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Fundamentals of Programming II

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Lecture 13

Standard Template Library (STL) - Part I

C++ **Standard ISO/IEC 14882**
Programming Language

Outline

Topics Covered

01 Associative Containers (Sorted)

02 Sorted Sets

03 Unordered Containers

04 Container Adapters

05 Advanced String Components

06 Practice & Strategy

Learning Objectives

By the end of this lecture you will be able to:

- **Understand** How maps differ fundamentally from sequences
- Master **sorted containers** how red-black trees ensure O(log n) operations
- Master **unordered containers** handling collisions and load factors
- Use **container adapters** when specialized interfaces enhance code clarity
- **Optimize with strings** advanced std::string functions;
- Make **informed decisions** Choose containers based on operations
- **Avoid common pitfalls** Key immutability, iterator invalidation, hash function design

Categorizing Containers

1. **Sequence Containers (Part I)** — *Maintain insertion order. Access by position/index.*
2. **Associative Containers (Sorted)** — *Organize by key; maintain sorted order. O(log n). Red-black trees.*
3. **Unordered Associative Containers** — *Organize by hash; no guaranteed order. Average O(1). Hash tables.*
4. **Container Adapters** — *Constrain interfaces on sequence containers; specialized semantics.*

Maps: Introduction

std::map<Key, Value> - Key-Value Associative Container

Definition

- Stores unique key-value pairs. Each key maps to exactly one value.
- The building block. Access via .first (key) and .second (value).
- Maintains ascending order by key. Enables range queries and ordered iteration.

```
#include <map>   ->   std::map<K, V>
```

Sorted Map Visualization

Key	Value
apple	5
banana	3
cherry	7
date	2

O(log n) *All operations*

Sorted *Key order*

Unique *Keys only*

Stable *Iterators*

Maps: Internal Mechanics

Red-Black Tree - Self-Balancing BST

Coloring Rule
Every node is colored RED or BLACK.

Black Depth
Every root-to-leaf path has the same number of black nodes.

No Double Red
Red nodes never have red children.

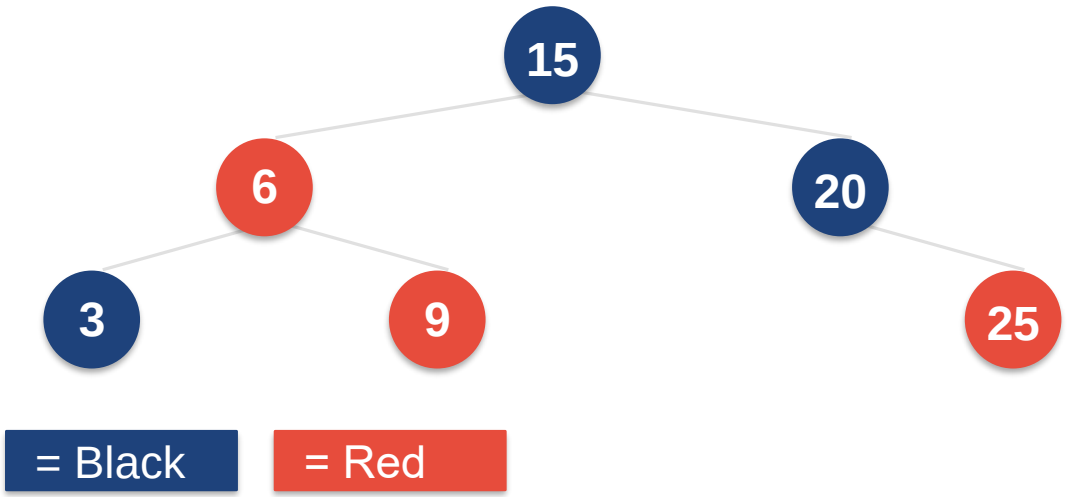
Height Guarantee
These invariants ensure height = O(log n).

Iterator Stability
Insert/delete only invalidates the erased iterator.

Operation Complexity

Operation	Complexity
Insertion	O(log n)
Search	O(log n)
Deletion	O(log n)
Range query	O(log n + k)

Simplified Red-Black Tree



Maps: Syntax

```cpp
#include <map>
#include <utility>  // std::pair, std::make_pair

// Default: empty map
std::map<std::string, int> dictionary;

// Initializer list (C++11)
std::map<std::string, int> fruits = {
    {"apple", 5}, {"banana", 3}, {"cherry", 7}
};

// operator[] - creates key if missing!
std::map<int, std::string> ids;
ids[1] = "Alice";

// insert() - returns pair<iterator, bool>
ids.insert({2, "Bob"});
ids.insert(std::make_pair(3, "Charlie"));
```

```cpp
// C++17 structured bindings
auto [it, inserted] = ids.insert({1, "Updated"});
// inserted == false: key 1 already exists

// Safe access: throws out_of_range
try {
    std::cout << fruits.at("grape");
} catch (const std::out_of_range& e) {
    std::cout << "Key not found\n";
}

// find(): never creates entries
auto it2 = fruits.find("banana");
if (it2 != fruits.end())
    std::cout << it2->first << " -> " << it2->second;
```

Maps: Insertion

operator[ ]	insert( )	emplace( )
`m["key"] = value;`	`m.insert({"key", val});`	`m.emplace("key", 42);`
Creates key if missing	Preserves existing keys	Constructs in-place
Returns value reference	Returns pair<iter,bool>	No temporary pair
Convenient but risky	Explicit, safe	Most efficient
Creates missing entries with default value. Dangerous in loops.	*If key exists, fails silently. bool indicates success.*	*C++11. Avoids temporary pair. Best for expensive types.*

operator[ ] -> O(log n) **insert( ) -> O(log n)** **emplace( ) -> O(log n)**

Maps: Search & Access

find(key)

```
auto it = m.find(key);
```

Returns iterator or end(). O(log n).
Never creates entries. Safe.

count(key)

```
if (m.count(key)) { ... }
```

Returns 0 or 1. O(log n).
Concise existence check.

at(key)

```
value = m.at(key);
```

Returns reference. Throws out_of_range.
O(log n). Never creates entries.

Maps: Iteration

```cpp
// Range-based for (C++17 structured bindings)
for (const auto& [key, value] : fruits) {
    std::cout << key << " -> " << value << "\n";
}

// C++14 / no structured bindings:
for (const auto& pair : fruits) {
    std::cout << pair.first << " -> "
              << pair.second << "\n";
}

// Iterator loop (fine-grained control):
for (auto it = m.begin(); it != m.end(); ++it) {
    std::cout << it->first << ": "
              << it->second << "\n";
}

// Reverse iteration (descending key order):
for (auto it = m.rbegin(); it != m.rend(); ++it) {
    // process in reverse
}

// Range query with lower/upper_bound:
auto lo = m.lower_bound("banana");
auto hi = m.upper_bound("date");
for (auto it = lo; it != hi; ++it) {
    std::cout << it->first << "\n";
}
// equal_range returns both as pair:
auto [lo2, hi2] = m.equal_range("cherry");
```

Maps: Performance

Operation	map / set	unordered_map	vector	list
Insert	O(log n)	O(1) avg	O(n)	O(1)*
Search	O(log n)	O(1) avg	O(n)	O(n)
Delete	O(log n)	O(1) avg	O(n)	O(1)*
Ordered iter?	Yes	No	N/A	N/A

25,000x faster

1M elements: vector search ~500,000 comparisons vs. map ~20 comparisons.

Worst-case guarantee

O(log n) is guaranteed always. unordered_map worst-case is O(n).

Use map when

Sorted access, range queries, or worst-case guarantees matter.

Maps: Example Program

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

int main() {
  // Registry: employee name -> department
  std::map<std::string,std::string> registry;

  registry["Alice"] = "Engineering";
  registry["Bob"]   = "Marketing";
  registry["Carol"] = "Engineering";

  // Lookup — O(log n)
  if (registry.count("Alice"))
    std::cout << registry["Alice"]; // Engineering

  // Iterate in sorted key order
  for (auto& [name, dept] : registry)
    std::cout << name << ": " << dept;
}
```

Key Observations

operator[]

Creates a default value if key is missing.

count(key)

Returns 0 or 1 (keys are unique). Safe way to check membership.

Sorted output

Iterating always yields keys in ascending order.

Erase

registry.erase("Bob") removes key in O(log n).

Multimap: Introduction

Feature	std::map	std::multimap
Duplicate keys	No	Yes
operator[]	Yes	No
insert() result	pair<iter,bool>	iterator
find() result	One element	One element
Get all by key	Direct	equal_range()
Count per key	0 or 1	0, 1, or more
Complexity	O(log n)	O(log n)

Multimap: Operations

```cpp
#include <map>  // also covers multimap

std::multimap<std::string, int> m;

// insert() always succeeds (no bool!)
m.insert({"apple", 5});
m.insert({"apple", 3});  // Allowed!
m.insert({"apple", 7});  // Three apples

// find() -> only ONE element
auto it = m.find("apple");
// it points to just one apple, not all three

// equal_range() -> ALL elements with key
auto [lower, upper] = m.equal_range("apple");
for (auto it2 = lower; it2 != upper; ++it2) {
    std::cout << it2->first << " -> "
              << it2->second << "\n";
}
// Prints: apple->5, apple->3, apple->7

// count() returns actual multiplicity
int n = m.count("apple");  // n == 3

// lower_bound / upper_bound still work
auto lb = m.lower_bound("apple"); // first apple
auto ub = m.upper_bound("apple"); // first non-apple
// [lb, ub) == equal_range("apple")
```

Multimap State Visualization

apple	5
apple	3
apple	7
banana	2
banana	6

insert() -> iter only

No bool: multimap never rejects duplicates.

find() limitation

Returns one; use equal_range() for all.

count() usefulness

Returns actual count (not just 0 or 1).

equal_range() idiom

[lower, upper) is the canonical access pattern.

Multimap: Example Program

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

int main() {
  // dept -> multiple employee names
  std::multimap<std::string,std::string> dept;

  dept.insert({"Eng", "Alice"});
  dept.insert({"Eng", "Bob"});   // duplicate key OK
  dept.insert({"HR",  "Carol"});
  dept.insert({"HR",  "Dave"});

  // Retrieve all Eng employees
  auto [lo, hi] = dept.equal_range("Eng");
  for (auto it = lo; it != hi; ++it)
    std::cout << it->second; // Alice, Bob

  std::cout << dept.count("Eng"); // 2
```

Multimap Mechanics

insert() always inserts

Always adds a new entry, never rejecting duplicate keys.

equal_range() idiom

Returns the start and end boundaries to loop through a key's values.

count(key)

Returns the exact number of entries for a key, not just 0 or 1.

Quick Check: Maps vs. Multimaps

Q1 What is the main difference between std::map and std::multimap?

A) Both allow duplicate keys

B) Maps have unique keys; multimaps allow duplicates

C) Multimaps are faster

D) Maps can't use find()

Answer: B

Q2 Why doesn't std::multimap support operator[]?

A) Performance reasons

B) Iterator stability

C) Ambiguous: which value for duplicate keys?

D) operator[] is deprecated in C++17

Answer: C

Q3 How do you retrieve all values for a multimap key?

A) Use find() and loop

B) Use equal_range() to get [lower, upper)

C) Use operator[]

D) Iterate the whole container

Answer: B

Sets: Introduction

std::set<T> - Sorted Unique Collection

Definition

Stores unique elements in sorted order.
Conceptually: a map with only keys, no values.

Declaration - std::set<ElementType>

Uniqueness - Duplicate insertions are rejected.

Sorted Order - in ascending order

Set vs Map - Key Distinction

```
std::set<int>  s;
```

2	5	7	11	13	17

-> Each element appears exactly once, in sorted order

Feature	std::set	std::map
Template params	1 (element)	2 (key, value)
operator[]	No	Yes
Value immutable	Yes	Keys only
Complexity	O(log n)	O(log n)

Sets: Internal Mechanics

Red-Black Tree Implementation

Like maps, sets use red-black trees for O(log n) insertion, deletion, and search.
The height of the tree stays logarithmic, ensuring all operations remain efficient.

Immutability Constraint

Elements in a set are const. You cannot modify them in-place.
Doing so could violate sort order and corrupt the tree structure.

Solution: Erase & Re-insert

To 'change' an element: erase the old one (O(log n)), then insert the new value (O(log n)).
This is the only safe path.

Sorting Customization

Default uses std::less<T> (ascending). Supply std::greater<int> or a custom comparator for descending or custom ordering.

Sets: Common Operations

Operation	Returns	Key Behaviour
insert(x)	pair<it,bool>	Rejected silently if duplicate; bool=false
find(x)	iterator	Returns end() if not found; O(log n)
count(x)	0 or 1	Quick membership test idiom
erase(x)	size_t	By value, by iterator, or by range
begin/end	iterator	Sorted ascending order always

Uniqueness

Duplicates fail to insert and return false.

Always Sorted

Elements always iterate in ascending order.

count() vs find()

Use count() checks existence;, and find() returns the iterator.

Sets: Math-like Operations

`std::set_union()`

{1,2,3,4,5}

All elements from either set

`std::set_intersection()`

{3}

Elements common to both sets

`std::set_difference()`

{1,5}

In first set, NOT in second

`std::set_symmetric_difference()`

{1,2,4,5}

In one set or the other, not both

Sets: Multiset

std::set<T>

- ✓ Unique elements only
- ✓ Sorted ascending
- ✓ Elements are const (immutable)

insert() returns pair<it, bool>
count() returns 0 or 1
e.g.: { 2, 3, 5, 7 }

std::multiset<T>

- ✓ Duplicate elements allowed
- ✓ Sorted ascending
- ✓ Elements are const (immutable)

insert() returns only an iterator
count() returns 0, 1, 2 … n
e.g.: { 2, 3, 3, 5, 5, 5, 7 }

```cpp
std::multiset<int> m;
m.insert(5); m.insert(5); m.insert(5); // Three 5s — all accepted!

int c = m.count(5);
// c = 3

auto [lo, hi] = m.equal_range(5);
// [lo, hi) spans all three 5s
for (auto it = lo; it != hi; ++it) std::cout << *it; // 5 5 5
```

Sets: Example Program

```cpp
std::vector<int> data = {5,2,8,2,9,5,1,8,3,5};

// 1. Deduplicate & sort — one liner!
std::set<int> s(data.begin(), data.end());
// s = {1,2,3,5,8,9}

// 2. Membership test  O(log n)
if (s.count(8)) { /* 8 exists */ }

// 3. Range query — elements in [3, 8)
auto lo = s.lower_bound(3), hi = s.lower_bound(8);
for (auto it=lo; it!=hi; ++it) cout << *it; // 3 5

// 4. Set union with another set
std::set<int> other={1,4,6,9}, u;
std::set_union(s.begin(),s.end(),other.begin(),other.end(),
    std::inserter(u, u.begin())); // {1,2,3,4,5,6,8,9}
```

Original

5 2 8 2 9 5 1 8 3 5

Deduplicated

1 2 3 5 8 9

Range [3,8)

3 5

Union

1 2 3 4 5 6 8 9

Unordered Containers: Overview

Ordered Containers

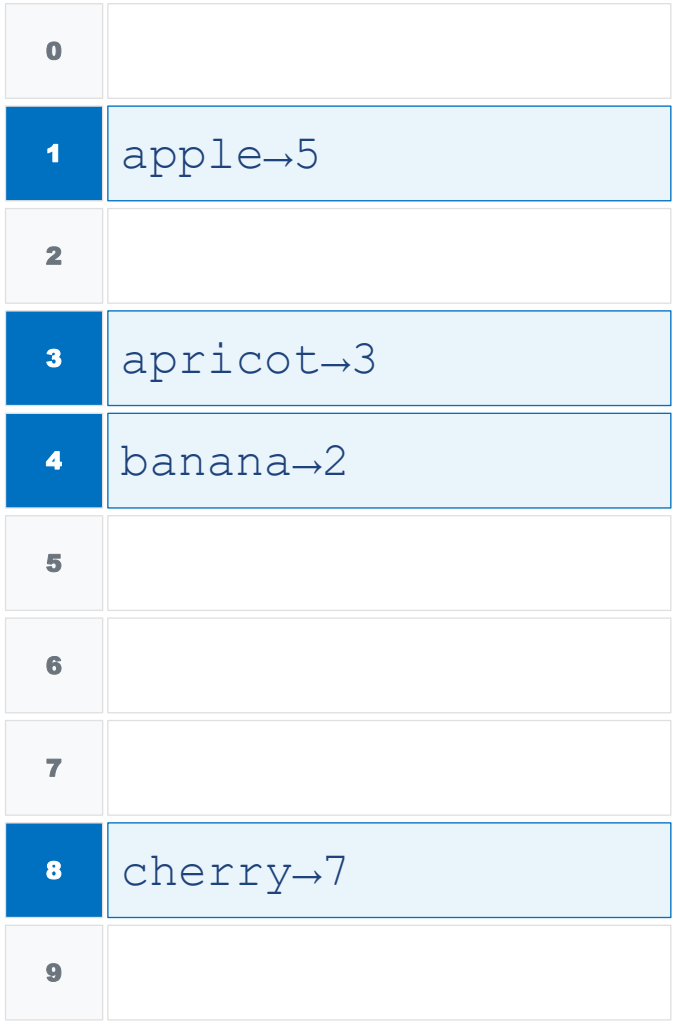
- **Engine:** Red-Black Tree with guaranteed O(log n) operations.
- **Benefits:** Automatically sorted keys, efficient range queries, and stable iterators.
- **When to use:** When you need sorted order, range searches, or strict O(log n) performance.

Unordered Containers

- **Engine:** Hash Table with average O(1) operations, but worst-case O(n) if keys collide.
- **Behavior:** Undefined iteration order with no support for range queries.
- **When to use:** When you need maximum lookup speed and element order does not matter.

💡 Choose Ordered when: sorted iteration, range queries, or worst-case guarantees matter.
Choose Unordered when: pure lookup speed on large datasets and order is irrelevant.

Unordered: Mechanics



Hash Function

h(key) → bucket index. A good function distributes keys uniformly, minimising collisions.

Collision Resolution

Multiple keys → same bucket? Resolved by chaining (list per bucket) or open addressing.

Load Factor λ = n / buckets

λ < 0.75 → sparse, fast. λ > 1.0 → chains grow, lookups degrade. Rehash triggers when threshold exceeded.

Rehashing

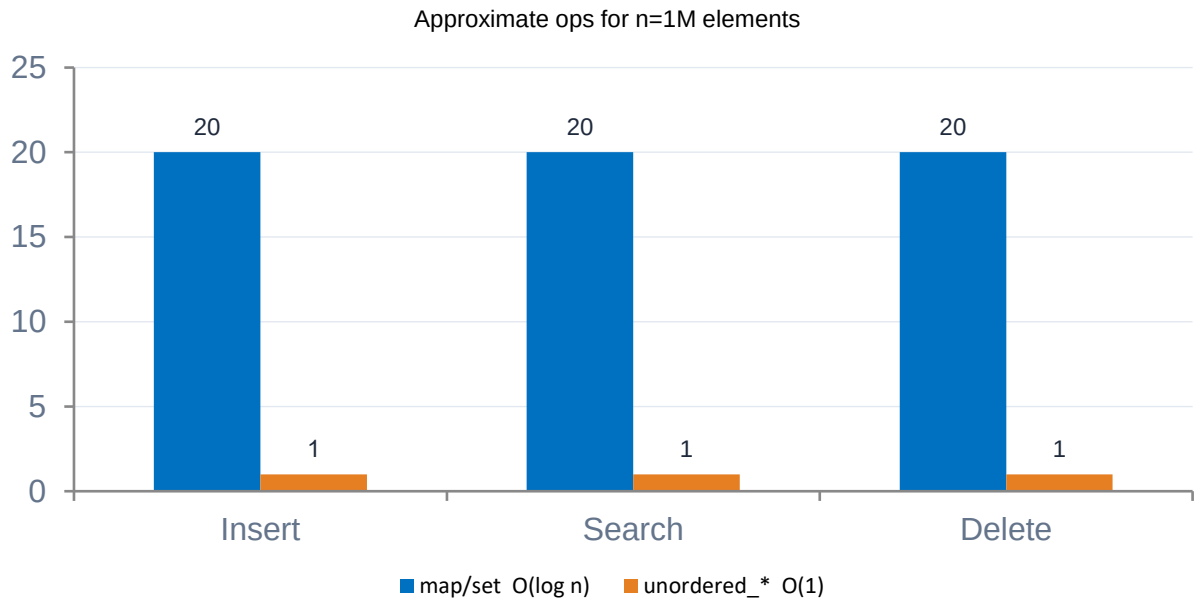
Allocates a larger bucket array and recomputes all hashes. Expensive O(n) but rare — amortised O(1).

Unordered Map/Set: Operations

```cpp
#include <unordered_map>
#include <unordered_set>

std::unordered_map<std::string,int> wc;
wc["apple"]=5; wc["banana"]=3; wc["cherry"]=7;

// Search  O(1) avg
auto it = wc.find("banana");
if (it != wc.end()) cout << it->second; // 3

// Iteration — order UNDEFINED
for (const auto& [k,v] : wc) cout << k << v;
// order may be: cherry, apple, banana …

// unordered_set
std::unordered_set<int> nums = {10,20,30};
nums.erase(20); // O(1) avg
if (nums.count(10)) { /* found */ }
```

Operation	map/set	unordered_*
insert / operator[]	O(log n)	**O(1) avg**
find / count	O(log n)	**O(1) avg**
erase	O(log n)	**O(1) avg**
Range query	**O(log n+k)**	O(n)
Sorted iteration	**✓ Yes**	✗ No
Worst-case guarantee	**O(log n)**	O(n)

Ordered vs. Unordered Performance



Practical Benchmark (n = 1,000,000 random integers)

map::find() ~40 comparisons (balanced tree depth ≈ 20)

unordered_map::find() ~1 operation (direct hash lookup)

Range query [1000,2000]: map O(log n + k) vs. unordered_map O(n)

Choose map / set when …

- Sorted iteration needed
- Range queries (lower/upper_bound)
- Worst-case O(log n) required
- Hash function unreliable

Choose unordered_* when …

- Fastest average lookup
- No ordering needed
- Large datasets (1M+ elements)
- Workload: insert/search/delete only

Unordered: Example Program

```cpp
std::unordered_map<std::string,int> word_freq;
std::vector<std::string> words = {"apple","banana","apple",
    "cherry","banana","apple","date","apple"};

// Count frequencies — O(1) per increment
for (const auto& w : words) word_freq[w]++;

// Query membership  O(1) avg
if (word_freq.count("cherry"))
    cout << word_freq["cherry"]; // 1

// 1M-element lookup benchmark
std::unordered_set<int> big_set;
for (int i=0; i<1'000'000; ++i) big_set.insert(i);
auto t0 = chrono::high_resolution_clock::now();
bool found = big_set.count(500000) > 0;
auto t1 = chrono::high_resolution_clock::now();
// Elapsed: ~10-50 nanoseconds  (essentially O(1)!)
```

Word Frequencies

```
apple: 4
banana: 2
cherry: 1
date: 1
(order undefined)
```

Unique Words Count

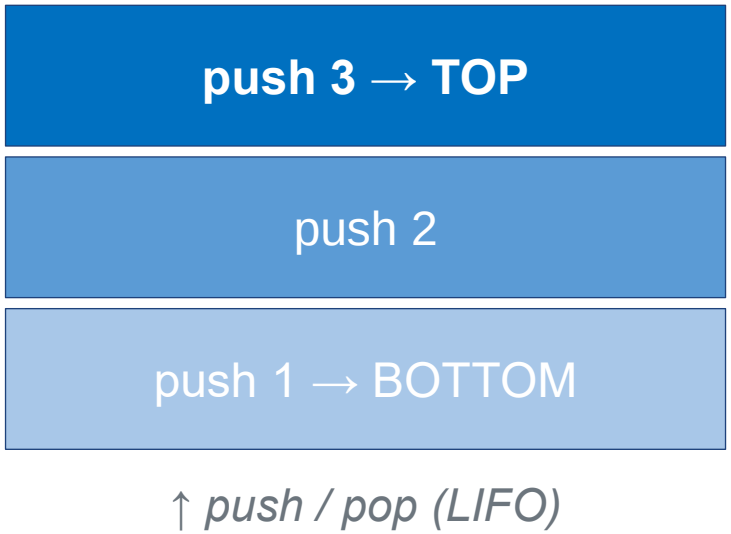
```
4 unique words
```

1M Lookup Time

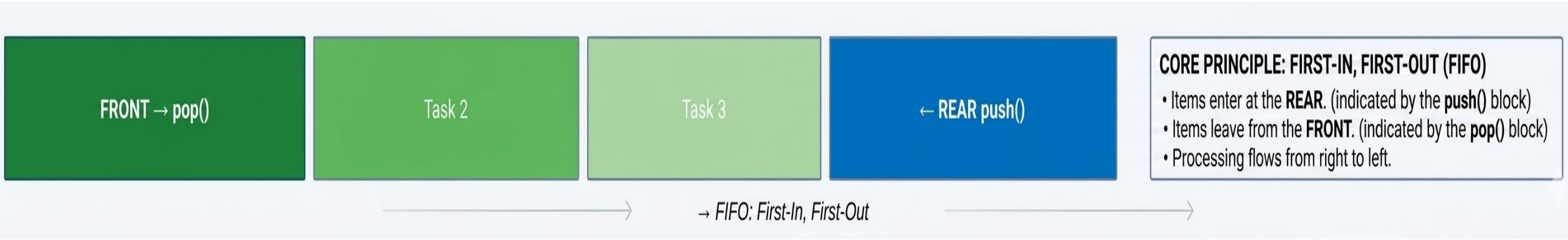
```
~10-50 nanoseconds
vs. map: ~400-600 ns
```

Container Adapters: Stack

Operation	Behaviour	Complexity
push(v)	Add to top	O(1) amortized
pop()	Remove top	O(1) amortized
top()	Read top	O(1)
size()	Count	O(1)
empty()	Check empty	O(1)



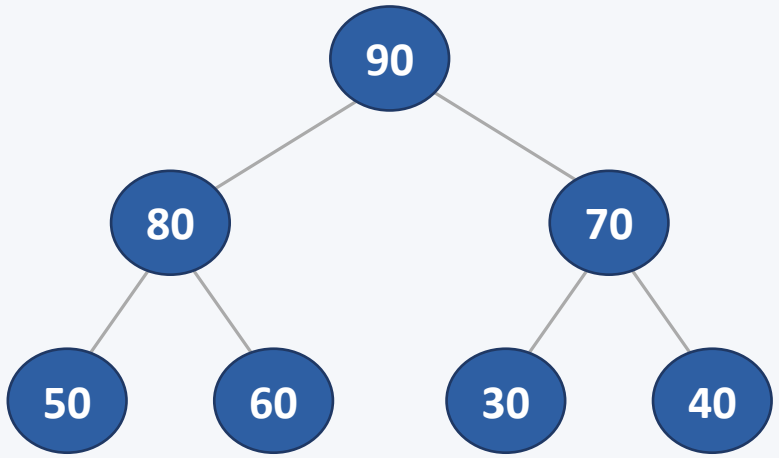
Container Adapters: Queue



Operation	Behaviour	Complexity
push(v)	Add to rear	O(1)
pop()	Remove front	O(1)
front()	Read front	O(1)
back()	Read rear	O(1)
empty()	Check empty	O(1)

Container Adapters: Priority Queue

Max-Heap Visualisation



↑ *top() always returns the largest element*

```
Stored as: [90, 80, 70, 50, 60, 30, 40]
```

Operation	Behaviour	Complexity
push(v)	Insert + re-heap	O(log n)
pop()	Remove top + re-heap	O(log n)
top()	Read maximum (or min)	O(1)
size()	Count elements	O(1)
empty()	Check if empty	O(1)

String Components

substr(pos, len) · O(k)

Extract k characters starting at pos. Returns a new string.

find(str, pos) · O(n·m)

Find first occurrence. Returns position or string::npos if not found.

replace(p,l,str) · O(n)

Replace substring at [p, p+l) with str.

compare(str) · O(n)

Lexicographic comparison. Returns <0, 0, or >0.

c_str() · O(1)

Returns const char* to internal buffer. Valid until string is modified.

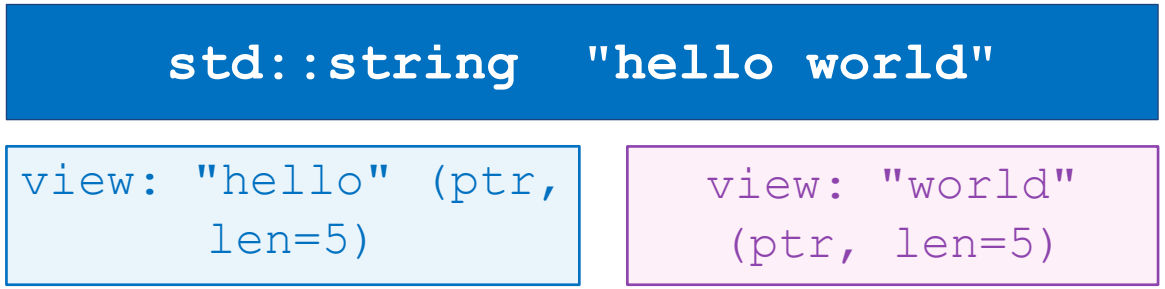
reserve(n) · O(n)

Pre-allocate capacity to avoid reallocations.

```cpp
std::string s = "hello world";
string sub  = s.substr(6, 5);   // "world"
size_t pos  = s.find("world");   // 6
s.replace(6, 5, "STL");          // s = "hello STL"
if (pos != std::string::npos) { /* found */ }
```

String View

Memory Layout



Key Advantage: Zero-Copy

string_view is just a pointer + length (16 bytes). No allocation, no copy — even for substrings.

⚠ Danger: Dangling Views

If the source string is modified or destroyed, the view becomes a dangling reference — undefined behaviour!

```cpp
// Without string_view – allocates copy!
void process(const std::string& s);
process(bigStr.substr(0, 5)); // ❌ heap allocation

// With string_view – zero copy ✅
void process(std::string_view sv);
process(std::string_view(bigStr).substr(0,5)); // no allocation

// Safe usage – source must outlive view!
std::string src = "hello world";
std::string_view sv = src;  // OK while src alive
```

Common Mistakes

1. Modifying Keys In-Place

```
m[5]->first = 10;  // ❌ COMPILE ERROR
```

```
string v = m[5]; m.erase(5); m[10] = v;// ✅
```

2. Using Erased Iterators

```
m.erase(it);  cout << it->first;  // ❌ undefined behaviour
```

```
it = m.erase(it);  // ✅ erase() returns next valid iterator
```

3. Erasing While Iterating

```
for (auto it=m.begin(); it!=m.end(); ++it)
if (cond) m.erase(it);  // ❌ it is now dangling
```

```
if (cond) it = m.erase(it); else ++it; // ✅
```

4. Hash Order Assumptions

```
Assuming unordered_map iterates in insertion order ❌
```

```
Use map/set if you need ordered iteration ✅
```

Best Practices

1. Need sorted order / range queries?	YES → map / set NO → unordered_map / set
2. Key-value pairs or just keys?	YES → map / unordered_map NO → set / unordered_set
3. Multiple values per key?	YES → multimap / multiset NO → map / set
4. Need LIFO, FIFO, or priority order?	YES → stack / queue / priority_queue NO → sequence or assoc. container
5. Need random access by index?	YES → vector NO → associative container

References

Textbooks

- **C++ How to Program** [10th edition], Deitel, P. & Deitel, H., Global Edition, Global Edition (2017).
- **Problem Solving With C++** [10th edition], Walter Savitch, University of California, San Diego, 2018.

Reference Books

- **Programming: Principles and Practice Using C++** by Bjarne Stroustrup, Addison-Wesley, 2014.
- **An Introduction to Programming with C++** (8th Edition), Diane Zak, Cengage Learning, 2016

Online Resources

- https://www.geeksforgeeks.org/cpp/c-plus-plus/
- https://www.w3schools.com/cpp/default.asp
- https://programiz.pro/resources/cpp
- https://www.hackerrank.com/domains/cpp
- https://cplusplus.com/doc/tutorial/

💡 ***Study Tip:*** *Don't just read the code! Retype the examples from these slides and resources into your IDE, compile them, and modify them to see what happens.*

Thank You!

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