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Self-Study Report

on

C++ Standard Template Library

by

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CERTIFICATE

I (Navjot Singh) hereby solemnly affirm that the project report entitled "Advanced C++ Concepts" being submitted by me in partial fulfilment of the requirements for the award of the degree of Bachelor of Technology in Mathematics & Computing, to the Delhi Technological University, is a record of the bonafide work carried out by me under the guidance of Dr. H.C. Taneja. The work reported in this report in full or in part has not been submitted to any University or Institute for the award of any degree or diploma.

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Index

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I also place on record, my sense of gratitude to one and all, who directly or indirectly have lent their helping hand in this venture.

Last, but never the least, I thank my parents for being with me, in every sense.

Introduction

C++ is a statically typed, compiled, general-purpose, case-sensitive, free-form programming language that supports procedural, object-oriented, and generic programming. It is regarded as a middle-level language, as it comprises a combination of both high-level and low-level language features. It is a superset of C & a legal C program is a legal C++ program.

It was designed with a bias toward system programming and embedded, resource-constrained and large systems, with performance, efficiency and flexibility of use as its design highlights. It has also been found useful in desktop applications, servers (e.g. e-commerce, web search or SQL servers) & performance-critical applications (space probes).

It is an object oriented programming language as it supports the following characteristics:

Encapsulation	•It is the wrapping up of data and the functions (using that data) together into a single unit. It can be implemented by classes and structures.
Data Abstraction	•Abstraction is the representation of only the essential features without including background details. Classes show data abstraction as members of classes by default have private visibility.
Inheritence	•Inheritence is the process by which objects of one class acquire the properties of objects of another class. It allows hierarchical classification and code re-usability.
Polymorphism	•Polymorphism is the ability to take more than one form. An operation (function) may exhibit different behaviour in different instances depending on the type of data used. It can be exhibited by an operator or a function.
Modularity	•Modularity is the breaking up of code into different parts or modules. It can be implemented by diving the program into classes. It encourages code re-usability.
Dynamic Binding	•Dynamic Binding means that the code associated with a given function is not known until the time of call at run-time. It is associated with polymorphism and inheritence.

History

C++ was developed by Bjarne Stroustrup at AT&T Bell Labs in 1979, as an extension of the C language. He wanted an efficient and flexible language similar to C, which also provided high-level features for program organization.

Stroustrup, began work on "C with Classes", the predecessor to C++, in 1979. The motivation for creating a new language originated from the fact that Simula had features that were very helpful for large software development, but was too slow for practical use, while BCPL was fast but too low-level to be suitable for large software development. C was chosen because it was general-purpose, fast, portable and widely used.

Initially, "C with Classes" added features to the C compiler, Cpre, including classes, derived classes, strong typing, inlining and default arguments.

In 1983, *C with Classes* was renamed *C++* ("++" being the increment operator in C) adding new features including virtual functions, function name and operator overloading, references, constants, type-safe free-store memory allocation (new/delete), improved type checking, and BCPL style single-line comments with two forward slashes (//), as well as development of a compiler for C++, Cfront.

In 1989, C++ 2.0 was released. New features included multiple inheritance, abstract classes, static member functions, const member functions, and protected members. In 1990, Later feature additions included templates, exceptions, namespaces, new casts, and a boolean type.

After the 2.0 update, C++ evolved relatively slowly until, in 2011, the C++11 standard was released, adding numerous new features, enlarging the standard library further, and providing more facilities to C++ programmers. After a minor C++14 update, released in December 2014, various new additions are planned for 2017.

Generic Programming

Generic programming is a style of computer programming in which algorithms are written in terms of types that can be specified later that are then instantiated when needed for specific types which are provided as parameters. It permits writing common functions or types that differ only in the set of types on which they operate when used, thus reducing duplication.

The generic programming paradigm is an approach to software decomposition whereby fundamental requirements on types are abstracted from across concrete examples of algorithms and data structures and formalised as concepts, analogously to the abstraction of algebraic theories in abstract algebra.

Templates

When creating container classes in statically typed languages, it is inconvenient to have to write specific implementations for each data type contained, especially if the code for each data type is virtually identical. For example, in C++, this duplication of code can be circumvented by defining a class template.

```
template<typename T>
class List
{
  /* class contents */
};
List<Animal> list_of_animals;
List<Car> list_of_cars;
```

Above, T is a placeholder for whatever type is specified when the list is created. These "containers-of-type-T", commonly called templates, allow a class to be reused with different data types as long as certain contracts such as subtypes and signature are kept.

Templates can also be used for type-independent functions. This can be illustrated by the example of a program which swaps two elements of any data type. Using this function, two variables- irrespective of their data types can be swapped. Hence, different swap functions for every data type need not be defined.

```
template<typename T>
void Swap(T & a, T & b) //"&" passes parameters by reference
{
T temp = b;
b = a;
a = temp;
}
string hello = "world!", world = "Hello, ";
Swap( world, hello );
cout << hello << world << endl; //Output is "Hello, world!"
```

Advantages of Templates over macros:

1. Both macros and templates are expanded at compile time. Macros are always expanded inline, while templates are only expanded inline when the compiler deems it appropriate. When expanded inline, macro functions and function templates have no extraneous runtime overhead. Template functions with many lines of code will incur runtime overhead when they are not expanded inline, but the reduction in code size may help the code to load from disk more quickly or fit within RAM caches.
2. Macro arguments are not evaluated prior to expansion. The expression using the macro defined above `max(0, std::rand() - 100)` may evaluate to a negative number (because std::rand() will be called twice as specified in the macro, using different random numbers for comparison and output respectively), while the call to template function `std::max(0, std::rand() - 100)` will always evaluate to a non-negative number.
3. As opposed to macros, templates are considered type-safe; that is, they require type-checking at compile time. Hence, the compiler can determine at compile time whether the type associated with a template definition can perform all of the functions required by that template definition.
4. By design, templates can be utilized in very complex problem spaces, whereas macros are substantially more limited.

Disadvantages of Templates:

1. Historically, some compilers exhibit poor support for templates. So, the use of templates could decrease code portability.
2. Many compilers lack clear instructions when they detect a template definition error. This can increase the effort of developing templates, and has prompted the development of concepts for possible inclusion in a future C++ standard.
3. Since the compiler generates additional code for each template type, indiscriminate use of templates can lead to code bloat, resulting in larger executables.
4. Because a template by its nature exposes its implementation, injudicious use in large systems can lead to longer build times.
5. It can be difficult to debug code that is developed using templates. Since the compiler replaces the templates, it becomes difficult for the debugger to locate the code at runtime.
6. Templates of templates (nested templates) are not supported by all compilers, or might have a limit on the nesting level.
7. Templates are in the headers, which require a complete rebuild of all project pieces when changes are made.
8. No information hiding. All code is exposed in the header file. No one library can solely contain the code.

Application of Generic Programming

A C++ program implementing Queue Data Structure compatible with all data types can be implemented as follows-

```
template <typename T> //Typename is a keyword used to signify a class
class queue
{
	T* array;	//array of objects of type T
	int nextIndex;
	int firstIndex;
	int size;
	int arraySize;
	public:
	queue(){
		array = new T[10];
		size = 0;
		arraySize = 10;
		firstIndex = -1;
		nextIndex = 0;
	}
```

```
	int getSize()
	{	return size; }
	bool isEmpty(){
		if (size == 0)
			return true;
		else
			return false;
	}
	T front(){
		if (isEmpty())
			return 0;
		return array[firstIndex];
	}
	void enqueue(T element){
		if (size == arraySize)	// handle array full
		{
			T* temp = new T[arraySize * 2];
			int k = 0;
			for (int i = 0; i < firstIndex; i++, k++)
				temp[k] = array[i];
			firstIndex = 0;
			nextIndex = arraySize;
			arraySize = arraySize * 2;
			delete [] array;
			array = temp;
		}
		array[nextIndex] = element;
		if (size == 0)
			firstIndex = 0;
		nextIndex = (nextIndex + 1) % arraySize;
		size++;
	}
	T dequeue(){
		if (isEmpty())
			return 0;
		T output = array[firstIndex];
		firstIndex = (firstIndex + 1) % arraySize;
		size--;
		if (size == 0){
			firstIndex = -1;
			nextIndex = 0;
		}
		return output;
	}
	~queue() {
		delete [] array;
	}
};
```

Standard Library

In the C++ programming language, the C++ Standard Library is a collection of classes and functions which are written in the core language and part of the C++ ISO Standard itself.

> The C++ Standard Library provides several generic containers, functions to utilize and manipulate these containers, function objects, generic strings and streams (including interactive and file I/O), support for some language features, and everyday functions for tasks such as finding the square root of a number.

The C++ Standard Library is based upon conventions introduced by the Standard Template Library (STL), and has been influenced by research in generic programming and developers of the STL such as Alexander Stepanov and Meng Lee. Although the C++ Standard Library and the STL share many features, neither is a strict superset of the other.

A noteworthy feature of the C++ Standard Library is that it not only specifies the syntax and semantics of generic algorithms, but also places requirements on their performance. These performance requirements often correspond to a well-known algorithm, which is expected but not required to be used. In most cases this requires linear time O(n) or linearithmic time O(n log n), but in some cases higher bounds are allowed, such as quasilinear time O(n $\log^2 n$) for stable sort (to allow in-place merge sort)

The C++ Standard Library underwent ISO standardization as part of the C++ ISO Standardization effort, and is undergoing further work regarding standardization of expanded functionality.

Standard Template Library

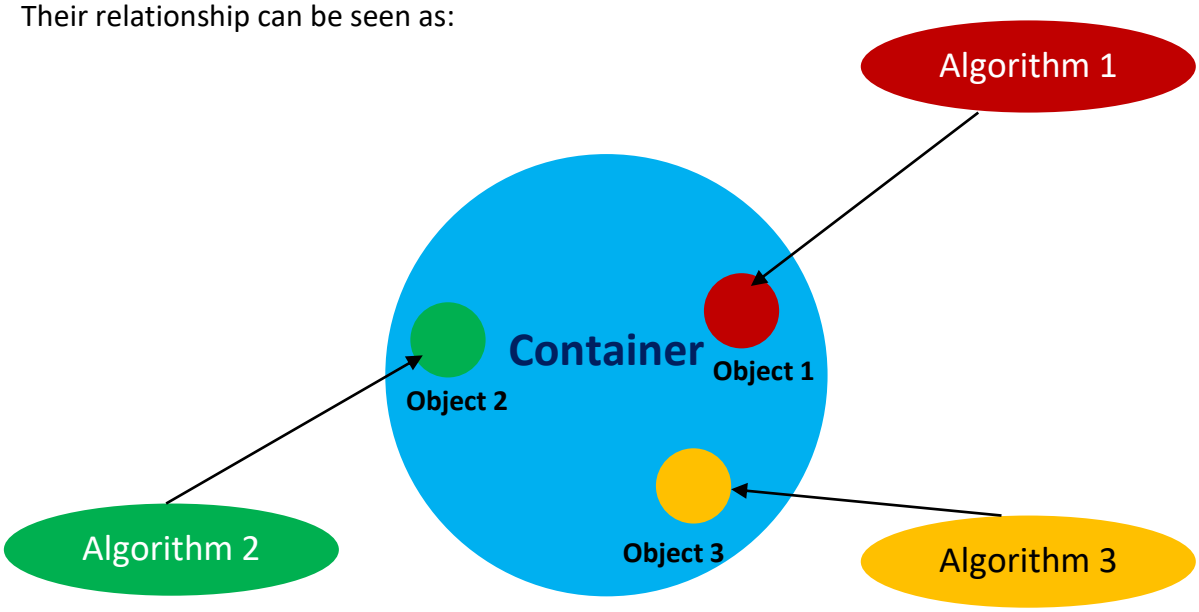
The C++ Standard Template Library is a powerful set of general-purpose templatized classes (data structures) and functions (algorithms) that can be used for storing and processing data. It includes implementation of common data structures like vectors, lists, queues, and stacks. It was developed by Alexander Stepanov and Meng Lee while working at HP.

STL is large and complex and using it can save considerable time & effort and lend high quality to programs. All these benefits are possible because the well written and well tested components defined in STL are being reused.

At the core of the C++ STL are following three well-structured components:

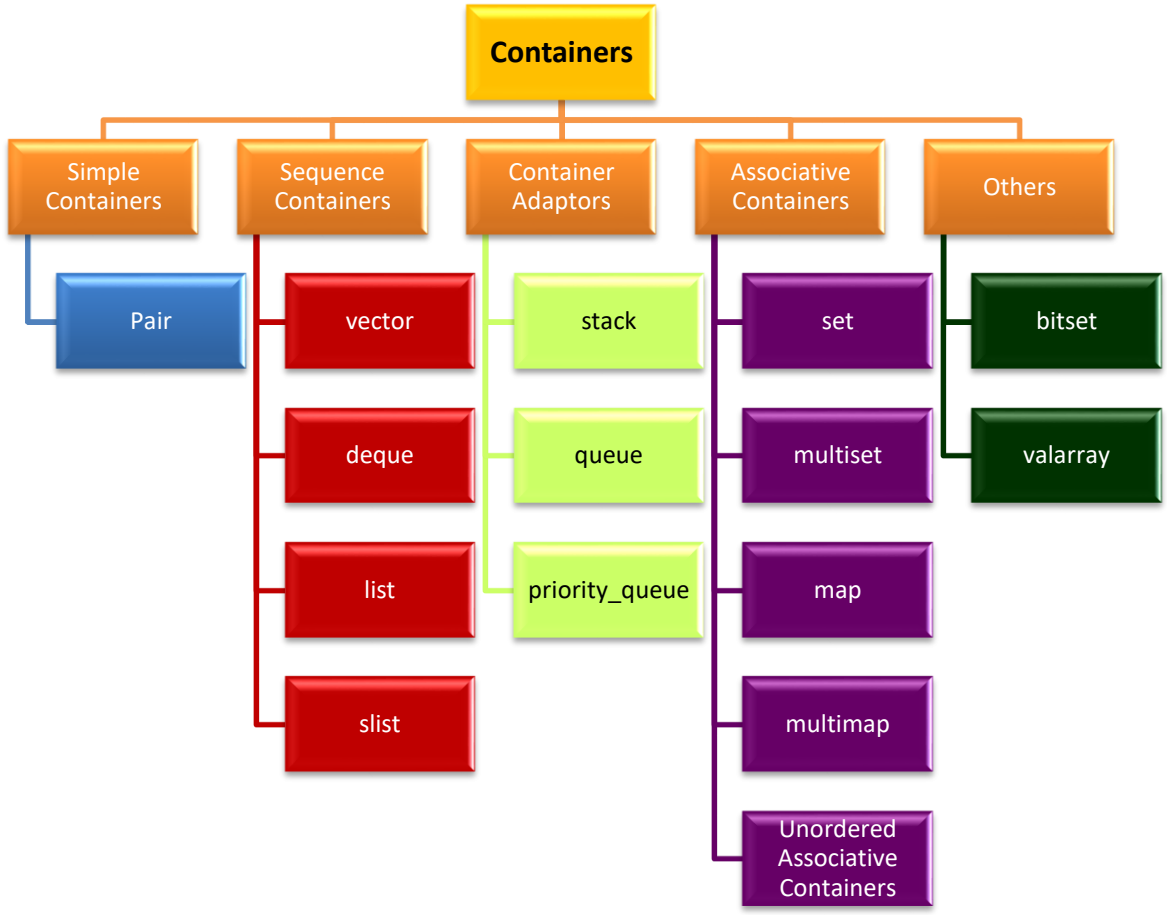
Containers	Algorithms	Iterators
• Containers are used to manage collections of objects of a certain kind. • It is the way data is organized in the memory. • They are implemented by template classes and therefore can hold different types of data.	• Algorithm is a procedure used to process data stored in containers. • STL includes different algorithms to provide support to tasks such as initializing, searching, copying, sorting and merging.	• Iterator is an object that points to an element in a container. It is be used to move through the content of containers. • They connect algorithms with containers & play a key role in manipulation of data in containers

Their relationship can be seen as:



Containers

As stated earlier, containers are objects that hold data of the same type. The STL provides 15 containers which can be grouped as the following:



Simple Containers

- **pair**

The pair container is a simple associative container consisting of a 2-tuple of data elements or objects, called 'first' and 'second', in that fixed order. The STL 'pair' can be assigned, copied and compared. The array of objects allocated in a map are of type 'pair' by default, where all the 'first' elements act as the unique keys, each associated with their 'second' value objects.

Sequence Containers

Sequence Containers store elements in a linear sequence. Each element is related to other elements by its position along a line.

vector

- It Is a dynamic array capable of random access with the ability to resize automatically when inserting or erasing an object.
- Inserting an element to the back of the vector at the end takes amortized constant time.
- Removing the last element takes only constant time, because no resizing happens. Inserting and erasing at the beginning or in the middle is linear in time.

list

- It is a bidirectional linear list (doubly linked list) in which the elements are not stored in contiguous memory.
- It shows opposite performance from a vector.
- Slow lookup and access (linear time), but once a position has been found, quick insertion and deletion (constant time).

slist (forward_list)

- It is a unidirectional linear list (singly linked list)
- Works like list but has slightly more efficient insertion, deletion and uses less memory.
- However, it can only be iterated forwards

deque

- It is a double ended queue which allows insertion and deletion at both ends as well as direct access to any element

Container Adaptors (Derived Containers)

These containers can be created from different sequence containers. Therefore, they do not support iterators and hence can't be used for data manipulation. However, they support certain member functions like push and pop that help in implementing insertion and deletion operations

queue

- It provides a FIFO (First-In-First-Out) queue interface in terms of push/ pop/ front/ back operations.
- Any sequence supporting operations front(), back(), push_back() and pop_front() can be used to instantiate queue
- e.g list and deque

priority_queue

- It provides priority queue interface in terms of push/ pop/ top (the element with the highest priority is on top).
- Any random-access sequence supporting operations front(), push_back() and pop_back() operations can be used to instantiate priority_queue
- e.g. vector and deque

stack

- Provides LIFO stack interface in terms of push/ pop/ top operations (the last-inserted element is on top).
- Any sequence supporting operations back(), push_back(), and pop_back() can be used to instantiate stack
- e.g. vector, list, and deque.

Associative Containers

These containers are designed to support direct access to elements using keys. They are not sequential and store data using the "Tree" data structure. This facilitates fast searching, deletion and insertion. However, these are very slow for random access and inefficient for sorting.

set

- It represents a mathematical set.
- Stores a number of unique items and provides operations for manipulating them using the values as keys.
- It also provides set operations however the type of data must implement comparison operator '<' since data in a set is always sorted.
- Duplicate values are not allowed in a set.

multiset

- It represents a mathematical multiset.
- It is the same as set but allows duplicate values.

map

- Map is an associative array as it allows mapping from one data item (a key) to another (a value).
- The key has to be unique as the mapping is one-one.
- Type of key must implement comparison operator '<' or custom comparator function must be specified.
- Therefore, it is used to store pairs of items which can be manipulated using the 'key' values.

multimap

- Multimap is the same as map but allows duplicate keys.
- Therefore, in effect a multimap implements one-many mapping.

unordered_set/ unordered_multiset/ unordered_map/ unordered_multimap

- These are similar to a set/multiset/map/multimap respectively, but are implemented using a hash table.
- Therefore, the keys are not ordered, but a hash function must exist for the key type.

Others

➢ bitset

A bitset stores bits (elements with only two possible values: 0 or 1, true or false, ...). The class emulates an array of bool elements, but optimized for space allocation: generally, each element occupies only one bit (which, on most systems, is eight times less than the smallest elemental type: char).
Each bit position can be accessed individually like a regular array accesses its elements.

Bitsets have the feature of being able to be constructed from and converted to both integer values and binary strings (members to_ulong and to_string). They can also be directly inserted and extracted from streams in binary format.

- **valarray**

A valarray object is designed to hold an array of values, and easily perform mathematical operations on them. It also allows special mechanisms to refer to subsets of elements in the arrays. Most mathematical operations can be applied directly to valarray objects, including arithmetical and comparison operators, affecting all its elements.
The valarray specification allows for libraries to implement it with several efficiency optimizations.

Algorithms

Algorithms are functions that can be used generally across a variety of containers for processing their contents. Although each container provides functions for its basic operations, STL provides more than sixty standard algorithms to support more extended or complex applications. STL algorithms reinforce the philosophy of reusability.

To access STL algorithms, the header **<algorithm>** must be included.

STL Algorithms can be categorized on the basis of operations they perform. Some of the major Algorithms are described below:

Non-Mutating Algorithms

count()	Counts occurrence of a value in a sequence
equal()	Returns true if 2 ranges are the same
find()	Finds first occurrence of a value in a sequence
find_end()	Finds last occurrence of a value In a sequence
search()	Finds a subsequence within a sequence
adjacent_find(), count_if(), for_each(), mismatch(), search_n() are some other non-mutating algorithms.	

Mutating Algorithms

copy()	Copies a sequence
fill()	Fills a sequence with a specified value
generate()	Replaces all elements with the result of n operation

Iter_swap()	Swaps elements pointed to by the iterators
remove()	Deletes elements of a specified value
replace()	Replaces elements with a specified value
reverse()	Reverses the order of elements
rotate()	Rotates elements
swap()	Swaps two elements

copy_backward(),fill_n(), random_shuffle(), remove_copy(), remove_if(), replace_copy(), replace_if(), reverse_if(), swap_ranges, transform() are some other mutating algorithms.

Sorting Algorithms

binary_search()	Conducts a binary search
Inplace_merge()	Merges two consecutive sorted sequences
merge()	Merges two sorted elements
nth_element()	Puts a specific element in its proper place
sort()	Sorts a sequence
make_heap()	Replaces elements with a specified value
partial_sort()	Sorts a part of a sequence

equal_range(), lower_bound(), Partition(), push_heap(), pop_heap() are some other Sorting Algorithms.

Set Algorithms

includes()	Finds whether a sequence Is a subsequence of another
set_difference()	Constructs a sequence that is difference of two ordered sets
set_intersection()	Constructs a sequence that contains intersection of two sets
set_symmetric_difference()	Produces a set which is the symmetric difference of two sets
Set_union()	Produces sorted union of two ordered sets

Relational Algorithms

equal()	Finds whether two sequences are the same
max()	Gives maximum of two values
max_element()	Finds the maximum element within the sequence
min()	Gives minimum of two values

min_element()	Finds the minimum element within the sequence
mismatch()	Finds the first mismatch between the elements in 2 sequences

Numeric Algorithms

accumulate()	Accumulates the results of operation on a sequence
adjacent_difference()	Produces a sequence consisting of difference of adjacent elements of a given sequence
Inner_product()	Accumulates the results of operation on a pair of sequences
partial_sum()	Produces a sequence by operation on a sequence- resulting in cumulative answer of all elements before that element
iota()	Assigns to every element in a range in a sequence, successive values which may be regularly incremented

Iterators

Iterators behave like pointers and are used to access container elements. They are used to traverse from one element to another. The STL implements 5 different types of iterators-

Iterator	Access Method	Movement Direction	i/o capability
Input	Linear	Forward	Read
Output	Linear	Forward	Write
Forward	Linear	Forward	Read & Write
Bidirectional	Linear	Forward & Backward	Read & Write
Random	Random	Forward & Backward	Read & Write

Following are some of the important iterator methods:

begin	Returns an iterator pointing to the first element
end	Returns an iterator referring to the *past-the-end* element. The *past-the-end* element is the theoretical element that would follow the last element. It does not point to any element.
rbegin	Returns a *reverse iterator* pointing to the last element. *It* iterates backwards: increasing it moves them towards the beginning of the container.
rend	Returns a *reverse iterator* pointing to the theoretical element preceding the first element (which is considered its *reverse end*).

size	Returns the number of elements
clear	Returns whether the sequence is empty (i.e. whether its size is 0).
capacity	Returns the size of the storage space currently allocated for the sequence, expressed in terms of elements. This *capacity* is not necessarily equal to the size. It can be equal or greater, with the extra space allowing to accommodate for growth without the need to reallocate on each insertion.
front	Returns a reference to the first element. Unlike member begin, which returns an iterator to this same element, this function returns a direct reference.
back	Returns a reference to the last element. Unlike member end, which returns an iterator just past this element, this function returns a direct reference.
at	Returns a reference to the element at position *n*. The function automatically checks whether *n* is within the bounds of valid elements, throwing an out_of_range exception if it is not
assign	Assigns new contents to a sequence, replacing its current contents, and modifying its size accordingly.
insert	Removes all elements from the sequence (which are destroyed), leaving the container with a size of 0.
vector::push_back	Adds a new element at the end of the vector, after its current last element. The content of *val* is copied (or moved) to the new element.
vector::pop_back	Removes the last element in the vector, effectively reducing the container size by one.

String Class

A string is a sequence of characters. An array of char type to store characters together to form a string is known as “C-String”. This string is actually a one-dimensional array of characters which is terminated by a null character '\0'. Thus a null-terminated string contains the characters that comprise the string followed by a null. This continues to be supported in C++.

Operations on C-strings often become complex and inefficient. Therefore, the standard C++ library provides a string class type that supports all the operations of a C-String and additionally provides much more functionality.

Constructors

Commonly used string constructors are:

- String(); //For creating an empty string
- String(const char *str); //For creating string object from a C-String
- String(const string & str); //For creating string object from other string object

Important Iterators on String Class

begin	Return iterator to beginning
end	Return iterator to end
rbegin	Return reverse iterator to end
rend	Return reverse iterator to beginning
cbegin, cend, crbegin, crend are some other iterators on String Class	

Important String Characteristics

size	Returns length of string
resize	Resize String but does not alter capacity
capacity	Returns size of allocated storage
reserve	Request a change in capacity
clear	Clear string
empty	Test if string Is empty
length, max_size, shrink_to_fit are some other iterators on String Class	

Functions to access elements of String Objects

[]	Get character of string at mentioned index
at	Get character of string at mentioned position

back	Access last character
front	Access first character
substr	Generates substring within two positions

Functions to modify/act on String Objects

append	Append to string
push_back	Append character to string
assign	Assign content to string
insert	Insert into string
erase	Erase characters from string
replace	Replace portion of string
swap	Swap string values
pop_back	Delete last character
copy	Copy sequence of characters from string
find	Find content in string
rfind	Find last occurrence of content in string
compare	Compares two strings

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