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(@InBeg,@InEnd)
```

source container

Access Element Values

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

```
.front()
.back()
.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)), S)                          O(1)
.splice(next(begin(T)), S, next(begin(S)))          O(1)
.splice(next(begin(T)), S, 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( )
```

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( , M)  → @Mth_element
```

$\mathcal{O}(M)$

Reorder Elements

```
.sort()
.sort(std::greater<>{})
.reverse()
```

$f(o,o) \mapsto$ bool

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)         → 4
.unique()                   → 2
.unique(equal_abs)          → 2
```

$f(o) \mapsto$ bool

$f(o,o) \mapsto$ bool

C++20

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

std::vector<*ValueType*>

C++'s "default" dynamic array

`#include <vector>`

h/cpp hackingcpp.com

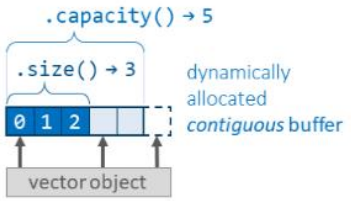
Construct A New Vector Object

```
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

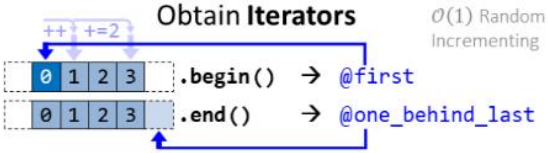
```
vector w {7,4,2};   // vector<int>
```

Typical Memory Layout

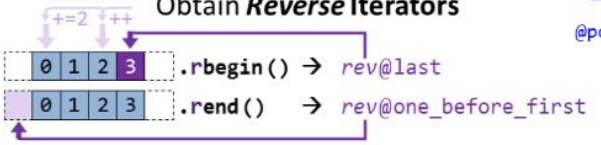


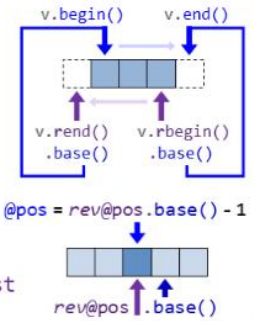
Obtain Iterators

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



Obtain *Reverse* Iterators



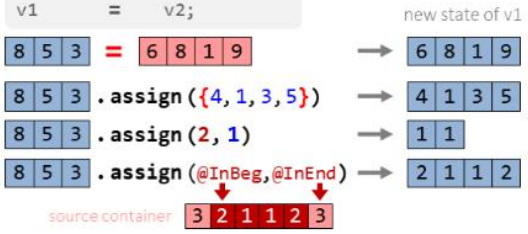


Assign New Content To An Existing Vector

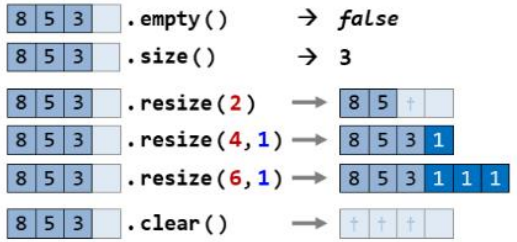
```
vector<int> v1 {8,5,3};
vector<int> v2 {6,8,1,9};
v1 = v2;
```

(deep copy from source)

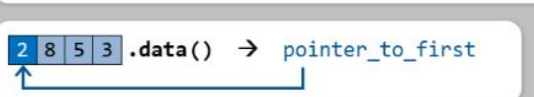
new state of v1



Query/Change Size (= Number of Elements)



Query/Grow Capactiy (= Memory Buffer Size)



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

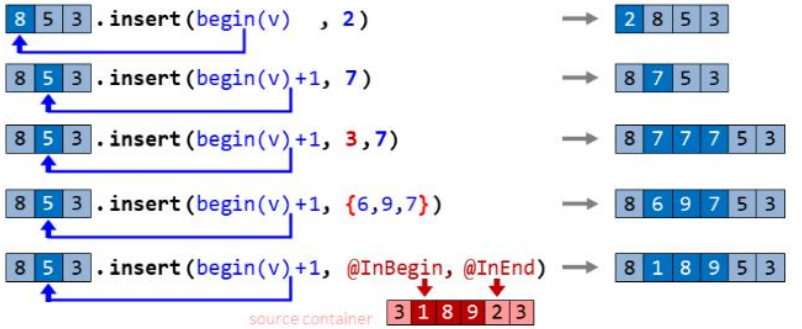
Append Elements

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

Insert Elements at Arbitrary Positions

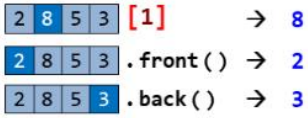
$\mathcal{O}(n)$ Worst Case

```
vector<int> v {8,5,3};
```



Get Element Values

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



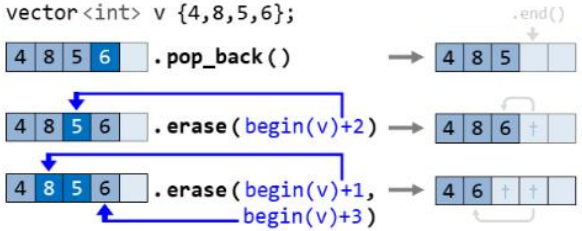
Change Element Values

Out of Bounds Access

Erase Elements

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

```
vector<int> v {4,8,5,6};
```



Shrink The Capacity

(might be inefficient)

Erasing, resizing or clearing will not shrink the capacity!

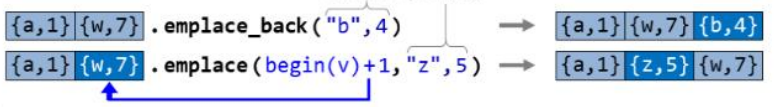
```
vector<int> v (1024,0);   // capacity is at least 1024
v.resize(40);             // capacity unchanged!
v.shrink_to_fit();        // may shrink (not guaranteed)
v.swap(vector<int>(v));   // shrinks but has copy overhead
```

Insert & Construct Elements in Place

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

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

constructor parameters



v1.1

std::string

#include <string>

h/cpp hackingcpp.com

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

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 indices

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..."
size	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)            ➡ e f g h
                 source  iterator range
               b c d e f g h i j
string ( a b c d )   copy/move        ➡ a b c d
         source string object
```

Obtain Iterators or Reverse Iterators

```
.begin()  → @first
              a b c d e f
.end()    → @one_behind_last
  don't use to access elements!
              a b c d e f

.rbegin() → reverse@last .base()
              a b c d e f
.rend()   → reverse@one_before_first
  don't use to access elements!   .base()
            a b c d e f
```

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

std::string_view

#include <string_view> C++17 h/cpp hackingcpp.com

- 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.");
          0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15   indices
```

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!
```

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}
deque<int> d2 (begin(d1)+3, end(d1))
deque<int> d3 (5,3)
deque<int> deep_copy_of_d1 (d1)
```

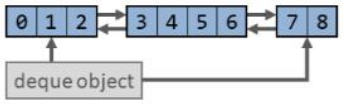
C++17 value type deducable from argument type

```
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 implementd.

dynamically allocated contiguous chunks



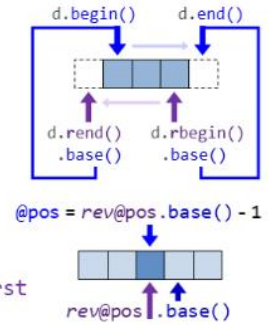
Obtain Iterators

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

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

Obtain *Reverse* Iterators

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



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

std::set<*KeyType*, *Compare*>

(unique keys)

#include <set>

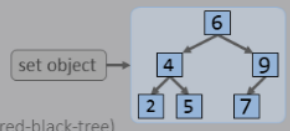
h/cpp hackingcpp.com

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

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

```
.contains(2) → false
.contains(5) → true
```

C++20

```
.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

```
.erase(2) → 0
.erase(5) → 1
```

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

```
.erase(@pos) → @after_erased
```

$\mathcal{O}(1)$ amortized

```
.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
```

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

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

rev@pos .base()

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( )
```

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

Insert Nodes

C++17

members of the return type

```
.insert(5) → {.position|.inserted|.node}   // true, (empty)
.insert(1) → {.position|.inserted|.node}   // false, 1
(empty node)
.insert( ) → {.position|.inserted|.node}   // false, (empty)
.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));
}
```

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

```
.contains(2) → false
.contains(3) → true
.count(2) → 0
.count(3) → 1
.find(2) → @end (= no match)
.find(3) → @match
.equal_range(5) → {@first_equal, @after}
```

C++20

can be > 1 only for std::unordered_multiset

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

potential performance benefit by hinting at probable insert position

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

Insert Multiple Keys

$\mathcal{O}(\#ins)$ avg., $\mathcal{O}(n \cdot \#ins + \#ins)$ 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) → {(if inserted) @inserted, true}
```

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

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

```
.erase(2) → 0
.erase(3) → 1
.erase(@pos) → @after_erased
.erase(@beg, @end) → @after_erased
```

#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)
```

bucket index, hash bucket

(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( )
```

Insert Nodes

C++17

members of the return type

```
.insert(8) → {.position|.inserted|.node}
.insert(1) → {.position|.inserted|.node}
(empty node)
.insert( ) → {.position|.inserted|.node}
.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)

h/cpp hackingcpp.com

default: std::less<KeyType>

std::multimap<KeyType,MappedType,KeyCompare>

(multiple equivalent keys allowed)

#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

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

(inserted yes/no)

```
.insert({2,"W"}) → {@inserted,true}
.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
```

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

Obtain *Reverse* Iterators

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

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

- 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
.contains(5) → true
```

C++20

```
.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

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

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

source container

Insert & Construct Key-Value Pair

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

(inserted yes/no)

```
.emplace(2,"W") → {@inserted,true}
```

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

$\mathcal{O}(1)$ amortized

```
.erase(@pos) → @after_erased
```

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

```
.erase(@b,@e) → @after_erased
```

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(
```

Extract Nodes

Allows efficient transfer of key-value pairs.

C++17

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

(Re-)Insert Nodes

members of the return type

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

(empty node) true false (empty)

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

```
L1 = L2
L1.assign({4,1,3,5})
L1.assign(2, 1)
L1.assign(@InBeg, @InEnd)
```

source container

Access Element Values

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

```
L1.front()
L1.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!

```
L1.empty()   → false
L1.resize(2)
L1.resize(5,1)
L1.clear()
```

Insert Elements at Arbitrary Positions

$\mathcal{O}$(#inserted)

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

```
L.emplace_front("c",6)
L.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};
```

source list

```
T.splice_after(begin(T), S)
T.splice_after(begin(T), S, begin(S))
T.splice_after(begin(T), S, begin(S), end(S))
```

$\mathcal{O}(1)$ $\mathcal{O}(1)$ $\mathcal{O}$(#inserted)

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};
L1.merge(L2)
```

Erase Elements Based on **Values**

$\mathcal{O}(n)$

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

Obtain **Iterators**

$\mathcal{O}(1)$

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

Increment Iterators

$\mathcal{O}(M)$

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

Prepend Elements

$\mathcal{O}(1)$

```
L.push_front(7)
```

Reorder Elements

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

Erase Elements Based on **Positions**

$\mathcal{O}$(#deleted)

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

h/cpp hackingcpp.com

#include <unordered_map>

std::unordered_multimap<KeyT,MappedT,Hash,KeyEq> (multiple equiv. keys allowed)

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}

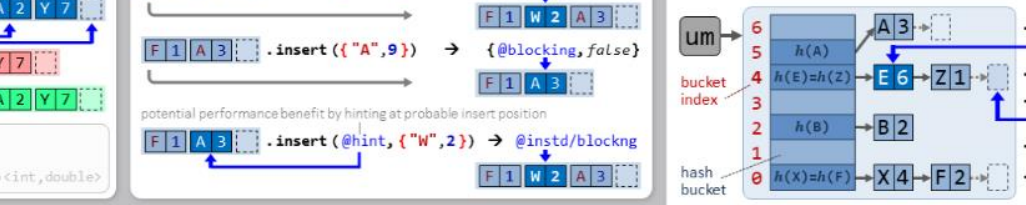
potential performance benefit by hinting at probable insert position

.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}};
```



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 →

Attention: [k] inserts new pair if key k is not present!

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

(Re-)Insert Nodes

members of the return type

.insert(N 5) → {.position|.inserted|.node} → true

.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(A 2 X 7) → X 7 ($\mathcal{O}(n_2)$ average, $\mathcal{O}(n_1 \cdot n_2 + n_2)$ worst case)

Query Size

.empty() → false

.size() → 2

Erase All

.clear()

Obtain Iterators

.begin() → @first

.end() → @one_behind_last

v1.2