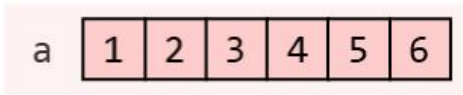
array<*T*, *size*>

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

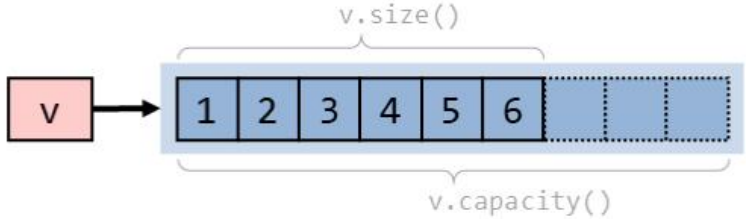
vector<*T*>

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
```



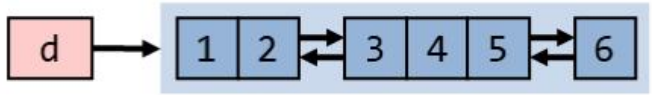
contiguous memory; random access;
fast linear traversal; fast insertion/deletion at the ends

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
```



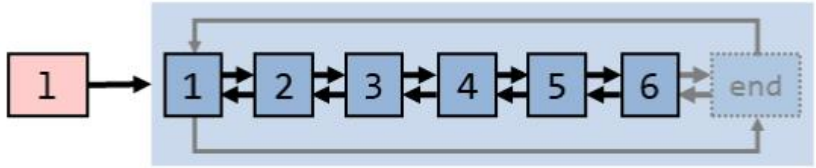
fast insertion/deletion at both ends

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();
```



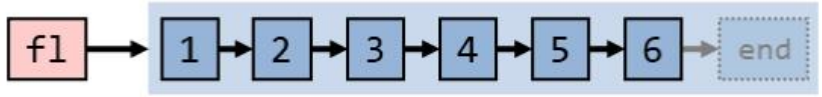
fast splicing; many operations without copy/move of elements

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

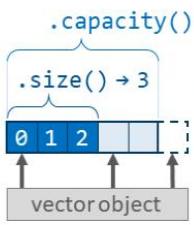
Construct A New Vector Object

```
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>
```

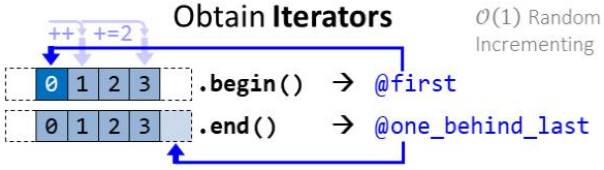
Typical Memory Layout



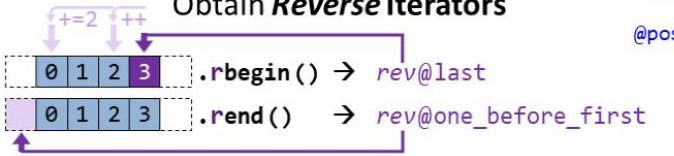
dynamically allocated *contiguous* buffer

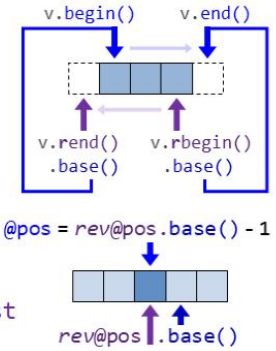
Obtain Iterators

$\mathcal{O}(1)$ 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;
```

new state of v1

```
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/Change Size (= Number of Elements)

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

Query/Grow Capactiy (= Memory Buffer Size)

```
8 5 3 .capacity()   → 4
8 5 3 .reserve(6)   → 8 5 3
```

```
2 8 5 3 .data() → pointer_to_first
```

Append Elements

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

```
8 5 3 .push_back(7) → 8 5 3 7
```

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

Insert Elements at Arbitrary Positions

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

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

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

```
vector<int> v {4,8,5,6};
4 8 5 6 .pop_back()        → 4 8 5
4 8 5 6 .erase(begin(v)+2) → 4 8 6
4 8 5 6 .erase(begin(v)+1, begin(v)+3) → 4 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}};
{a,1} {w,7} .emplace_back("b",4)   → {a,1} {w,7} {b,4}
{a,1} {w,7} .emplace(begin(v)+1,"z",5) → {a,1} {z,5} {w,7}
```

constructor parameters

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)
```

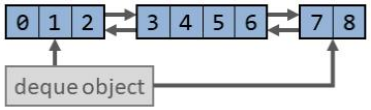
C++17 value type deducable from argument type

```
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 implemented.

dynamically allocated contiguous chunks



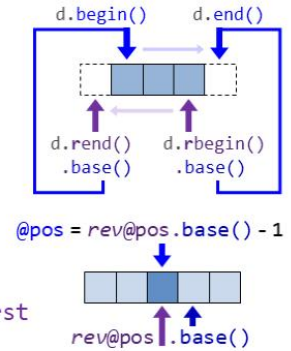
Obtain Iterators

$\mathcal{O}(1)$ 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;
```

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}
```

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

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

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

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

```
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+1 ), M )  → @Mth_element   O(M)
```

Reorder Elements

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

Erase Elements Based on **Positions**

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

```
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   C++20
.remove_if(is_even)    f(○)↦ bool   → 4
.unique()                           → 2
.unique( equal_abs )   f(○,○)↦ bool → 2
```

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

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	
s[0]	→	'I'	(character at position 0)
s.find("r")	→	6	(first occurrence from start)
s.rfind("r")	→	7	(first occurrence from end)
s.find("X")	→	string::npos	(not found, invalid index)
s.find(' ', 5)	→	10	(first occurr. starts at 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 = ""	
s.resize(3)	⇒	s = "I'm"	
s.resize(20, '?')	⇒	s = "I'm sorry, Dave.????";	
index based			
s.insert(4, "very ")	⇒	s = "I'm very sorry, Dave."	
s.erase(5, 2)	⇒	s = "I'm sry, Dave."	
s[15] = '!'	⇒	s = "I'm sorry, Dave!"	
s.replace(11, 5, "Frank")	⇒	s = "I'm sorry, Frank"	
iterator based			
s.insert(s.begin(), "HAL: ")	⇒	s = "HAL: I'm sorry, Dave."	
s.insert(s.begin()+4, "very ")	⇒	s = "I'm very sorry, Dave."	
s.erase(s.begin()+5)	⇒	s = "I'm srry, Dave."	
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

.rbegin() → reverse@last .base()
            a b c d e f

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

.rend() → reverse@one_before_first .base()
          don't use to access elements!
          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 | unsigned long | unsigned long long | float | double | long double

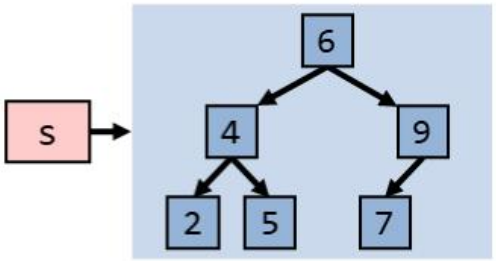
set<*Key*>

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)

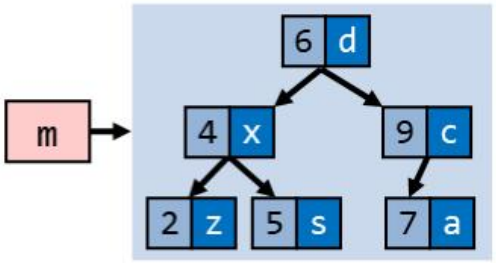
map<*Key*,*Value*>

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)

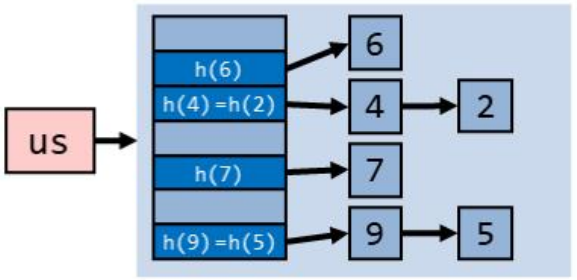
unordered_set<*Key*>

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

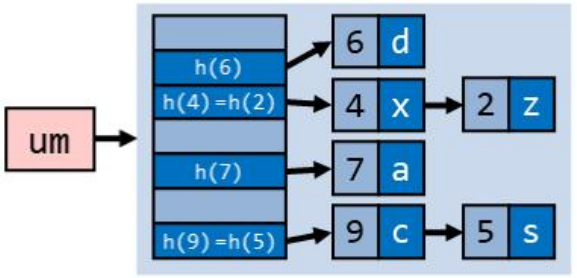
unordered_map<*Key*,*Value*>

unique key → value-pairs; hashed by keys

unordered_multimap<*Key*,*Value*>

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

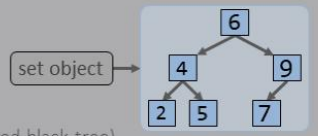
```
unordered_map<int,char> um;
um.insert({7,'a'});  …
um[4] = 'x';             // insert 4→x
auto i = um.find(7); // → iterator
if(i != um.end())    // found?
  cout << i->first   // 7
       << i->second; // a
if(s.contains(7)) {…}     C++20
```



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

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

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

```
.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
```

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()

Extract Nodes

C++17

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

```
.extract(5) → 5   // O(logn)
.extract(@pos) → 5   // O(1)
```

Merge Two Sets

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

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

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

No direct modification 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::multimap<KeyType,MappedType,KeyCompare> (multiple equivalent keys allowed)

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}
.insert(@hint, {2,"W"}) → @ins/block   potential performance benefit by hinting at probable insert position
```

Obtain Iterators

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

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

Insert Multiple Key-Value Pairs $\mathcal{O}(\#\text{inserted} \cdot \log n)$

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

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] → ""
```

Extract Nodes

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

```
.extract(2) → 2 R   O(log n)
.extract(@pos) → 2 R   O(1)
```

(Re-)Insert Nodes

members of the return type

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

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
```

Insert & Construct Key-Value Pair $\mathcal{O}(\log n)$

```
.emplace(2,"W") → {@inserted, true}   (inserted yes/no)
.emplace_hint(@hint, 2,"W") → @inserted   potential performance benefit by hinting at probable insert position
.try_emplace(2,"W") → {@inserted, true}   C++17
```

advantage: does not move from rvalue input parameters if not inserted

Insert or Assign Value $\mathcal{O}(\log n)$ C++17

```
.insert_or_assign(3,"X") → {@as, false}   (inserted yes/no)
.insert_or_assign(5,"R") → {@ins, true}
.insert_or_assign(@hint, 3,"W") → @as
.insert_or_assign(@hint, 2,"G") → @ins
```

Erase Key-Value-Pair(s)

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

Erase All

```
.clear()
```

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( 2 A 5 X )
```

Query Size (= number of key-value pairs)

```
.empty() → false
.size() → 2
```

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));
}
```

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        C++20
.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) → {.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) .first @inserted, .second 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

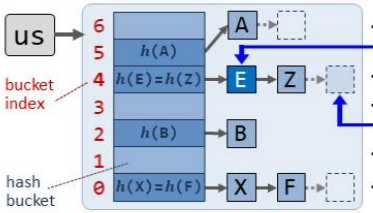
$\mathcal{O}(\#erased)$ avg. $\mathcal{O}(n)$ worst case

```
.erase(2) → 0
.erase(3) → 1        (#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)
```

(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)

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

Modify Key

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

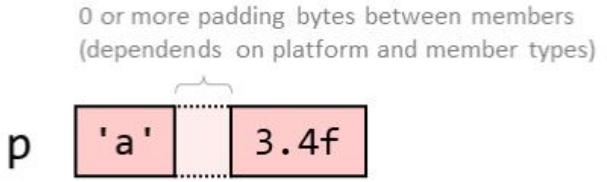
```
unordered_set s {1,7,5};
auto node = s.extract(5);
if (node) { // if key existed
  node.value() = 8;
  s.insert(move(node));
}
```

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);
```

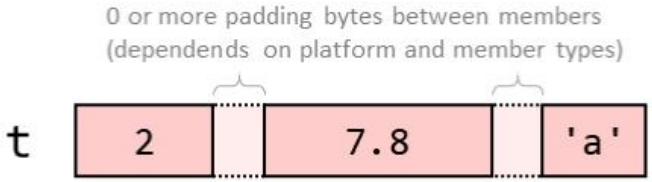


tuple<A,B,C,…>

#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'
```

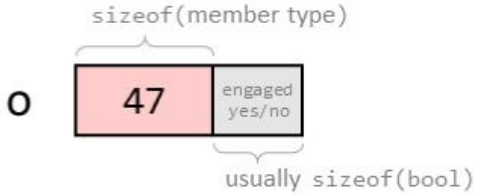


optional<*T*>

#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
```

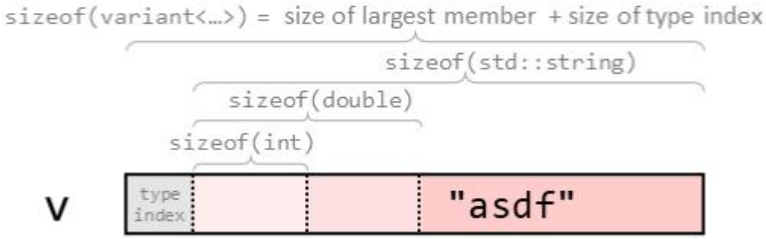


variant<*A*,*B*,*C*,…>

#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
```

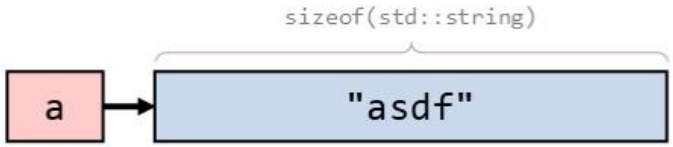


any

#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&) { /* … */ }
```



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}
```

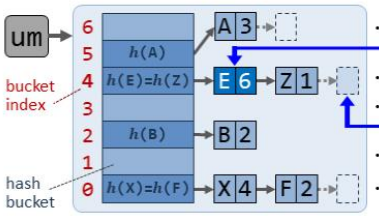
potential performance benefit by hinting at probable insert position

```
.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}};
```




```
.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}}) → K 9 A 3 G 4
.insert(@inBegin, @inEnd) → K 9 A 3 G 4
```

source container G 4 K 9 A 7 X 2

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}};
```

C++20

```
.contains("W") → false
.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   (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(  ) → F 1 A 2 S 3 X 5   X 7
```

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

Query Size

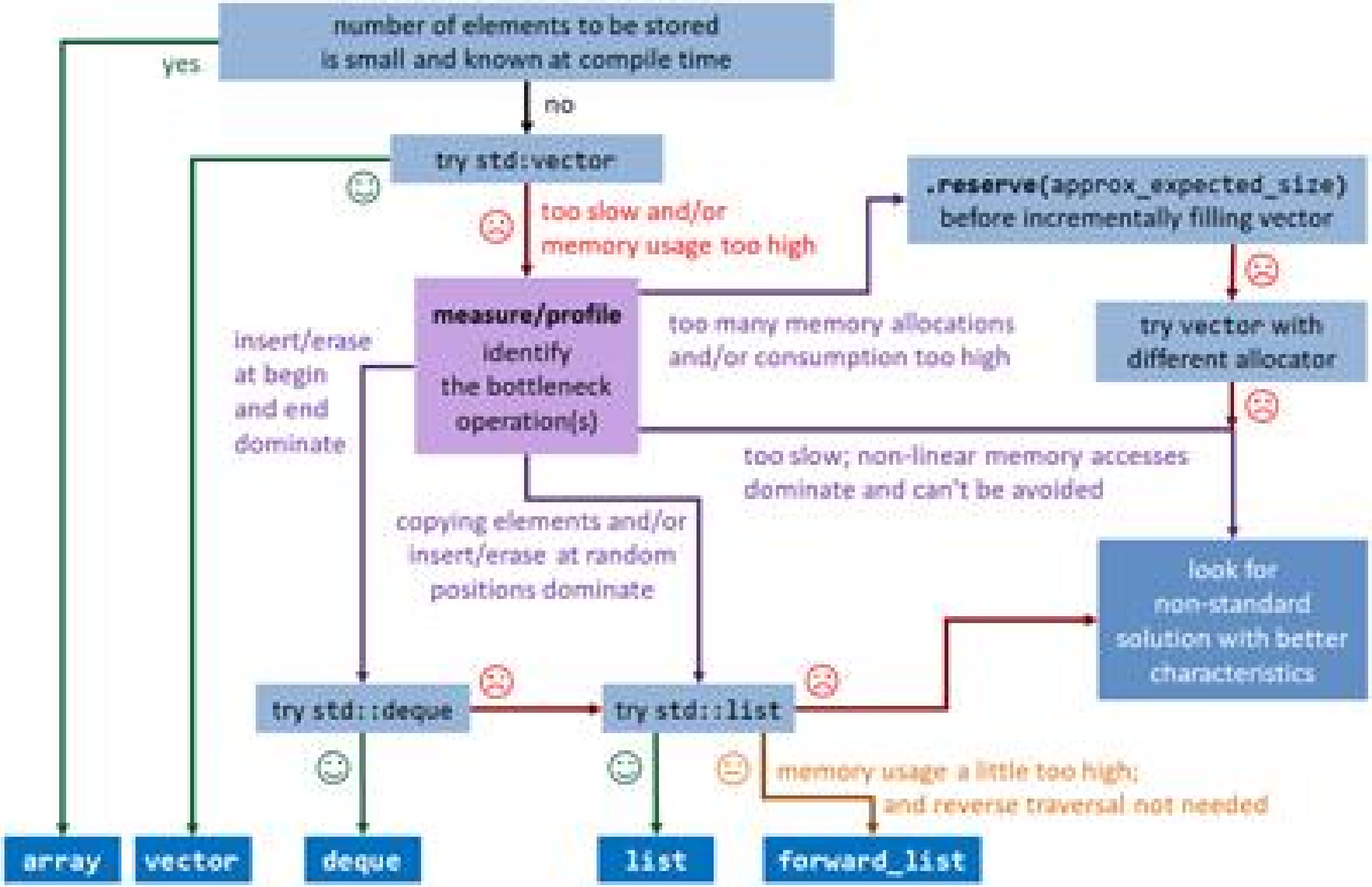
```
.empty() → false
.size() → 2
```

Erase All

```
.clear()
```

Obtain Iterators

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


number of elements to be stored
is small and known at compile time
yes
no
array
try std::vector
vector
too slow and/or
memory usage too high
.reserve(approx_expected_size)
before incrementally filling vector
too many memory allocations
and/or consumption too high
try vector with
different allocator
too slow; non-linear memory accesses
dominate and can't be avoided
measure/profile
identify
the bottleneck
operation(s)
insert/erase
at begin
and end
dominate
copying elements and/or
insert/erase at random
positions dominate
look for
non-standard
solution with better
characteristics
try std::deque
try std::list
deque
list
memory usage a little too high;
and reverse traversal not needed
forward_list

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

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

source list

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

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};
.merge( )
```

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
```

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

C++11

Obtain **Iterators**

$\mathcal{O}(1)$

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

Increment Iterators

$\mathcal{O}(M)$

```
next( begin( , 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) )
```