template Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered Multiset

Container Adapters

Algorithms

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

```
1 int count_a(void *buf)
2 {
3     int count;
4     char *bufr;
5     count = 0;
6     bufr = (char*)buf;
7     for(int i = 0; i < bufr != '/0'; ++i)
8     {
9         if(bufr[i] == 'a')
10        {
11            ++count;
12        }
13    }
14    return count;
15 }
```

► From this ...



```
1 size_t count_a(const std::vector<char> &vec)
2 {
3     size_t count;
4
5
6
7     for(const auto c : vec)
8     {
9         if(c == 'a')
10        {
11            ++count;
12        }
13    }
14    return count;
15 }
```

► ... over this ...

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

```
1 size_t count_a(const std::vector<char> &vec)
2 {
3     return std::count(vec.begin(), vec.end(), 'a');
4 }
```

► .. to finally this

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ The standard template library (STL) is a set of template classes and functions that supply the programmer with
 1. **Containers** for storing information
 2. **Iterators** for accessing the information stored
 3. **Algorithms** for manipulating the content of the containers

Standard Template Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ The standard template library (STL) is a set of template classes and functions that supply the programmer with
 1. **Containers** for storing information
 2. **Iterators** for accessing the information stored
 3. **Algorithms** for manipulating the content of the containers



Algorithms



Containers

- ▶ N algorithms, M containers $\rightarrow N \cdot M$ implementations



Standard Template Library

Containers

Sequential Containers

Vector
Deque
List
Array

Associative Containers

Set / Multiset
Map / Multimap

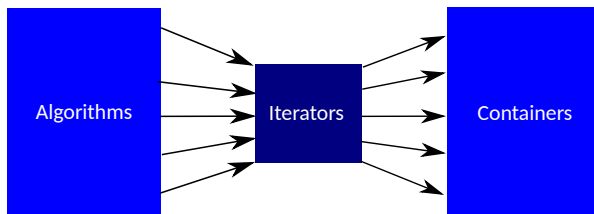
Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ The standard template library (STL) is a set of template classes and functions that supply the programmer with
 1. **Containers** for storing information
 2. **Iterators** for accessing the information stored
 3. **Algorithms** for manipulating the content of the containers



- ▶ N algorithms, M containers $\rightarrow N + M$ implementations

Standard Template Library

Containers

Sequential Containers

Vector
Deque
List
Array

Associative Containers

Set / Multiset
Map / Multimap

Unordered Containers

Unordered Set / Unordered Multiset

Container Adapters

Algorithms

Standard Template
Library

Containers

Sequential Containers

- Vector
- Deque
- List
- Array

Associative Containers

- Set / Multiset
- Map / Multimaps

Unordered Containers

- Unordered Set / Unordered Multiset

Container Adapters

Algorithms

```

1  #include <iostream>
2  #include <vector>
3
4  // Everything in STL Library is defined in the namespace std
5  using namespace std;
6
7  int main()
8  {
9      // Container
10     vector<int> vec;
11     vec.push_back(4);
12     vec.push_back(1);
13     vec.push_back(8); // vec{4, 1, 8}
14
15     // Iterator
16     vector<int>::iterator itr1 = vec.begin(); // Points to first
17     element
18     vector<int>::iterator itr2 = vec.end(); // Points to the
19     spot after the last element!
20
21     for(vector<int>::iterator itr = itr1; itr!=itr2; ++itr)
22         cout << *itr << " "; // Print out: 4 1 8
23
24     // Algorithms work on iterators
25     sort(itr1,itr2); // vec: {1, 4, 8}
26
27     return 0;
28 }
```


Example of STL Work Flow

- ▶ The majority of our C++ programs should be using STL!
- ▶ **Code reuse**, no need to re-invent the wheel
- ▶ **Efficiency** Modern C++ compilers are tuned to optimize for C++ STL code
- ▶ **Bullet prove**
- ▶ **less buggy**
- ▶ **clean and readable**
- ▶ Best use of data structure and algorithms under the hood



Standard Template Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms



Containers

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

- ▶ Containers are STL classes that are used to store data. STL supplies three types of container classes:
 1. **Sequential containers**
 2. **Associative containers**
 3. **Unordered containers**
- ▶ In addition classes called *container adapters* with reduced functionality are provided



STL - Containers

Sequential Containers (array and linked list)

Sequential containers are characterized by a **fast insertion time**, but are relatively **slow in find operations**.



STL - Containers

Sequential Containers (array and linked list)

Sequential containers are characterized by a **fast insertion time**, but are relatively **slow in find operations**.

- ▶ `std::vector` - Operates like a dynamic array and grows only at the end



STL - Containers

Sequential Containers (array and linked list)

Sequential containers are characterized by a **fast insertion time**, but are relatively **slow in find operations**.

- ▶ `std::vector` - Operates like a dynamic array and grows only at the end
- ▶ `std::deque` - Similar to `std::vector` except that it allows for new elements to be inserted or removed at the beginning, too



STL - Containers

Sequential Containers (array and linked list)

Sequential containers are characterized by a **fast insertion time**, but are relatively **slow in find operations**.

- ▶ `std::vector` - Operates like a dynamic array and grows only at the end
- ▶ `std::deque` - Similar to `std::vector` except that it allows for new elements to be inserted or removed at the beginning, too
- ▶ `std::list` - Operates like a double linked list. Like a chain where an object is a link in the chain. You can add or remove links, *i.e.* objects at any position



STL - Containers

Sequential Containers (array and linked list)

Sequential containers are characterized by a **fast insertion time**, but are relatively **slow in find operations**.

- ▶ `std::vector` - Operates like a dynamic array and grows only at the end
- ▶ `std::deque` - Similar to `std::vector` except that it allows for new elements to be inserted or removed at the beginning, too
- ▶ `std::list` - Operates like a double linked list. Like a chain where an object is a link in the chain. You can add or remove links, *i.e.* objects at any position
- ▶ `std::forward_list` Similar to a `std::list` except that it is a singly linked list of elements that allows you to iterate only in one direction



STL - Containers

Sequential Containers (array and linked list)

Sequential containers are characterized by a **fast insertion time**, but are relatively **slow in find operations**.

- ▶ `std::vector` - Operates like a dynamic array and grows only at the end
- ▶ `std::deque` - Similar to `std::vector` except that it allows for new elements to be inserted or removed at the beginning, too
- ▶ `std::list` - Operates like a double linked list. Like a chain where an object is a link in the chain. You can add or remove links, *i.e.* objects at any position
- ▶ `std::forward_list` Similar to a `std::list` except that it is a singly linked list of elements that allows you to iterate only in one direction
- ▶ `std::array` Fixed size array with the performance and accessibility of a C-style array with the benefits of a standard container, such as knowing its own size, supporting assignment, random access iterators, etc.



STL - Containers

Associative Containers (binary trees)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**



STL - Containers

Associative Containers (binary trees)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::set` - Stores unique values sorted on insertion in a container featuring logarithmic complexity $\mathcal{O}(\log n)$



STL - Containers

Associative Containers (binary trees)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::set` - Stores unique values sorted on insertion in a container featuring logarithmic complexity $\mathcal{O}(\log n)$
- ▶ `std::multiset` - Like `set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(\log n)$



STL - Containers

Associative Containers (binary trees)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::set` - Stores unique values sorted on insertion in a container featuring logarithmic complexity $\mathcal{O}(\log n)$
- ▶ `std::multiset` - Like `set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(\log n)$
- ▶ `std::map` - Stores key-value pairs sorted by their unique keys in a container with logarithmic complexity $\mathcal{O}(\log n)$



STL - Containers

Associative Containers (binary trees)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::set` - Stores unique values sorted on insertion in a container featuring logarithmic complexity $\mathcal{O}(\log n)$
- ▶ `std::multiset` - Like `set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(\log n)$
- ▶ `std::map` - Stores key-value pairs sorted by their unique keys in a container with logarithmic complexity $\mathcal{O}(\log n)$



STL - Containers

Associative Containers (binary trees)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::set` - Stores unique values sorted on insertion in a container featuring logarithmic complexity $\mathcal{O}(\log n)$
- ▶ `std::multiset` - Like `set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(\log n)$
- ▶ `std::map` - Stores key-value pairs sorted by their unique keys in a container with logarithmic complexity $\mathcal{O}(\log n)$
- ▶ `std::multimap` - Like `map`. Additionally, supports the ability to store key-value pairs where keys don't need to be unique. $\mathcal{O}(\log n)$



STL - Containers

Unordered Containers (hash tables)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**



STL - Containers

Unordered Containers (hash tables)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::unordered_set` - Stores unique values sorted on insertion in a container featuring near constant complexity $\mathcal{O}(1)$. Available starting C++ 11



STL - Containers

Unordered Containers (hash tables)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::unordered_set` - Stores unique values sorted on insertion in a container featuring near constant complexity $\mathcal{O}(1)$. Available starting C++ 11
- ▶ `std::unordered_multiset` - Like `unordered_set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(1)$ (since C++ 11)



STL - Containers

Unordered Containers (hash tables)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::unordered_set` - Stores unique values sorted on insertion in a container featuring near constant complexity $\mathcal{O}(1)$. Available starting C++ 11
- ▶ `std::unordered_multiset` - Like `unordered_set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(1)$ (since C++ 11)
- ▶ `std::unordered_map` - Stores key-value pairs sorted by their unique keys in a container with near constant complexity $\mathcal{O}(1)$ (since C++ 11)



STL - Containers

Unordered Containers (hash tables)

Associative containers store data in a sorted fashion. This results in **slower insertion times**, but **optimized search performance**

- ▶ `std::unordered_set` - Stores unique values sorted on insertion in a container featuring near constant complexity $\mathcal{O}(1)$. Available starting C++ 11
- ▶ `std::unordered_multiset` - Like `unordered_set`. Additionally, supports the ability to store multiple items having the same value; that is, the value doesn't need to be unique $\mathcal{O}(1)$ (since C++ 11)
- ▶ `std::unordered_map` - Stores key-value pairs sorted by their unique keys in a container with near constant complexity $\mathcal{O}(1)$ (since C++ 11)
- ▶ `std::unordered_multimap` - Like `unordered_map`. Additionally, supports the ability to store key-value pairs where keys don't need to be unique $\mathcal{O}(1)$ (since C++ 11)



STL - Containers

Container Adapters

Container adapters are variants of sequential and associative containers that have limited functionality and are intended to fulfill a particular purpose



STL - Containers

Container Adapters

Container adapters are variants of sequential and associative containers that have limited functionality and are intended to fulfill a particular purpose

- ▶ `std::stack` - Stores elements in a LIFO (last-in-first-out) fashion, allowing elements to be inserted (pushed) and removed (popped) at the top



STL - Containers

Container Adapters

Container adapters are variants of sequential and associative containers that have limited functionality and are intended to fulfill a particular purpose

- ▶ `std::stack` - Stores elements in a LIFO (last-in-first-out) fashion, allowing elements to be inserted (pushed) and removed (popped) at the top
- ▶ `std::queue` - Stores elements in FIFO (first-in-first-out) fashion, allowing the first element to be removed in the order they're inserted



STL - Containers

Container Adapters

Container adapters are variants of sequential and associative containers that have limited functionality and are intended to fulfill a particular purpose

- ▶ `std::stack` - Stores elements in a LIFO (last-in-first-out) fashion, allowing elements to be inserted (pushed) and removed (popped) at the top
- ▶ `std::queue` - Stores elements in FIFO (first-in-first-out) fashion, allowing the first element to be removed in the order they're inserted
- ▶ `std::priority_queue` - Stores elements in a sorted order, such that the one whose value is evaluated to be the highest is always first in the queue



STL - Containers

Headers

In order to use STL containers you have to use the following headers:

```
1 #include <vector>
2 #include <deque>
3 #include <list>
4 #include <set>           // set and multiset
5 #include <map>           // map and multimap
6 #include <unordered_set> // unordered set/multiset
7 #include <unordered_map> // unordered map/multimap
8 #include <queue>         // queue / priority_queue
9 #include <stack>
10 #include <iterator>
11 #include <algorithm>
12 #include <numeric>      // some numeric algorithms
13 #include <functional>
```





Sequential Containers

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL - Vector

Initializing Vectors

```
1 std::vector<int> vec1; // empty vector of ints
2 std::vector<int> vec2(3); // 3 ints
3 std::vector<int> vec2(3,10); // 3 ints with value 10
4 std::vector<int> vec3{1,2,3,4}; // 4 ints: 1,2,3,4
5
6 std::vector<int> vec4(vec2.begin(),vec2.end()); // via vec2
7 std::vector<int> vec5(vec3); // a copy of vec3
8
9 int myInt[] = {1,2,3}; // construct from arrays
10 std::vector<int> vec6(myInt, myInt + sizeof(myInt)/sizeof(int));
```

Lecture 2

Prof. Dr. P. Arnold



Bern University
of Applied Sciences

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL - Vector

Using Vectors

Lecture 2

Prof. Dr. P. Arnold



Bern University
of Applied Sciences

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

```
1 vector<int> vec;           // vec.size() -> 0
2 vec.push_back(4);
3 vec.push_back(1);
4 vec.push_back(8);         // vec{4, 1, 8}: vec.size() -> 3
5
6 // Vector specific (random access)
7 cout << vec[2];           // 8 (no range check)
8 cout << vec.at(2);         // 8 (throws exception out of range)
9
10 for(int i = 0; i < vec.size(); ++i)
11     cout << vec[i] << " "; // Random access possible
12
13 vector<int>::iterator itr; // Create iterator
14 for(itr = vec.begin(); itr!=vec.end(); itr++)
15     cout << *itr << " ";   // Recommended to use iterators:
16                             // 1) Faster than random access;
17                             // 2) Universal way of container
18                             //     traversing
19
20 for(auto elem : vec)         // C++ 11 - Most convenient
21     cout << elem << " ";
22
23 // Vector is a dynamically allocated contiguous array in memory
24 int* p = &vec[0];
```

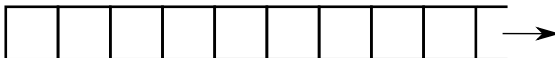


```
1 // Common member functions for all containers
2
3 if (vec.empty())
4     cout << "no elements ";
5
6 vec.size();           // 3
7
8 vector<int> vec2 (vec); // Copy Contructr, vec2: {4, 1, 8}
9
10 vec.clear();          // Remove all items: vec.size() -> 0
11
12 vec2.swap (vec);      // vec2 becomes empty, vec has 3 elements
```

Properties of STL-Vector:

- ▶ fast insert/remove at end: $\mathcal{O}(1)$
- ▶ slow insert/remove at the beginning and middle: $\mathcal{O}(n)$
- ▶ slow search: $\mathcal{O}(n)$

vector



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

Vectors grow dynamically, and every vector has a specific size. When we add a new element to a vector, the computer reallocates memory and may even copy all of the vector elements into this new memory! This can cause a performance hit.



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

Vectors grow dynamically, and every vector has a specific size. When we add a new element to a vector, the computer reallocates memory and may even copy all of the vector elements into this new memory! This can cause a performance hit.

- ▶ `capacity()` - returns the capacity of the vector, *i.e.* the number of elements that a vector can hold before a program must allocate more memory



Vectors grow dynamically, and every vector has a specific size. When we add a new element to a vector, the computer reallocates memory and may even copy all of the vector elements into this new memory! This can cause a performance hit.

- ▶ `capacity()` - returns the capacity of the vector, *i.e.* the number of elements that a vector can hold before a program must allocate more memory
- ▶ `size()` - returns the currently filled level, which is always equal to or less than the capacity



Vectors grow dynamically, and every vector has a specific size. When we add a new element to a vector, the computer reallocates memory and may even copy all of the vector elements into this new memory! This can cause a performance hit.

- ▶ `capacity()` - returns the capacity of the vector, *i.e.* the number of elements that a vector can hold before a program must allocate more memory
- ▶ `size()` - returns the currently filled level, which is always equal to or less than the capacity
- ▶ `reserve()` - increases the capacity of a vector to the number supplied as an argument



Vectors grow dynamically, and every vector has a specific size. When we add a new element to a vector, the computer reallocates memory and may even copy all of the vector elements into this new memory! This can cause a performance hit.

- ▶ `capacity()` - returns the capacity of the vector, *i.e.* the number of elements that a vector can hold before a program must allocate more memory
- ▶ `size()` - returns the currently filled level, which is always equal to or less than the capacity
- ▶ `reserve()` - increases the capacity of a vector to the number supplied as an argument

```
1 vector<int> v;  
2 for(int i = 0; i < 1000; ++i)  
3     v.push_back(i);
```

- ▶ Requires 2-18 reallocations!



Vectors grow dynamically, and every vector has a specific size. When we add a new element to a vector, the computer reallocates memory and may even copy all of the vector elements into this new memory! This can cause a performance hit.

- ▶ `capacity()` - returns the capacity of the vector, *i.e.* the number of elements that a vector can hold before a program must allocate more memory
- ▶ `size()` - returns the currently filled level, which is always equal to or less than the capacity
- ▶ `reserve()` - increases the capacity of a vector to the number supplied as an argument

```
1 vector<int> v;  
2 for(int i = 0; i < 1000; ++i)  
3     v.push_back(i);
```

- ▶ Requires 2-18 reallocations!

```
1 vector<int> v;  
2 v.reserve(1000);  
3  
4 for(int i = 0; i < 1000; ++i)  
5     v.push_back(i);
```

- ▶ Reduces cost



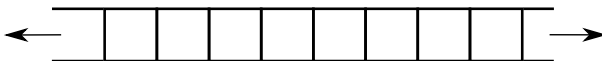
STL - Deque - Double-ended-queue

Usage

vector



deque



STL - Deque - Double-ended-queue

Usage

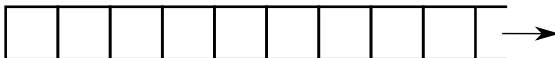
```
1 deque<int> deq = {4, 6, 7};           // C++11 container initialisation
2 deq.push_front(2);                   // deq: {2, 4, 6, 7}
3 deq.push_back(3);                    // deq: {2, 4, 6, 7, 3}
4
5 // Similar interface with vector
6 cout << deq[1];                      // 4
```

Properties of STL-Deque:

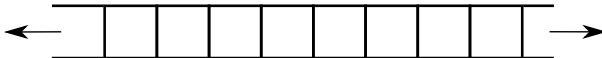
- ▶ fast insert/remove at beginning and end: $\mathcal{O}(1)$
- ▶ slow insert/remove at the middle: $\mathcal{O}(n)$
- ▶ slow search: $\mathcal{O}(n)$
- ▶ Not contiguous in memory



vector



deque



list



STL - List

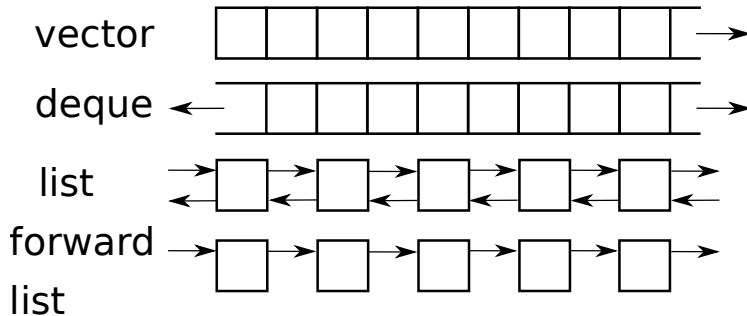
Usage

```
1 list<int> l = {5, 2, 9} ;           // C++11 container initialisation
2 l.push_back(6);                     // l: {5, 2, 9, 6}
3 l.push_front(4);                    // l: {4, 5, 2, 9, 6}
4
5 list<int>::iterator itr = find(l.begin(), l.end(), 2); // itr -> 2
6 l.insert(itr, 8);                    // l: {4, 5, 8, 2, 9, 6}
7                                     // O(1), faster than vector
8 itr++;                               // itr -> 9
9 l.erase(itr);                        // l: {4, 5, 8, 2, 6} O(1)
10
11 // Main reason to use list:
12 myList1.splice(itr, myList2, itr_a, itr_b); // O(1)
```

Properties of STL-List:

- ▶ fast insert/remove at any place: $\mathcal{O}(1)$
- ▶ slow search: $\mathcal{O}(n)$, slower than vector!
- ▶ no random access, no [] operator
- ▶ Not contiguous in memory
- ▶ Unique killer feature is splice $\mathcal{O}(1)$





```
1 int a[3] = {3,4,5};
2 a.begin();    // not existing!
3 a.end();      // not existing!
4 a.size();     // not existing!
5 a.swap();     // not existing!
6
7 // Solution
8 array<int,3> b = {3,4,5};
9 b.end();
10 b.size();
11 b.swap();
```

Properties of STL-Array:

- ▶ Thin layer around C-Array
- ▶ Provides STL functionality
- ▶ Size is fixed
- ▶ Size is deduced in the type: `array<int, 3>` is not the same type as `array<int, 4>`





Associative Containers

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

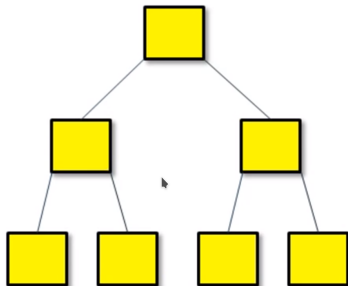
Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms



- ▶ Implemented with binray tree (red-black tree ¹)
- ▶ Always sorted, default criteria is $<$, but can be freely choosen

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

¹https://en.wikipedia.org/wiki/Red-black_tree



```
1 set<int> myset;  
2 myset.insert(3);    // myset: {3}  
3 myset.insert(1);    // myset: {1, 3}  
4 myset.insert(7);    // myset: {1, 3, 7}, O(log(n))  
5  
6 // Note: find function  
7 set<int>::iterator it;  
8 it = myset.find(7); // O(log(n)), it points to 7  
9  
10 // Check insertion  
11 pair<set<int>::iterator, bool> ret;  
12 ret = myset.insert(3); // no new element inserted  
13  
14 if (ret.second==false)  
15     it=ret.first;    // "it" now points to element 3
```

Properties of STL-Set:

- ▶ Sorting at insertion
- ▶ No duplicates allowed
- ▶ `insert()` ($\mathcal{O}(\log n)$)
- ▶ insertion checkable
- ▶ Fast `find()` function available ($\mathcal{O}(\log n)$)



STL - Set / Multiset



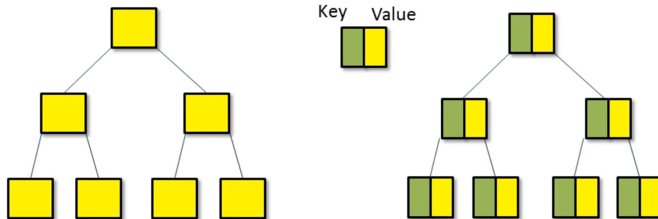
```
1 // Insert with hint:  $O(\log(n)) \Rightarrow O(1)$ 
2 myset.insert(it, 9); // myset: {1, 3, 7, 9}
3                       // it points still to 3
4
5 myset.erase(it);      // myset: {1, 7, 9}
6
7 // Note: erase by element
8 myset.erase(7);      // myset: {1, 9}
```

Advanced properties of STL-Set:

- ▶ Fast insertion with hint ($O(1)$)
- ▶ `erase()` by iterator
- ▶ `erase()` by value!
- ▶ Note: `set<int>::iterator` are read only!
- ▶ Traversing is slow comp. to `vector` & `deque`
- ▶ No random access with `[]` operator

STL-Multiset

Multiset works the same as set, but allows duplicated items



- ▶ Have **key** / **value** pairs
- ▶ Implemented with binray tree (red-black tree ¹)
- ▶ Always sorted, default criteria is $<$, but can be freely choosen
- ▶ Items are sorted by **key**

¹https://en.wikipedia.org/wiki/Red-black_tree

STL - Map / Multimap

Usage

```
1 map<char,int> mymap;
2
3 // Init
4 mymap.insert( pair<char,int>('a',100) );
5 mymap.insert( make_pair('z',200) ); // types detected
6
7 map<char,int>::iterator it = mymap.begin();
8 mymap.insert(it, pair<char,int>('b',300)); // "it" is a hint
9
10 it = mymap.find('z'); // O(log(n))
11
12 // showing contents:
13 for ( it=mymap.begin() ; it != mymap.end(); it++ )
14 cout << (*it).first << " => " << (*it).second << endl;
```

Properties of STL-Map:

- ▶ Sorting at insertion
- ▶ No duplicated **keys** allowed
- ▶ `insert()` ($\mathcal{O}(\log n)$)
- ▶ insertion checkable
- ▶ Fast `find()` function available ($\mathcal{O}(\log n)$)

STL-Multimap

Multimap works the same as map, but allows duplicated keys





Unordered Containers

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

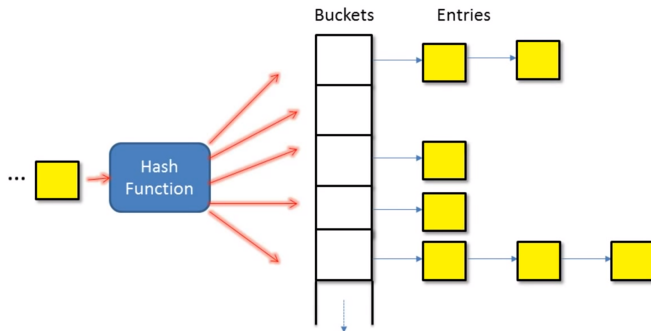
Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms



- ▶ The order of elements is not defined and may change over time
- ▶ Implemented with *hash tables* (which is an array (*buckets*) of linked-list (*entries*))
- ▶ The hash function is used for insert and search
- ▶ Default hash function defined for fundamental types and string
- ▶ Finding an element is very fast/ fastest among all containers ($\mathcal{O}(1)$)

STL - Unordered Set / Unordered Multiset

Usage

```
1 unordered_set<string> myset = { "red", "green", "blue" };
2 unordered_set<string>::const_iterator itr = myset.find("green");
3 // Note: O(1) –fastest search possible!
4
5 if (itr != myset.end())    // Important check
6     cout << *itr << endl;
7 myset.insert("yellow"); // O(1)
8
9 vector<string> vec = {"purple", "pink"};
10 myset.insert(vec.begin(), vec.end());
```

Properties of STL-Unordered Set:

- ▶ Sorting at insertion
- ▶ No subscript operator[] or at()
- ▶ No push_back(), push_front()
- ▶ Order of element values can not be changed

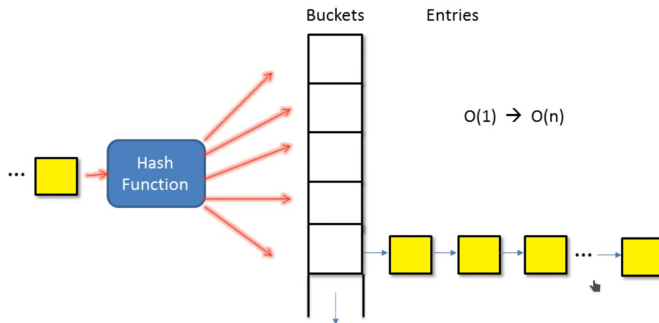
STL-Unordered Multiset

Unordered Multiset works the same as unordered set, but allows duplicated values



STL - Unordered Set / Unordered Multiset

Hash Collision



- ▶ In the worst case, all elements are inserted into one bucket!
- ▶ Search performance degrades from $O(1) \rightarrow O(n)$

► Hash specific API's

```
1 // Hash table specific APIs:
2 cout << "load_factor = " << myset.load_factor() << endl;
3
4 string x = "red";
5 cout << x << " is in bucket #" << myset.bucket(x) << endl;
6 cout << "Total bucket #" << myset.bucket_count() << endl;
```



STL - Unordered Map Example

Associative Array

```
1 unordered_map<char, string> day = {{'S', "Sunday"}, {'M', "Monday"}};
2
3 cout << day['S'] << endl;    // No range check
4 cout << day.at('S') << endl; // Has range check
5
6 vector<int> vec = {1, 2, 3};
7 vec[5] = 5;    // Compile Error
8
9 day['W'] = "Wednesday"; // Inserting {'W', "Wednesday"}
10 day.insert(make_pair('F', "Friday")); // Insert {'F', "Friday"}
11
12 day.insert(make_pair('M', "MONDAY")); // Fail to modify
13 day['M'] = "MONDAY"; // Succeed to modify
```

- ▶ Associative array can be implemented using `map` or `multimap`
 1. test
 2. Search time:
 `unordered_map`: $\mathcal{O}(1)$
 `map`: $\mathcal{O}(\log(n))$
 3. `unordered_map` may degrade to $\mathcal{O}(n)$, `map` guarantees $\mathcal{O}(\log(n))!$
- ▶ To modify elements use subscript operator `[]`
- ▶ This means the subscript operator provides a write access to the container



STL - Unordered Map Example

Associative Array

```
1 void print(const unordered_map<char, string>& m)
2 {
3     m['S'] = "SUNDAY";           // compile error
4     cout << m['S'] << endl;     // compile error
5
6     auto itr = m.find('S');
7
8     if (itr != m.end())
9         cout << *itr << endl;
10 }
11 print(day);
```

- Use iterators to access read-only elements





Container Adapters

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL - Container Adapters

For special needs

Container Adapters are implemented using fundamental container classes, providing a restricted interface for special needs:

- ▶ **stack**: **LIFO**, `push()`, `pop()`, `top()`
- ▶ **queue**: **FIFO**, `push()`, `pop()`, `front()`, `back()`
- ▶ **priority queue**: **first item always has the greatest priority**, `push()`, `pop()`, `top()`





Algorithms

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimap

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL Algorithms

Standard Programming Requirements

STL algorithms supplies the programmer with the most common used requirements



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL Algorithms

Standard Programming Requirements

STL algorithms supplies the programmer with the most common used requirements

- ▶ `std::find` - Finds a value in a collection



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL algorithms supplies the programmer with the most common used requirements

- ▶ `std::find` - Finds a value in a collection
- ▶ `std::find_if` - Finds a value in a collection on the basis of a specific user-defined predicate



Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms

STL algorithms supplies the programmer with the most common used requirements

- ▶ `std::find` - Finds a value in a collection
- ▶ `std::find_if` - Finds a value in a collection on the basis of a specific user-defined predicate
- ▶ `std::reverse` - Reverses a collection



STL algorithms supplies the programmer with the most common used requirements

- ▶ `std::find` - Finds a value in a collection
- ▶ `std::find_if` - Finds a value in a collection on the basis of a specific user-defined predicate
- ▶ `std::reverse` - Reverses a collection
- ▶ `std::remove_if` - Removes an item from a collection on the basis of a user-defined predicate



STL Algorithms

Standard Programming Requirements

STL algorithms supplies the programmer with the most common used requirements

- ▶ `std::find` - Finds a value in a collection
- ▶ `std::find_if` - Finds a value in a collection on the basis of a specific user-defined predicate
- ▶ `std::reverse` - Reverses a collection
- ▶ `std::remove_if` - Removes an item from a collection on the basis of a user-defined predicate
- ▶ `std::transform` - Applies a user-defined transformation function to elements in a container

STL Algorithms

To use those algorithms include the standard header `<algorithm>`



STL Algorithms

Example - find

```
1 #include <iostream>
2 #include <vector>
3 #include <algorithm>
4 using namespace std;
5 int main()
6 {
7     // A dynamic array of integers
8     vector<int> intArray;
9     intArray.push_back(50);
10    intArray.push_back(2991);
11    intArray.push_back(23);
12    intArray.push_back(9999);
13
14    // Find an element (say 2991) using the 'find' algorithm
15    vector<int>::iterator elFound = find(intArray.begin(),
16    intArray.end(), 2991);
17    // Check if value was found
18    if (elFound != intArray.end())
19    {
20        // Determine position of element using std::distance
21        int elPos = distance(intArray.begin(), elFound);
22        cout << "Value " << *elFound;
23        cout << " found in the vector at position: " << elPos <<
24        endl;
25    }
26    return 0;
27 }
```



STL Algorithms

Example - find

```
1 #include <iostream>
2 #include <vector>
3 #include <algorithm>
4 using namespace std;
5 int main()
6 {
7     // A dynamic array of integers
8     vector<int> intArray;
9     intArray.push_back(50);
10    intArray.push_back(2991);
11    intArray.push_back(23);
12    intArray.push_back(9999);
13
14    // Use auto for convenience
15    auto elFound = find(intArray.begin(), intArray.end(), 2991);
16    // Check if value was found
17    if (elFound != intArray.end())
18    {
19        // Determine position of element using std::distance
20        int elPos = distance(intArray.begin(), elFound);
21        cout << "Value " << *elFound;
22        cout << " found in the vector at position: " << elPos <<
23            endl;
24    }
25    return 0;
}
```

Choosing the right Container

- ▶ If you're developing a new application, your requirements might be satisfied by more than one STL container. Nevertheless, the wrong choice could result in performance issues and scalability bottlenecks
- ▶ Refer to the companion book to find a comprehensive list (p. 429)

Container	Advantages	Disadvantages
<code>std::unordered_multiset</code> (Associative Container)	Should be preferred over an <code>unordered_set</code> when you need to contain nonunique values too. Performance is similar to <code>unordered_set</code> , namely, constant average time for search, insertion, and removal of elements, independent of size of container.	Elements are weakly ordered, so one cannot rely on their relative position within the container.
<code>std::map</code> (Associative Container)	Key-value pairs container that offers search performance proportional to the logarithm of number of elements in the container and hence often significantly faster than sequential containers.	Elements (pairs) are sorted on insertion, hence insertion will be slower than in a sequential container of pairs.
<code>std::unordered_map</code> (Associative Container)	Offers advantage of near constant time search, insertion, and removal of elements independent of the size of the container.	Elements are weakly ordered and hence not suited to cases where order is important.
<code>std::multimap</code> (Associative Container)	To be selected over <code>std::map</code> when requirements	Insertion of elements will be slower than in a sequential

Thank You

Questions

???

Lecture 2

Prof. Dr. P. Arnold



Bern University
of Applied Sciences

Standard Template
Library

Containers

Sequential Containers

Vector

Deque

List

Array

Associative Containers

Set / Multiset

Map / Multimaps

Unordered Containers

Unordered Set / Unordered
Multiset

Container Adapters

Algorithms