Reverse Iterators

Obtainable from (many, but not all) standard containers

either with member functions:

`container.rbegin()` → *@last_element*

`container.rend()` → *@one_before_first_element*

or with free-standing functions: C++11

`std::rbegin(container)` → *@last_element*

`std::rend(container)` → *@one_before_first_element*

A reverse iterator refers to a position in a container:

```
vector<int> v
{1,2,3,4,5,6,7};
auto i = rbegin(v);
auto e = rend(v);
```

`*i` accesses the element at `i`'s position

```
cout << *i;
cout << *(i+2);
cout << *e;
```

```
prints 7
prints 5
✗ UNDEFINED BEHAVIOR
```

Iterator-Based Loops

Forward Direction

- works for all standard sequence containers
- out-of-bounds access bugs possible
- verbose

```
std::vector<int> v {1, 2, 3, 4, 5, 6};
for (auto i = begin(v); i != end(v); ++i) {
  cout << *i;
}
```

Reverse Direction

- works for all *bidirectional* containers
- out-of-bounds access bugs possible
- verbose

```
std::vector<int> v {1, 2, 3, 4, 5, 6};
for (auto i = rbegin(v); i != rend(v); ++i) {
  cout << *i;
}
```

Default Iterators

Obtainable from standard containers

either with member functions:

`container.begin()` → *@first_element*

`container.end()` → *@one_behind_last_element*

or with free-standing functions: C++11

`std::begin(container)` → *@first_element*

`std::end(container)` → *@one_behind_last_element*

std::list<*ValueType*>

A doubly-linked list of nodes each holding one value.

#include <list>

h/cpp hackingcpp.com

Construct A New List Object

```
list<int> L1 {9,8,5,4}
list<int> L2 (next(begin(L1)),end(L1))
list<int> L3 (4,3)
list<int> deep_copy_of_ls1 (L1)
```

C++17 value type deducable from argument type

```
list L4 {7,4,2};   // list<int>
```

Assign New Content To An Existing List

(deep copy from source)

```
list<int> L1 {8,5,3};
list<int> L2 {6,8,1,9};
L1        =  L2;
```

new state of L1

```
.assign({4,1,3,5})
.assign(2,1)
.assign(@InReg,@InEnd)
```

source container

Access Element Values

$\mathcal{O}(1)$ access only to first and last element

```
.front()  → 2
.back()   → 3
.front() = 7
.back()  = 7
```

Access Arbitrary Elements Using Iterators

```
list<int> ls {2,8,5,3};
auto i = ls.begin(); // obtain iterator
cout << *i;          // prints 2
++i;                 // go to next
*i = 7;              // change to 7
```

Query / Change Size (= Number of Elements)

```
.empty()  → false   O(1)
.size()   → 3       O(1)
.resize(2)
.resize(5,1)
.clear()
```

Append / Prepend Elements

$\mathcal{O}(1)$

```
.push_back(7)
.push_front(7)
```

Insert Elements at Arbitrary Positions

$\mathcal{O}$(#inserted)

```
list<int> L {8,5,3};
.insert(next(begin(L)), 7)
.insert(next(begin(L)), 2,7)
.insert(next(begin(L)), {6,9})
.insert(next(begin(L)), @b, @e)
```

source container

Insert & Construct Elements Without Copy / Move

$\mathcal{O}(1)$

```
list<pair<string,int>> L {{"a",1},{"w",7}};
```

constructor parameters

```
.emplace_back("b",4)
.emplace_front("c",6)
.emplace(next(begin(L)),"z",5)
```

Splice (Elements From) One Lists Into Another One

Does not copy or move elements!

```
list<int> T {8,5,3};   list<int> S {7,9,2};
.splice(next(begin(T)), 7,9,2 )          O(1)
.splice(next(begin(T)), 7,9,2, next(begin(S)) )   O(1)
.splice(next(begin(T)), 7,9,2, next(begin(S)), end(S) )   O(#inserted)
```

source list

Merge Already Sorted Lists

(stable: if two elements are equivalent, that from L1 will precede that from L2)

$\mathcal{O}(n_1 + n_2)$

```
list<int> L1 {2,4,5,8};
list<int> L2 {1,2};
.merge( 1,2,3 )
```

Obtain Iterators

```
.begin() → @first
.end()   → @one_behind_last
```

v.begin() v.end() v.rend().base() v.rbegin().base()

Obtain *Reverse* Iterators

```
.rbegin() → rev@last
.rend()   → rev@one_before_first
```

@pos = rev@pos.base() - 1

rev@pos .base()

Increment Iterators

```
next( begin( 0 1 ··· M ), M )  → @Mth_element
```

$\mathcal{O}(M)$

Reorder Elements

```
.sort()                  f(o,o)↦ bool
.sort(std::greater<>{})
.reverse()
```

Erase Elements Based on Positions

$\mathcal{O}$(#deleted)

```
list<int> L {8,4,3,5};
.pop_back()
.pop_front()
.erase(next(begin(L)))
.erase(next(begin(L)), next(begin(L),3))
```

Erase Elements Based on Values

$\mathcal{O}(n)$

```
.remove(7)                  → 3
.remove_if(is_even)         f(o)↦ bool   → 4
.unique()                   → 2
.unique(equal_abs)          f(o,o)↦ bool → 2
```

C++20 as of C++20 functions return the number of deleted elements

v1.1

std::vector<*ValueType*>

C++'s "default" dynamic array

#include <vector>

h/cpp hackingcpp.com

Construct A New Vector Object

```
vector<int> v1 {2,9,1,8,5,4}
vector<int> v2 (begin(v1)+3, end(v1))
vector<int> v3 (5,3)
vector<int> deep_copy_of_v1 (v1)
```

C++17 value type deducable from argument type

```
vector w {7,4,2};   // vector<int>
```

Typical Memory Layout

.capacity() → 5

.size() → 3

dynamically allocated *contiguous* buffer

vector object

Assign New Content To An Existing Vector

(deep copy from source)

```
vector<int> v1 {8,5,3};
vector<int> v2 {6,8,1,9};
v1      =   v2;
```

new state of v1

```
.assign({4,1,3,5})
.assign(2,1)
.assign(@InBeg,@InEnd)
```

source container

Query/Change Size (= Number of Elements)

```
.empty()  → false
.size()   → 3
.resize(2)
.resize(4,1)
.resize(6,1)
.clear()
```

Query/Grow Capactiy (= Memory Buffer Size)

```
.capacity()  → 4
.reserve(6)
```

Obtain Iterators

$\mathcal{O}(1)$ Random Incrementing

```
.begin()  → @first
.end()    → @one_behind_last
```

v.begin() v.end() v.rend().base() v.rbegin().base()

Obtain *Reverse* Iterators

```
.rbegin() → rev@last
.rend()   → rev@one_before_first
```

@pos = rev@pos.base() - 1

rev@pos .base()

```
.data()  → pointer_to_first
```

Avoid expensive memory allocations: **.reserve** capacity before appending / inserting if you know the (approximate) number of elements to be stored in advance!

Append Elements

$\mathcal{O}(1)$ Amortized Complexity

```
.push_back(7)
```

Get Element Values

$\mathcal{O}(1)$ Random Access

```
[1]   → 8
.front() → 2
.back()  → 3
```

Change Element Values

```
[1] = 7
.front() = 7
.back()  = 7
```

Out of Bounds Access

```
[6]      Undefined Behavior   (Invalid Index!)
.at(6)   Throws Exception std::out_of_range
```

Erase Elements

$\mathcal{O}(n)$ Worst Case

```
vector<int> v {4,8,5,6};
.pop_back()
.erase(begin(v)+2)
.erase(begin(v)+1, begin(v)+3)
```

.end()

Shrink The Capacity

(might be inefficient)

Erasing, resizing or clearing will not shrink the capacity!

```
vector<int> v (1024,0);   // capacity is at least 1024
v.resize(40);             // capacity unchanged!
v.shrink_to_fit();        // may shrink (not guaranteed)
v.swap(vector<int>(v));   // shrinks but has copy overhead
```

Insert Elements at Arbitrary Positions

$\mathcal{O}(n)$ Worst Case

```
vector<int> v {8,5,3};
.insert(begin(v)  , 2)
.insert(begin(v)+1, 7)
.insert(begin(v)+1, 3,7)
.insert(begin(v)+1, {6,9,7})
.insert(begin(v)+1, @InBegin, @InEnd)
```

source container

Insert & Construct Elements in Place

$\mathcal{O}(n)$ Worst Case

```
vector<pair<string,int>> v {{"a",1},{"w",7}};
```

constructor parameters

```
{a,1}{w,7} .emplace_back("b",4)
{a,1}{w,7} .emplace(begin(v)+1,"z",5)
```

v1.1

std::string

`#include <string>`


```
string s = "I'm sorry, Dave.";
```

indices: I=0 '=1 m=2 (space)=3 s=4 o=5 r=6 r=7 y=8 ,=9 (space)=10 D=11 a=12 v=13 e=14 .=15

non-mutating

s.size()	→	16	(number of characters)
s[2]	→	'm'	(character at index 2)
s.find("r")	→	6	(first match from start)
s.rfind("r")	→	7	(first match from end)
s.find("X")	→	string::npos	(not found, invalid index)
s.find(' ', 5)	→	10	(first match after index ≥ 5)
s.substr(4, 6)	→	string{"sorry,"}	
s.contains("sorry")	→	*true*	(C++23)
s.starts_with('I')	→	*true*	(C++20)
s.ends_with("Dave.")	→	*true*	(C++20)
s.compare("I'm sorry, Dave.")	→	0	(identical)
s.compare("I'm sorry, Anna.")	→	> 0	(same length, but 'D' > 'A')
s.compare("I'm sorry, Saul.")	→	< 0	(same length, but 'D' < 'S')

mutating

s += " I'm afraid I can't do that."	⇒	s = "I'm sorry, Dave. I'm afraid I can't do that."
s.append("..")	⇒	s = "I'm sorry, Dave..."
s.clear()	⇒	s = ""
size: s.resize(3)	⇒	s = "I'm"
size: s.resize(20, '?')	⇒	s = "I'm sorry, Dave.????";
index based: s.insert(4, "very ")	⇒	s = "I'm very sorry, Dave."
index based: s.erase(5, 2)	⇒	s = "I'm sry, Dave."
index based: s[15] = '!'	⇒	s = "I'm sorry, Dave!"
index based: s.replace(11, 5, "Frank")	⇒	s = "I'm sorry, Frank"
iterator based: s.insert(s.begin(), "HAL: ")	⇒	s = "HAL: I'm sorry, Dave."
iterator based: s.insert(s.begin()+4, "very ")	⇒	s = "I'm very sorry, Dave."
iterator based: s.erase(s.begin()+5)	⇒	s = "I'm srry, Dave."
iterator based: s.erase(s.begin(), s.begin()+4)	⇒	s = "sorry, Dave."

Constructors

string{'a','b','c'}	➡	[a][b][c]
string(4, '$')	➡	[$][$][$][$]
string(@firstIn, @lastIn) — source iterator range: [b][c][d][e][f][g][h][i][j]	➡	[e][f][g][h]
string([a][b][c][d]) — source string object; copy/move	➡	[a][b][c][d]

Obtain Iterators or Reverse Iterators

.begin() → @first	.rbegin() → *reverse@last* (.base())
.end() → @one_behind_last (don't use to access elements!)	.rend() → *reverse@one_before_first* (.base()) (don't use to access elements!)

String → Number Conversion

```
int                stoi (●,●,●);
long               stol (●,●,●);
long long          stoll(●,●,●);

unsigned long      stoul (●,●,●);
unsigned long long stoull(●,●,●);

float              stof (●,●,●);
double             stod (●,●,●);
long double        stold(●,●,●);
```

- const string& — input string
- std::size_t* p = nullptr — output for number of processed characters
- int base = 10 — base of target system; default: decimal

Number → String Conversion

```
string to_string( ● );
```

● : int | long | long long | unsigned | unsinged long | unsigned long long | float | double | long double

v1.6

std::string_view

`#include <string_view>` C++17

- lightweight (= cheap to copy, can & should be passed by value)
- non-owning (= not responsible for allocating or deleting memory)
- read-only view (= does not allow modification of target string)
- of a contiguous character range (std::string / "literal" / vector<char> / …)

```
void foo (std::string_view sv) {…}
     foo ("I'm sorry, Dave.");
```

indices: I=0 '=1 m=2 (space)=3 s=4 o=5 r=6 r=7 y=8 ,=9 (space)=10 D=11 a=12 v=13 e=14 .=15

sv.size()	→	16	(number of characters)	
sv[2]	→	'm'	(character at index 2)	
sv.front()	→	'I'	(first character)	
sv.back()	→	'.'	(last character)	
sv.find("r")	→	6	(first match from start)	
sv.rfind("r")	→	7	(first match from end)	
sv.find("X")	→	string_view::npos	(not found)	
sv.find(' ', 5)	→	10	(first match after index ≥ 5)	
sv.substr(4, 5)	→	string_view of substring "sorry"		
sv.contains("sorry")	→	*true*		(C++23)
sv.starts_with('I')	→	*true*		(C++20)
sv.ends_with("Dave.")	→	*true*		(C++20)
sv.find_first_of("ems")	→	2	(first occurence of 'm')	(C++17)
sv.find_last_of('r')	→	7	(last occurence of 'r')	(C++17)
sv.compare("I'm sorry, Dave.")	→	0	(identical)	
sv.compare("I'm sorry, Anna.")	→	> 0	(same length, but 'D' > 'A')	
sv.compare("I'm sorry, Saul.")	→	< 0	(same length, but 'D' < 'S')	
sv.remove_suffix(7);	⇒	std::cout << sv; // "I'm sorry"		
sv.remove_prefix(4);	⇒	std::cout << sv; // "sorry"		

Primary Use Case: As Read-Only Function Parameter

if a copy of the input string isn't always needed inside a function

Prevents Temporary Copies:

```
void f_cref (std::string const& s) { … }
void f_view (std::string_view s)   { … }

std::string std_str = "Standard String";
char * const  c_str = "C-String";
std::vector<char> v {'c','h','a','r','s','\0'};

f_cref (std_str);               // no copy (of course)
f_cref (c_str);                 // temp copy
f_cref ("Literal");             // temp copy
f_cref ({begin(v), end(v)});    // temp copy

f_view (std_str);               // no copy
f_view (c_str);                 // no copy
f_view ("Literal");             // no copy
f_view ({begin(v), end(v)});    // no copy
```

Easy To Pass Subranges Without Copying:

```
f_view ( {begin(std_str), begin(std_str) + 5} );  // "Stand"
f_view ( {begin(std_str) + 9, end(std_str)} );    // "String"
```

Special Literal "…"sv

```
using namespace std::string_view_literals;
auto literal_view = "C String Literal"sv
```

Careful: A View Might Outlive Its Target String!

```
std::string_view sv { std::string{"Text"} };
std::cout << sv; ⚡ // string object already destroyed!
```

v1.2

C++ Standard Library **Sequence Containers**

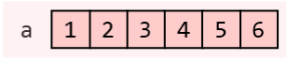
h/cpp hackingcpp.com

array<T, size>

fixed-size array

#include <array>

```
std::array<int,6> a {1,2,3,4,5,6};
cout << a.size();     // 6
cout << a[2];         // 3
a[0] = 7;             // 1st element ⇒ 7
```



contiguous memory; random access; fast linear traversal

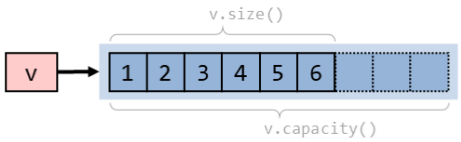
vector<T>

dynamic array

C++'s "default" container

#include <vector>

```
std::vector<int> v {1,2,3,4,5,6};
v.reserve(9);
cout << v.capacity();      // 9
cout << v.size();          // 6
v.push_back(7);            // appends '7'
v.insert(v.begin(), 0);    // prepends '0'
v.pop_back();              // removes last
v.erase(v.begin()+2);      // removes 3rd
v.resize(20, 0);           // size ⇒ 20
```



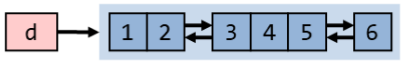
contiguous memory; random access;
fast linear traversal; fast insertion/deletion at the ends

deque<T>

double-ended queue

#include <deque>

```
std::deque<int> d {1,2,3,4,5,6};
// same operations as vector
// plus fast growth/deletion at front
d.push_front(-1);   // prepends '-1'
d.pop_front();      // removes 1st
```



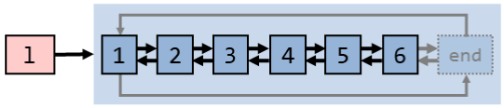
fast insertion/deletion at both ends

list<T>

doubly-linked list

#include <list>

```
std::list<int> l {1,5,6};
std::list<int> k {2,3,4};
// O(1) splice of k into l:
l.splice(l.begin()+1, std::move(k))
// some special member function algorithms:
l.reverse();
l.sort();
```



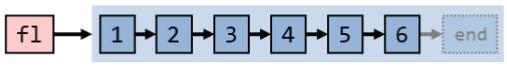
fast splicing; many operations without copy/move of elements

forward_list<T>

singly-linked list

#include <forward_list>

```
std::forward_list<int> fl {2,2,4,5,6};
fl.erase_after(begin(fl));
fl.insert_after(begin(fl), 3);
fl.insert_after(before_begin(fl), 1);
```



lower memory overhead than std::list; only forward traversal

v1.2

std::deque<ValueType>

"double-ended queue" #include <deque> h/cpp hackingcpp.com

Construct A New Deque Object

```
deque<int> d1 {2,9,1,8,5,4}          → 2 9 1 8 5 4
deque<int> d2 (begin(d1)+3, end(d1)) → 8 5 4
deque<int> d3 (5, 3)                 → 3 3 3 3 3
deque<int> deep_copy_of_d1 (d1)      → 2 9 1 8 5 4
```

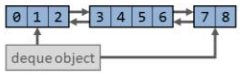
C++17 value type deducable from argument type

```
deque  d4 {7,4,2};   // deque<int>
```

Typical Memory Layout

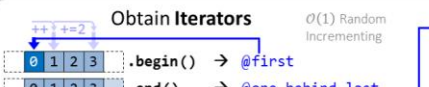
Note that the ISO standard only specifies the properties of deque (e.g., constant-time insert at both ends) but not how that should be implemented.

dynamically allocated contiguous chunks

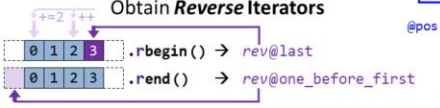


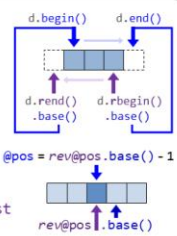
Obtain Iterators

$\mathcal{O}(1)$ Random Incrementing



Obtain *Reverse* Iterators





Assign New Content To An Existing Deque

```
deque<int> d1 {8,5,3};
deque<int> d2 {6,8,1,9};
d1      =     d2;
```

(deep copy from source)

new state of d1

```
8 5 3 = 6 8 1 9                  → 6 8 1 9
8 5 3 .assign ({4,1,3,5})        → 4 1 3 5
8 5 3 .assign (2, 1)             → 1 1
8 5 3 .assign (@InBeg,@InEnd)    → 2 1 1 2
```

source container: 3 2 1 1 2 3

Query Size (= Number of Elements) $\mathcal{O}(1)$

```
8 5 3 .empty() → false
8 5 3 .size()  → 3
```

Change Size $\mathcal{O}(|n - \text{newSize}|)$

```
8 5 3 .resize (2)   → 8 5
8 5 3 .resize (4,1) → 8 5 3 1
8 5 3 .resize (6,1) → 8 5 3 1 1 1
8 5 3 .clear()      →
```

Append Elements $\mathcal{O}(1)$

```
8 5 3 .push_back (7)  → 8 5 3 7
```

Prepend Elements $\mathcal{O}(1)$

```
8 5 3 .push_front (7) → 7 8 5 3
```

Insert Elements at Arbitrary Positions $\mathcal{O}(n)$ Worst Case

```
deque<int> d {8,5,3};
8 5 3 .insert (begin(d)+1, 7)          → 8 7 5 3
8 5 3 .insert (begin(d)+1, 3,7)        → 8 7 7 7 5 3
8 5 3 .insert (begin(d)+1, {6,9,7})    → 8 6 9 7 5 3
8 5 3 .insert (begin(d)+1, @InBegin,@InEnd) → 8 1 8 9 5 3
```

source container: 3 1 8 9 2 3

Get Element Values $\mathcal{O}(1)$ Random Access

```
2 8 5 3 [1]     → 8
2 8 5 3 .front() → 2
2 8 5 3 .back()  → 3
```

Change Element Values

```
2 8 5 3 [1] = 7 → 2 7 5 3
2 8 5 3 .front() = 7 → 7 8 5 3
2 8 5 3 .back() = 7 → 2 8 5 7
```

Out of Bounds Access

```
2 8 5 3 [6]      Undefined Behavior
  Invalid Index!
2 8 5 3 .at(6)   Throws Exception std::out_of_range
```

Erase Elements At The Ends $\mathcal{O}(1)$

```
4 8 5 6 .pop_back()  → 4 8 5
4 8 5 6 .pop_front() → 8 5 6
```

Erase Elements At Arbitrary Positions

```
deque<int> d {4,8,5,6};
```

$\mathcal{O}(n)$ Worst Case Complexity

```
4 8 5 6 .erase (begin(d)+2)            → 4 8 6
4 8 5 6 .erase (begin(d)+1, begin(d)+3) → 4 6
```

Insert & Construct Elements in Place $\mathcal{O}(n)$ Worst Case

```
deque<pair<string,int>> d {{"a",1},{"w",7}};
```

constructor parameters

```
{a,1}{w,7} .emplace_back ("b",4)     → {a,1}{w,7}{b,4}
{a,1}{w,7} .emplace_front ("c",6)    → {c,6}{a,1}{w,7}
{a,1}{w,7} .emplace (begin(d)+1,"z",5) → {a,1}{z,5}{w,7}
```

v1.1

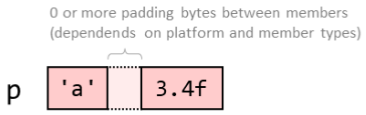
C++ Standard Library Special Containers

pair<A,B>

#include <utility>

contains *two* values
of same or different type

```
std::pair<char,float> p;
p.first  = 'a';
p.second = 3.4f;
char  x = std::get<0>(p);
float y = std::get<1>(p);
```

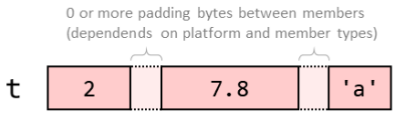


tuple<A,B,C,…>

#include <tuple>

contains *many* values
of same or different type

```
std::tuple<int,double,char> t { 2, 7.8, 'a' };
int    x = std::get<0>(t);
double y = std::get<1>(t);
char   z = std::get<2>(t);
auto [u,v,w] = t;  // u: 2  v: 7.8  w:  'a'
```

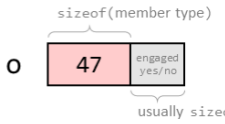


optional<T>

#include <optional>

either contains
one value of type *T* or *no* value

```
std::optional<int> o;
bool b = o.has_value(); // false
o = 47;          // has value '47' now
if(o) { std::cout << *o; }
o.reset();       // disengage => no value
```

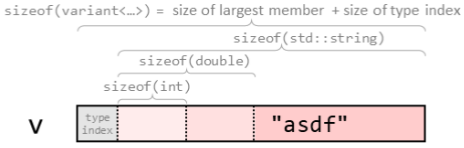


variant<A,B,C,…>

#include <variant>

contains *one* value of either
type *A* or type *B* or type *C*, etc.

```
std::variant<int,string,double> v { 47 };
bool b = std::holds_alternative<int>(v);
v = std::string("asdf");
auto i = v.index();       // 1 ⇔ string
```

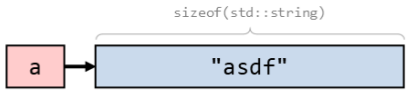


any

#include <any>

contains *one* value of any type

```
std::any a = 5;
a = std::string("abc");
a = std::set<int> {3,1,47,8,6};
try { int x = std::any_cast<int>(a); }
catch(std::bad_any_cast&) { /* … */ }
```



v1.1

C++ Standard Library Associative Containers

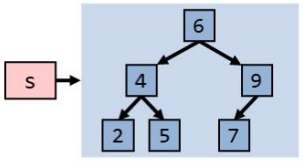
set<Key>

unique, ordered keys

multiset<K>

(non-unique) ordered keys

```
std::set<int> s;
s.insert(7); …
s.insert(5);
auto i = s.find(7);  // → iterator
if(i != s.end())     // found?
  cout << *i;        // 7
if(s.contains(7)) {…}     C++20
```



usually implemented
as balanced binary tree
(red-black tree)

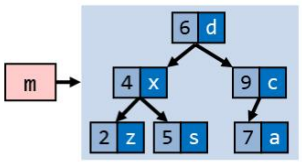
map<Key,Value>

unique key→value-pairs; ordered by keys

multimap<K,V>

(non-unique) key→value-pairs; ordered by keys

```
std::map<int,char> m;
m.insert({7,'a'}); …
m[4] = 'x';          // insert 4→x
auto i = s.find(7);  // → iterator
if(i != s.end())     // found?
  cout << i->first   // 7
       << i->second; // a
if(s.contains(7)) {…}     C++20
```



usually implemented
as balanced binary tree
(red-black tree)

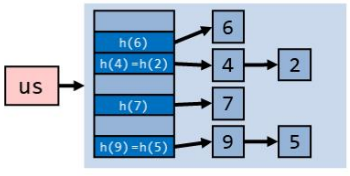
unordered_set<Key>

unique, hashable keys

unordered_multiset<Key>

(non-unique) hashable keys

```
std::unordered_set<int> us;
us.insert(7); …
us.insert(5);
auto i = us.find(7); // → iterator
if(i != us.end())    // found?
  cout << *i;        // 7
if(s.contains(7)) {…}     C++20
```



hash table for
key lookup,
linked nodes
for key storage

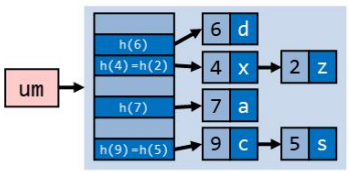
unordered_map<Key,Value>

unique key→value-pairs; hashed by keys

unordered_multimap<Key,Value>

(non-unique) key→value-pairs; hashed by keys

```
unordered_map<int,char> um;
um.insert({7,'a'}); …
um[4] = 'x';          // insert 4→x
auto i = um.find(7); // → iterator
if(i != um.end())    // found?
  cout << i->first   // 7
       << i->second; // a
if(s.contains(7)) {…}     C++20
```



hash table for
key lookup,
linked nodes
for (key, value)
pair storage

v1.1

std::set<KeyType, Compare>

(unique keys)

#include <set>

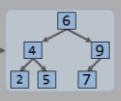
h/cpp hackingcpp.com

default: std::less<KeyType>

std::multiset<KeyType, Compare>

(multiple equivalent keys)

- keys are ordered according to their values
- keys are compared / matched based on *equivalence*: **a** and **b** are equivalent if neither is ordered before the other, e.g., if `not (a < b) and not (b < a)`
- default ordering comparator is `std::less`
- sets are usually implemented as a balanced binary tree (e.g., as red-black-tree)



Construct A New Set Object

```
set<int> s0 {}
set<int> s1 {2,1,8,5,4}
set<int> s2 (begin(s1)+2, end(s1))
set<int> deep_copy_of_s1 (s1)
```

C++17 key type deducable from argument type

```
set  s3 {7,2,4};   // set<int>
```

Assign New Content To An Existing Set

(deep copy from source)

```
set<int> s1 {1,3,5,7};
set<int> s2 {4,6,8};
s1 = s2;
```

new state of s1

Key Lookup

$\mathcal{O}(\log n)$

C++20

```
.contains(2) → false
.contains(5) → true
.count(2) → 0
.count(5) → 1
```

can be > 1 only for std::multiset

```
.find(2) → @end   (= no match)
.find(5) → @match
.lower_bound(3) → @first_not_smaller
.upper_bound(3) → @first_greater
.equal_range(3) → {@Lbound,@Ubound}
```

Query Size (= Number of Keys)

```
.empty() → false
.size() → 3
```

Erase All Keys

```
.clear()
```

Insert A Single Key

$\mathcal{O}(\log n)$

```
.insert(4) → {@inserted, true}   .first .second
.insert(5) → {@blocking, false}   (not inserted)
```

potential performance benefit by hinting at probable insert position

```
.insert(@hint,7) → @inserted_or_block
```

Insert Multiple Keys

$\mathcal{O}(\#\text{inserted} \cdot \log n)$

```
.insert({1,6,8}) → 
.insert(@inB,@inE) →
```

source container

Insert & Construct A Key in Place

$\mathcal{O}(\log n)$

```
set<pair<int,int>> s {{1,3},{5,6}};
.emplace(4,7) → {@inserted, true}   (if inserted)
```

pair constructor arguments

potential performance benefit by hinting at probable insert position

```
.emplace_hint(@hint,4,7) → @inserted
```

Erase One Key or A Range of Keys

$\mathcal{O}(\log n)$

```
.erase(2) → 0
.erase(5) → 1
```

#erased

$\mathcal{O}(1)$ amortized

```
.erase(@pos) → @after_erased
.erase(@beg,@end) → @after_erased
```

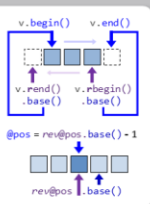
$\mathcal{O}(\log n + \#\text{erased})$

Obtain Iterators

```
.begin() → @first
.end() → @one_behind_last
```

Obtain *Reverse* Iterators

```
.rbegin() → rev@last
.rend() → rev@one_before_first
```



Extract Nodes

C++17

Allows efficient key modification and transfer of keys between different set objects.

```
.extract(5) → 5   O(log n)
.extract(@pos) → 5   O(1)
```

Merge Two Sets

C++17

```
set<int> S1 {1,3,5,7};
set<int> S2 {2,5,8};
.merge( 2 5 8 )
```

$\mathcal{O}(n_2 \cdot \log(n_1 + n_2))$

Insert Nodes

C++17

members of the return type

```
.insert(5) → {.position|.inserted|.node}   true
.insert(1) → {.position|.inserted|.node}   false
(empty node)
.insert( ) → {.position|.inserted|.node}   false
.insert(@hint,5) → @inserted
.insert(@hint,1) → @blocking
```

Modify Key

Direct modification not allowed! Instead: **extract** key, **modify** its value and **re-insert**.

```
set<int> s {1,5,7};
auto node = s.extract(5);
if (node) {   // if key existed
  node.value() = 8;
  s.insert(std::move(node));
}
```

v1.2

std::unordered_set<KeyT, Hash, KeyEqual>

(hash set of unique keys)

h/cpp hackingcpp.com

default: std::hash<KeyT>

default: std::equal_to<KeyT>

#include <unordered_set>

std::unordered_multiset<KeyT, Hash, KeyEqual>

(multiple equivalent keys allowed)

Construct A New Set Object

```
unordered_set<int> s0 {}
unordered_set<int> s1 {2,1,8,4,5}
unordered_set<int> s2 (begin(s1)+2, end(s1))
unordered_set<int> deep_copy_of_s1 (s1)
```

C++17 key type deducable from argument type

```
unordered_set  s3 {7,2,4};   // unordered_set<int>
```

Assign New Content To An Existing Set

(deep copy from source)

```
unordered_set<int> s1 {1,5,3,7};
unordered_set<int> s2 {8,4,6};
s1 = s2;
```

new state of s1

Key Lookup

$\mathcal{O}(1)$ average, $\mathcal{O}(n)$ worst case

C++20

```
.contains(2) → false
.contains(3) → true
.count(2) → 0
.count(3) → 1
```

can be > 1 only for std::unordered_multiset

```
.find(2) → @end   (= no match)
.find(3) → @match
.equal_range(5) → {@first_equal, @after}
```

Query Size (= Number of Keys)

```
.empty() → false
.size() → 3
```

Erase All Keys

```
.clear()
```

Obtain Iterators (to keys)

```
.begin() → @first
.end() → @one_behind_last
```

Insert A Single Key

$\mathcal{O}(1)$ average, $\mathcal{O}(n)$ worst case

```
.insert(4) → {@inserted, true}   .first .second
.insert(8) → {@blocking, false}   (not inserted)
```

potential performance benefit by hinting at probable insert position

```
.insert(@hint,7) → @inserted_or_block
```

Insert Multiple Keys

$\mathcal{O}(\#\text{ins})$ avg., $\mathcal{O}(n \cdot \#\text{ins} + \#\text{ins})$ worst

```
.insert({1,6,8}) → 
.insert(@inB,@inE) →
```

source container

Insert & Construct A Key in Place

$\mathcal{O}(1)$ avg., $\mathcal{O}(n)$ worst

```
unordered_set<pair<int,int>> s {{1,3},{5,6}};
.emplace(8,7) → {@inserted, true}   (if inserted)
```

pair constructor arguments

potential performance benefit by hinting at probable insert position

```
.emplace_hint(@hint,8,7) → @inserted
```

Erase One Key or A Range of Keys

$\mathcal{O}(\#\text{erased})$ avg. $\mathcal{O}(n)$ worst case

```
.erase(2) → 0
.erase(3) → 1
```

#erased

```
.erase(@pos) → @after_erased
.erase(@beg,@end) → @after_erased
```

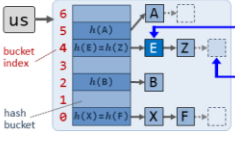
Query & Control Hash Table Properties

hash function: $h(key) \mapsto$ bucket index

```
unordered_set<char> us {'E','X','Z','A','F','B'};
.bucket('E') → 4   (key → hash buchet index)
.begin(4) → @first_in_bucket
.end(4) → @one_behind_last_in_bucket
.bucket_size(4) → 2
.bucket_count() → 7
us.load_factor() → 4 / 7 = 0.57
us.max_load_factor(0.8)   (set)
us.max_load_factor() → 0.8   (get)
.reserve(min_capacity)
.rehash(#hash_buckets)
```

(make table large enough to hande min_capacity elements)

(can allocate even more buckets if max. load factor demands it)



Extract Nodes

$\mathcal{O}(1)$ avg., $\mathcal{O}(n)$ worst

C++17

Allows efficient key modification and transfer of keys between different set objects.

```
.extract(5) → 5
.extract(@pos) → 5
```

Merge Two Sets

C++17

$\mathcal{O}(n_2)$ average, $\mathcal{O}(n_1 \cdot n_2 + n_2)$ worst case

```
unordered_set<int> S1 {1,5,3};
unordered_set<int> S2 {8,1,2};
.merge( 8 1 2 )
```

Insert Nodes

C++17

members of the return type

```
.insert(8) → {.position|.inserted|.node}   true
.insert(1) → {.position|.inserted|.node}   false
(empty node)
.insert( ) → {.position|.inserted|.node}   false
.insert(@hint,8) → @inserted
.insert(@hint,1) → @blocking
```

Modify Key

Direct modification not allowed! Instead: **extract** key, **modify** its value and **re-insert**.

```
unordered_set s {1,7,5};
auto node = s.extract(5);
if (node) {   // if key existed
  node.value() = 8;
  s.insert(move(node));
}
```

v1.3

std::map<KeyType,MappedType,KeyCompare>

(unique keys)

default: std::less<KeyType>

std::multimap<KeyType,MappedType,KeyCompare>

(multiple equivalent keys allowed)

h/cpp hackingcpp.com

#include <map>

Construct A New Map Object

```
map<int,string> m0 { }
map<int,string> m1 {{4,"Z"},{2,"A"},{7,"Y"}}
map<int,string> m2 ( begin(m1)+1, end(m1) )
map<int,string> deep_copy_of_m1(m1)
C++17  key and mapped types deducable from arguments
map    m3 {{2,3.14},{5,6.0}};   // map<int,double>
```

Insert A Single Key-Value Pair

$\mathcal{O}(\log n)$

```
.insert({2,"W"}) → {@inserted,true}   (inserted yes/no)
.insert({3,"X"}) → {@blocking,false}
potential performance benefit by hinting at probable insert position
.insert(@hint,{2,"W"}) → @ins/block
```

Obtain Iterators

```
.begin() → @first
.end()   → @one_behind_last
```

Obtain *Reverse* Iterators

```
.rbegin() → rev@last
.rend()   → rev@one_before_1st
```

v.begin() v.end() v.rend() v.rbegin() .base() .base()

@pos = rev@pos.base() - 1

- key-value pairs are ordered by key
- key matching is *equivalence*-based: 2 keys a and b are equivalent if not (a < b) and not (b < a)
- default key comparator is std::less
- maps are usually implemented as a balanced binary tree (e.g., as red-black-tree)

map object

Assign New Content To An Existing Map

```
map<int,string> m1 {{2,"X"}};
map<int,string> m2 {{1,"A"},{4,"G"}};
m1 = m2;
```

(deep copy from source)

new state of m1

Lookup Using Keys as Input

$\mathcal{O}(\log n)$

```
map<int,string> m {{3,"A"},{5,"X"},{1,"F"}};
.contains(2) → false        C++20
.contains(5) → true
.count(2) → 0
.count(5) → 1   can be > 1 only for std::multimap
.find(2) → @end   (= no match)
.find(5) → @match
.lower_bound(3) → @1st_not_smaller
.upper_bound(3) → @1st_greater
.equal_range(3) → {@Lower,@Upper}
.at(3) → "A"
.at(2) → Throws Exception std::out_of_range
```

Query Size (= number of key-value pairs)

```
.empty() → false
.size()  → 2
```

Insert Multiple Key-Value Pairs

$\mathcal{O}\left(\frac{\#\text{inserted}}{}\cdot\log n\right)$

```
.insert({{5,"K"},{3,"Y"},{1,"G"}})
.insert(@inB, @inE)
```

source container

Insert & Construct Key-Value Pair

$\mathcal{O}(\log n)$

```
.emplace(2,"W") → {@inserted,true}   (inserted yes/no)
potential performance benefit by hinting at probable insert position
.emplace_hint(@hint,2,"W") → @inserted
.try_emplace(2,"W") → {@inserted,true}   C++17
advantage: does not move from rvalue input parameters if not inserted
```

Erase Key-Value-Pair(s)

```
.erase(2) → 0
.erase(3) → 1   $\mathcal{O}(\log n)$ #erased
.erase(@pos) → @after_erased   $\mathcal{O}(1)$ amortized
.erase(@b,@e) → @after_erased   $\mathcal{O}(\log n + \#\text{deleted})$
```

Erase All

```
.clear()
```

Access / Modify Value

$\mathcal{O}(\log n)$

```
map<int,string> m {{1,"F"},{3,"A"}};
[3] = "A"
[3] = "X"
Attention: [k] inserts new pair if key k is not present!
[2] = "W"
[2] = ""
```

Insert or Assign Value

$\mathcal{O}(\log n)$ C++17

(inserted yes/no)

```
.insert_or_assign(3,"X") → {@as,false}
.insert_or_assign(5,"R") → {@ins,true}
.insert_or_assign(@hint,3,"W") → @as
.insert_or_assign(@hint,2,"G") → @ins
```

Merge Two Maps

$\mathcal{O}(n_2 \cdot \log(n_1+n_2))$ C++17

```
map<int,string> m1 {{1,"F"},{3,"S"},{5,"T"}};
map<int,string> m2 {{2,"A"},{5,"X"}};
.merge(m2)
```

Extract Nodes

Allows efficient transfer of key-value pairs. C++17

```
.extract(2) → 2R   $\mathcal{O}(\log n)$
.extract(@pos) → 2R   $\mathcal{O}(1)$
```

(Re-)Insert Nodes

members of the return type

```
.insert(5N) → {.position|.inserted|.node}   true
.insert(3Z) → {.position|.inserted|.node}   false
.insert()   → {.position|.inserted|.node}   (empty node)  false
.insert(@hint,5X) → @inserted
.insert(@hint,1G) → @blocking
```

Modify Key

Direct *key* modification not allowed!

Instead:
- extract
- modify
- re-insert

```
map<int,string> m {{1,"F"},{3,"A"}};
auto node = m.extract(3);
if (node) {  // if key existed
  node.key() = 8;
  m.insert(move(node));
}
```

v1.0

std::forward_list<ValueType>

#include <forward_list>

h/cpp hackingcpp.com

A singly-linked list of nodes each holding one value.

C++11

Construct A New List Object

```
forward_list<int> L1 {8,5,4}
forward_list<int> L2 (next(begin(L1)),end(L1))
forward_list<int> L3 (3,1)
forward_list<int> deep_copy_of_L1 (L1)
C++17  value type deducable from argument type
forward_list  L4 {7,4,2};   // forward_list<int>
```

Assign New Content To An Existing List

(deep copy from source)

```
forward_list<int> L1 {8,5,3};
forward_list<int> L2 {6,8,1,9};
L1 = L2;
```

new state of L1

```
.assign({4,1,3,5})
.assign(2,1)
.assign(@InBeg,@InEnd)
```

source container

Access Element Values

$\mathcal{O}(1)$ access only to first element

```
.front()   → 2
.front() = 7
```

Access Arbitrary Elements Using Iterators

```
forward_list<int> ls {2,8,5,3};
auto i = ls.begin();  // obtain iterator
cout << *i;           // prints 2
++i;                  // go to next
*i = 7;               // change to 7
```

Check Emptiness / Change Size (= Number of Elements)

There's no member function available to determine the size!

```
.empty()   → false   $\mathcal{O}(1)$
.resize(2)
.resize(5,1)
.clear()
```

Insert Elements at Arbitrary Positions

$\mathcal{O}(\#\text{inserted})$

```
forward_list<int> L {0,1,2};
.insert_after(begin(L),7)
.insert_after(begin(L),2,8)
.insert_after(begin(L),{6,4})
.insert_after(begin(L),@b,@e)
```

source container

Insert & Construct Elements Without Copy / Move

$\mathcal{O}(1)$

```
forward_list<pair<string,int>> L {{"a",1},{"w",7}};
```

constructor parameters

```
.emplace_front("c",6)
.emplace_after(begin(L),"z",5)
```

Splice (Elements From) One List Into Another One

does not copy or move elements!

```
forward_list<int> T {8,5,3};   forward_list<int> S {7,9,2};
.splice_after(begin(T),S)   $\mathcal{O}(1)$
.splice_after(begin(T),S,begin(S))   $\mathcal{O}(1)$
.splice_after(begin(T),S,begin(S),end(S))   $\mathcal{O}(\#\text{inserted})$
```

source list

Merge Already Sorted Lists

(stable: if two elements are equivalent, that from L1 will precede that from L2)

$\mathcal{O}(n_1+n_2)$

```
forward_list<int> L1 {2,4,5};
forward_list<int> L2 {1,3};
.merge(L2)
```

Erase Elements Based on Values

$\mathcal{O}(n)$

```
.remove(7)
.remove_if(is_even)   f(o)→bool
.unique()
.unique(equal_abs)   f(o,o)→bool
```

Obtain Iterators

$\mathcal{O}(1)$

```
.begin()  → @first
begin(L)  → @first
.before_begin() → @one_before_first
.end()    → @one_behind_last
end(L)    → @one_behind_last
```

Increment Iterators

$\mathcal{O}(M)$

```
next(begin(L),M) → @Mth_element
```

Prepend Elements

$\mathcal{O}(1)$

```
.push_front(7)
```

Reorder Elements

```
.sort()
.sort(std::greater<>())   f(o,o)→bool
.reverse()
```

Erase Elements Based on Positions

$\mathcal{O}(\#\text{deleted})$

```
forward_list<int> L {0,1,2};
.pop_front()
.erase_after(L.before_begin())
.erase_after(begin(L))
.erase_after(begin(L),end(L))
```

v1.1

std::unordered_map<KeyT, MappedT, Hash, KeyEqual>

default: std::hash<KeyT> — default: std::equal_to<KeyT>

std::unordered_multimap<KeyT, MappedT, Hash, KeyEq>

(multiple equiv. keys allowed)

h/cpp hackingcpp.com

#include <unordered_map>

Construct A New Map Object

```
unordered_map<string,int> m0 { }
unordered_map<string,int> m1 {{"A",2},{"Z",4},{"Y",7}}
unordered_map<string,int> m2 (begin(m1)+1, end(m1))
unordered_map<string,int> deep_copy_of_m1(m1)
C++17  key and mapped types deducable from arguments
unordered_map m3 {{2,3.14},{5,6.0}}; // unordered_map<int,double>
```

Insert A Single Key-Value Pair

$\mathcal{O}(1)$ avg., $\mathcal{O}(n)$ worst

```
.insert({"W",2}) → {@inserted,true}   (inserted yes/no)
.insert({"A",9}) → {@blocking,false}
potential performance benefit by hinting at probable insert position
.insert(@hint,{"W",2}) → @instd/blockng
```

Query & Control Hash Table Properties

hash function: $h(key) \mapsto$ bucket index

```
unordered_map<string,int> um {{"E",6},{"X",4},{"Z",1},{"A",3},{"F",2},{"B",2}};
.bucket("E") → 4   (key → hash buchet index)
.begin(4) → @first_in_bucket
.end(4) → @one_behind_last_in_bucket
.bucket_size(4) → 2
.bucket_count() → 7
um.load_factor() → 4/7 = 0.57
um.max_load_factor(0.8)   (set)
um.max_load_factor() → 0.8   (get)
(make table large enough to hande min_capacity elements)
.reserve(min_capacity)
.rehash(#hash_buckets)
(can allocate even more buckets if max. load factor demands it)
```

Assign New Content To An Existing Map

```
unordered_map<string,int> m1 {{"X",2}};
unordered_map<string,int> m2 {{"A",1},{"G",4}};
m1 = m2;
```

(deep copy from source)

new state of m1

Insert Multiple Key-Value Pairs

$\mathcal{O}(\#ins)$ avg., $\mathcal{O}(n \cdot \#ins + \#ins)$ worst

```
.insert({{"G",4},{"K",9},{"A",7}})
.insert(@inBegin, @inEnd)
source container
```

Lookup Using Keys as Input

$\mathcal{O}(1)$ average, $\mathcal{O}(n)$ worst case

```
unordered_map<string,int> m {{"S",3},{"X",5},{"F",1}};
.contains("W") → false   C++20
.contains("X") → true
.count("W") → 0
.count("X") → 1   (can be > 1 only for unordered_multimap)
.find("W") → @end   (= no match)
.find("X") → @match
.equal_range("F") → {@1st_equal,@after}
.at("F") → 1
.at("B") → Throws std::out_of_range
```

Construct Key-Value Pair

$\mathcal{O}(1)$ avg., $\mathcal{O}(n)$ worst

```
.emplace("W",2) → {@inserted,true}   (inserted yes/no)
potential performance benefit by hinting at probable insert position
.emplace_hint(@hint,"W",2) → @inserted
.try_emplace("W",2) → {@inserted,true}   C++17
advantage: does not move from rvalue input parameters if not inserted
```

Insert or Assign Value

$\mathcal{O}(1)$ avg., $\mathcal{O}(n)$ worst   C++17

```
.insert_or_assign("B",5) → {@as,false}   (inserted yes/no)
.insert_or_assign("R",6) → {@ins,true}
potential performance benefit by hinting at probable insert position
.insert_or_assign(@hint,"B",5) → @as
.insert_or_assign(@hint,"G",2) → @ins
```

Access / Modify Value

$\mathcal{O}(1)$ avg., $\mathcal{O}(n)$ worst

```
unordered_map<string,int> m {{"F",1},{"A",3}};
["A"] → 3
["A"] = 4 → A 4
Attention: [k] inserts new pair if key k is not present!
["W"] = 2 → W 2
["W"] → 0   (newly created mapped values are value-initialized (e.g. 0 for int))
```

Erase Key-Value-Pair(s)

$\mathcal{O}(\#erased)$ avg. $\mathcal{O}(n)$ worst case

```
.erase("W") → 0
.erase("A") → 1
.erase(@pos) → @after
.erase(@beg,@end) → @after
```

Modify Key

```
unordered_map<string,int> m {{"F",1},{"A",3}};
auto node = m.extract("A");
if (node) { node.key() = "X";
m.insert(move(node));
}
```

Extract Nodes

to efficiently transfer key-value pairs   C++17

```
.extract("R") → R 2
.extract(@pos) → R 2   O(1) avg., O(n) worst
```

(Re-)Insert Nodes

members of the return type

```
.insert(N 5) → {.position|.inserted|.node}
true   (empty)
.insert(A 6) → {.position|.inserted|.node}
false   Z 4
.insert(□) → {.position|.inserted|.node}   (empty node)
false   (empty)
.insert(@hint,X 5) → @inserted
.insert(@hint,F 6) → @blocking
```

Merge Two Maps

C++17

```
unordered_map<string,int> m1 {{"F",1},{"S",3},{"X",5}};
unordered_map<string,int> m2 {{"A",2},{"X",7}};
.merge(m2)   O(n2) average, O(n1 · n2 + n2) worst case
```

Query Size

```
.empty() → false
.size() → 2
```

Erase All

```
.clear()
```

Obtain Iterators

```
.begin() → @first
.end() → @one_behind_last
```