# Алгоритмизация и программирование

Лекция 4

# Последовательные контейнеры

# Последовательные контейнеры

## 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

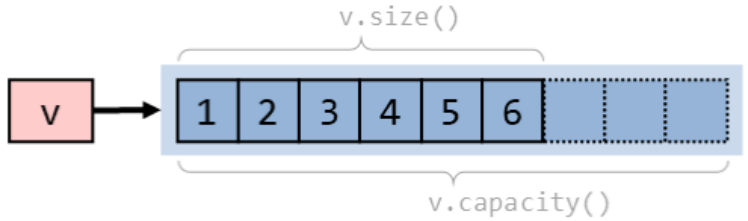
## vector<T>

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
```



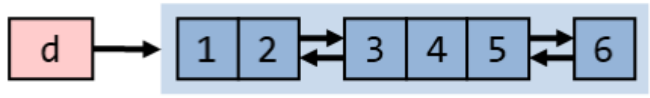

contiguous memory; random access;
fast linear traversal; fast insertion/deletion at the ends

## 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
```



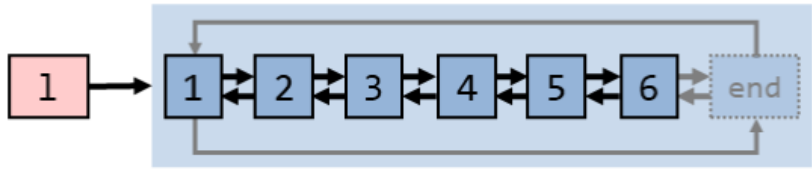

fast insertion/deletion at both ends

## 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();
```



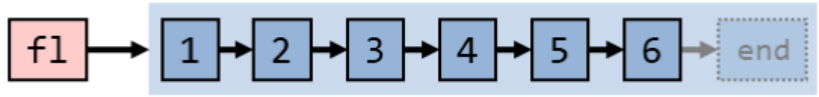

fast splicing; many operations without copy/move of elements

## 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

# std::array

# std::vector<*ValueType*>

C++'s "default" dynamic array

`#include <vector>`

h/cpp hackingcpp.com

std::vector

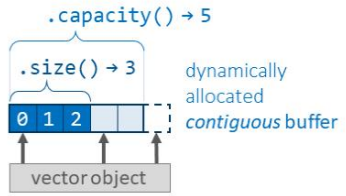
## Construct A New Vector Object

```
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

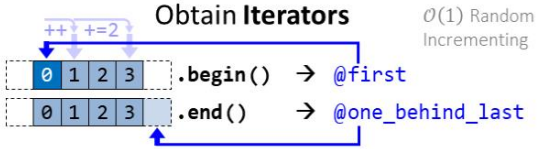
```
vector w {7,4,2};   // vector<int>
```

## Typical Memory Layout

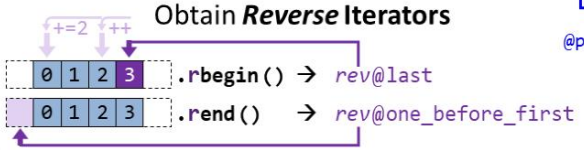


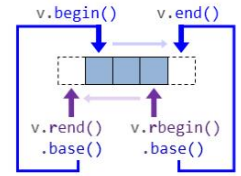

## Obtain Iterators

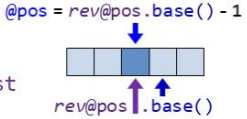
$\mathcal{O}(1)$ Random Incrementing




## 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

```
v1 = v2
v1.assign({4,1,3,5})
v1.assign(2,1)
v1.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)
```

```
2 8 5 3 .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

```
8 5 3 .push_back(7) → 8 5 3 7
```

## Insert Elements at Arbitrary Positions

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

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

source container

## 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 & Construct Elements in Place

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

```
vector<pair<string,int>> v {{"a",1},{"w",7}};
v.emplace_back("b",4)
v.emplace(begin(v)+1,"z",5)
```

constructor parameters

# deque

## 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)
```

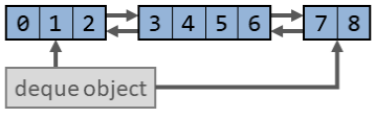
C++17 value type deducable from argument type

```
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



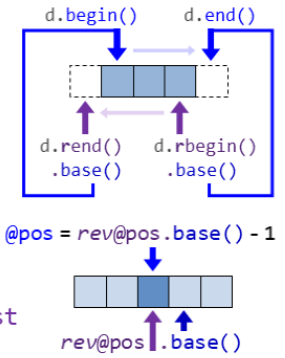

## Obtain Iterators

$\mathcal{O}(1)$ 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

```
d1 = d2;                    → 6 8 1 9
d1.assign({4,1,3,5})        → 4 1 3 5
d1.assign(2,1)              → 1 1
d1.assign(@InBeg,@InEnd)    → 2 1 1 2
```

source container: 3 2 1 1 2 3

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

```
.empty() → false
.size()  → 3
```

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

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

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

```
.push_back(7)  → 8 5 3 7
```

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

```
.push_front(7) → 7 8 5 3
```

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

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

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

## Change Element Values

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

## Out of Bounds Access

```
[6]   → Undefined Behavior
.at(6) → Throws Exception std::out_of_range
```

Invalid Index!

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

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

## Erase Elements At Arbitrary Positions

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

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

```
.erase(begin(d)+2)          → 4 8 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

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

# list

## 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

(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+1 , M)  → @Mth_element
```

$\mathcal{O}(M)$

## Reorder Elements

```
.sort()
.sort(std::greater<>{})      f(o,o)↦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(o)↦bool   → 4
.unique()                    → 2
.unique(equal_abs)           f(o,o)↦bool   → 2
```

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

# forward_list

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

```
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
.resize(2)
.resize(5,1)
.clear()
```

## Insert Elements at Arbitrary Positions

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

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

constructor parameters

## 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),
.splice_after(begin(T),
```

source list

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

## 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};
.merge(
```

## Erase Elements Based on Values

$\mathcal{O}(n)$

```
.remove(7)
.remove_if(is_even)
.unique()
.unique(equal_abs)
```

$f(\circ)\mapsto bool$ $f(\circ,\circ)\mapsto bool$

## 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<>{})
.reverse()
```

$f(\circ,\circ)\mapsto bool$

## Erase Elements Based on Positions

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

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

Контейнеры адаптеры

std::stack

std::queue

std::priority_queue

# Ассоциативные контейнеры

# Ассоциативные контейнеры

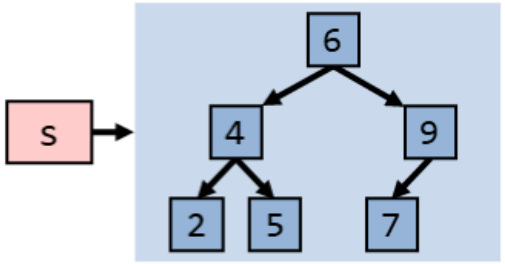
## set<Key>

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)

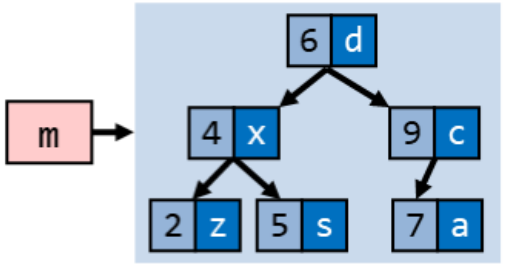
## map<Key,Value>

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)

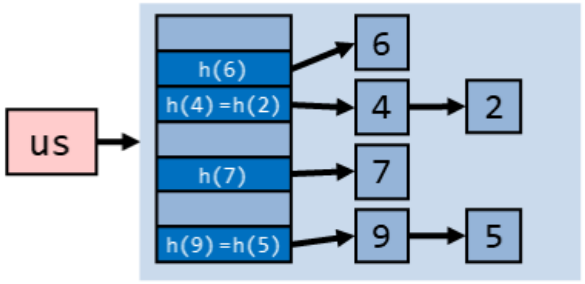
## unordered_set<Key>

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

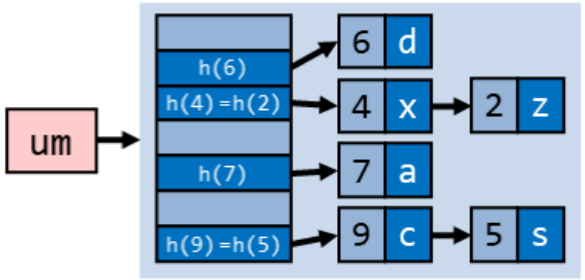
## unordered_map<Key,Value>

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::set<KeyType, Compare>

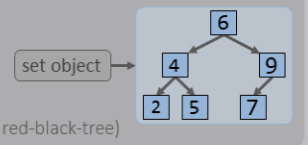
(unique keys) #include <set> h/cpp hackingcpp.com

default: std::less<KeyType>

std::multiset<KeyType, Compare> (multiple equivalent keys)

std::set

- 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

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

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

O(#inserted · log n)

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

source container

## Insert & Construct A Key in Place

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

O(log n)

```
.erase(2) → 0
.erase(5) → 1
```

#erased

O(1) amortized

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

O(log n + #erased)

## Obtain Iterators

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

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

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

## Obtain Reverse Iterators

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

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( )
```

O(n2 · log(n1 + n2))

## Insert Nodes

C++17

members of the return type {.position|.inserted|.node}

```
.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));
}
```

# unordered_set

## 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) → {@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

$\mathcal{O}(\#ins)$ 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) → {@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

$\mathcal{O}(\#erased)$ 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
```

bucket index, hash bucket

```
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 {.position|.inserted|.node}

```
.insert(8) → true  (empty)
.insert(1) → false
(empty node)
.insert( ) → 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));
}
```

# std::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
```

## Obtain *Reverse* Iterators

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

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

@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
.extract(@pos) → 2 R
```

$\mathcal{O}(\log n)$ $\mathcal{O}(1)$

## (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
```

## 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

## 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
```

## 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
```

## 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
```

## 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 )
```

## 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));
}
```

## Query Size (= number of key-value pairs)

```
.empty() → false
.size()  → 2
```

## Erase All

```
.clear()
```

# 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}
.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}
```

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}
.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(  )
```

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

## Query Size

```
.empty() → false
.size() → 2
```

## Erase All

```
.clear()
```

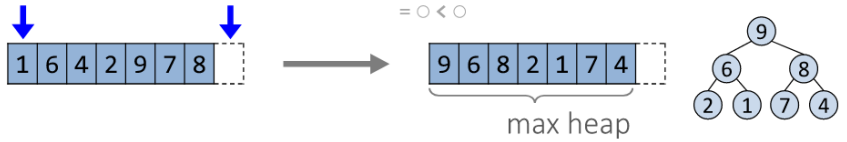
## Obtain Iterators

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

# Heap operations

**make_heap(@begin, @end, compare(○,○)↦bool)**

= ○ < ○

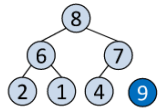




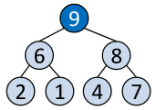


**push_heap(@begin, @end, compare(○,○)↦bool)**

= ○ < ○

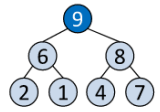


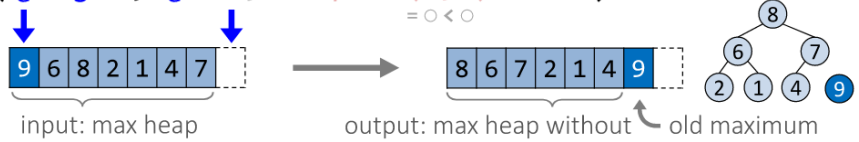





**pop_heap( @begin, @end, compare(○,○)↦bool)**

= ○ < ○



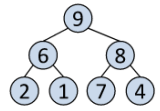







**sort_heap(@begin, @end, compare(○,○)↦bool)**

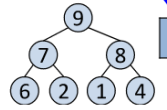
= ○ < ○

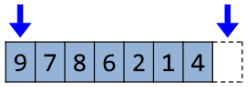




**is_heap( @begin, @end, compare(○,○)↦bool)** → ***true***, if the input range is a *max* heap

= ○ < ○

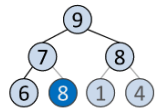


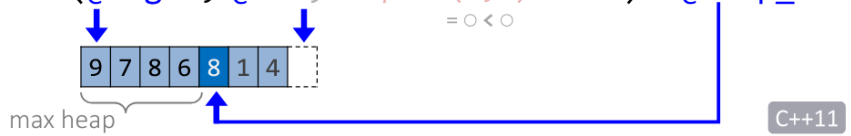




C++11

**is_heap_until(@begin, @end, compare(○,○)↦bool)→ @heap_end**

= ○ < ○

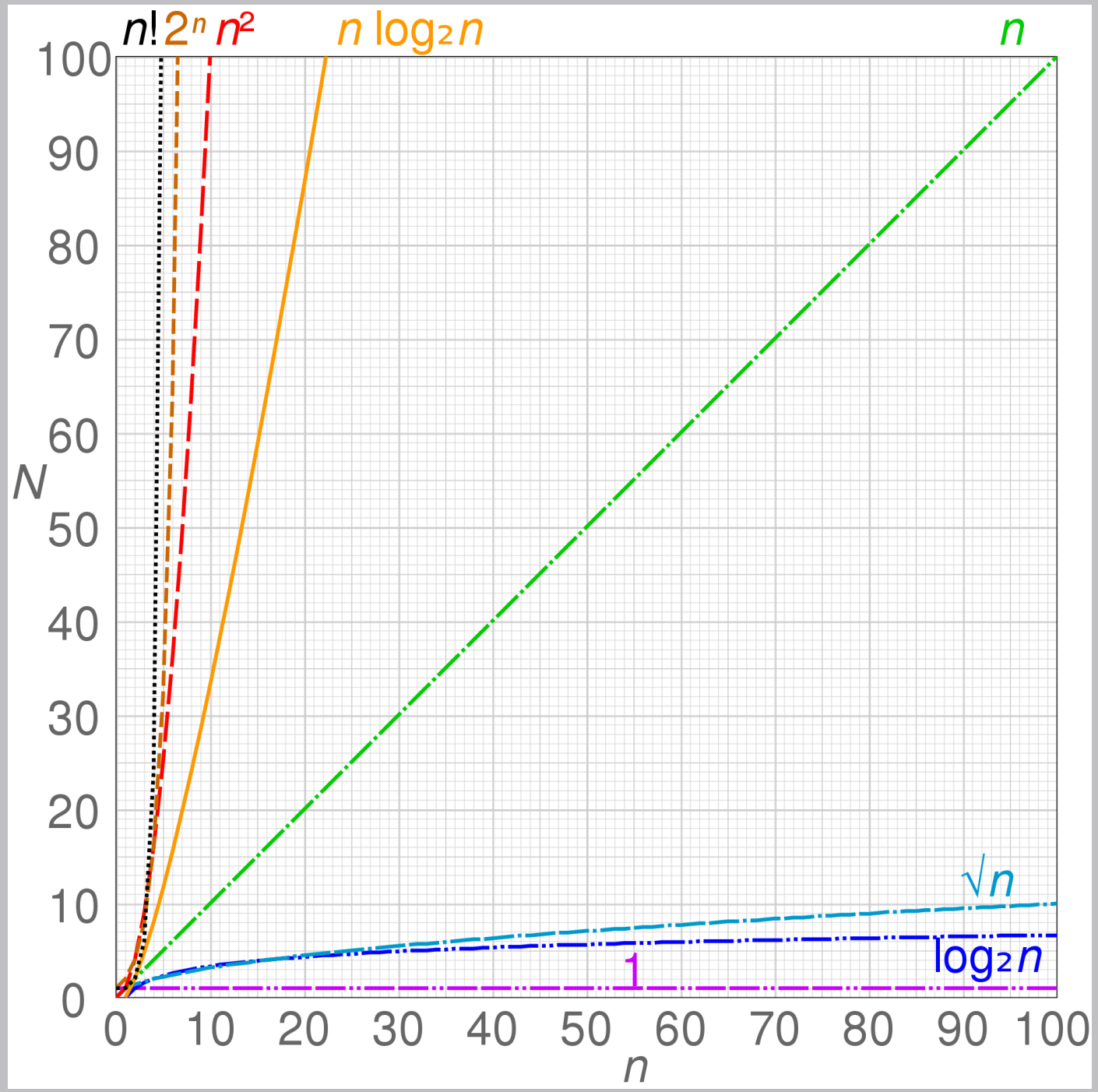



C++11

# Сложность алгоритмов

# Оценка сложности Big-O



# Оценка сложности для контейнеров STL

| Container | Insert Head | Insert Tail | **Insert** | Remove Head | Remove Tail | **Remove** | Index Search | Find |
|---|---|---|---|---|---|---|---|---|
| **vector** | n/a | O(1) | O(n) | O(1) | O(1) | O(n) | O(1) | O(log n) |
| **list** | O(1) | O(1) | O(1) | O(1) | O(1) | O(1) | n/a | O(n) |
| **deque** | O(1) | O(1) | n/a | O(1) | O(1) | O(n) | n/a | n/a |
| **queue** | n/a | O(1) | n/a | O(1) | n/a | n/a | O(1) | O(log n ) |
| **stack** | O(1) | n/a | n/a | O(1) | n/a | n/a | n/a | n/a |
| **map** | n/a | n/a | O(log n) | n/a | n/a | O(log n) | O(1) | O(log n) |
| **multimap** | n/a | n/a | O(log n) | n/a | n/a | O(log n) | O(1)* | O(log n) |
| **set** | n/a | n/a | O(log n) | n/a | n/a | O(log n) | O(1) | O(log n) |
| **multiset** | n/a | n/a | O(log n) | n/a | n/a | O(log n) | O(1)* | O(log n) |

https://users.cs.northwestern.edu/~riesbeck/programming/c++/stl-summary.html

# Лямбда выражения

# Лямбда выражения

**C++11**

```
[CAPTURES] {BODY}
[CAPTURES] -> RETURN-TYPE {BODY}
```

**C++23**

```
[CAPTURES] SPECIFIERS {BODY}
[CAPTURES] SPECIFIERS -> RETURN-TYPE {BODY}
```

**C++11**

```
[CAPTURES](PARAMETERS) {BODY}
[CAPTURES](PARAMETERS) -> RETURN-TYPE {BODY}
[CAPTURES](PARAMETERS) SPECIFIERS {BODY}
[CAPTURES](PARAMETERS) SPECIFIERS -> RETURN-TYPE {BODY}
```

**C++20**

```
[CAPTURES]<TYPE-PARAMETERS>(PARAMETERS) {BODY}
[CAPTURES]<TYPE-PARAMETERS>(PARAMETERS) -> RETURN-TYPE {BODY}
[CAPTURES]<TYPE-PARAMETERS>(PARAMETERS) SPECIFIERS {BODY}
[CAPTURES]<TYPE-PARAMETERS>(PARAMETERS) SPECIFIERS -> RETURN-TYPE {BODY}
```

| SPECIFIERS | C++11 | | | C++17 | C++20 | |
|---|---|---|---|---|---|---|
| | `mutable` | `noexcept` | `[[attribute]]` | `constexpr` | `consteval` | `requires…` |

Лямбда выражения

# C++ Lambda Expressions

Lambda = Compiler Generated Function Object

h/cpp hackingcpp.com

```
auto f1 = [] { return 47; };                          auto x = f1();      // ⇔ int x = 47;
auto f2 = [] (int x, int y) { return 0.5*(x+y); };    auto y = f2(2,3);   // ⇔ double y = 2.5;
auto f3 = [] (int x) -> float { return x*x; };        auto z = f3(2);     // ⇔ float z = 4.0f;
```

C++11

## Capturing

of variables from the surrounding scope

### by reference

```
int x = 1;
auto f = [&](int y){ x+=2; return x*y; };
cout << f(2);  // 6
cout << x;     // 3
```

### by value

```
int x = 1;                          // lambda-local variable x=1
auto f = [=](int y){ return x*y; };
cout << f(2);  // 2
cout << x;     // 1
```

| | |
|---|---|
| `[=]` | capture all by value |
| `[&]` | capture all by reference |
| `[=,&x]` | x by reference, all others by value |
| `[&,x]` | x by value, all others by reference |
| `[x,&y]` | only x by value and y by reference |
| `[&x,y]` | only x by reference and y by value |
| `[&x,y,&z]` | only x by ref, y by value and z by ref |

### init captures

define lambda-local variables C++14

```
auto f = [x=2](int y){ return x*y; };

std::vector<char> v (1000,'a');
auto g = [w=std::move(v)](){ /* use w */ };
```

## Immediately Invoked Function Expressions (IIFE)

```
int z = [](int x){ return x*x; }(2);  // create lambda and call it ⇔ int z = 4;
```

## Mutable Lambdas

```
int y = 1;
auto f = [=]() {
  y += 2;
  return y;
};
```

❌ COMPILER ERROR: local variable 'y' is const!

```
int y = 1;
auto f = [=]() mutable {
  y += 2;
  return y;
};
cout << f();  // 3
cout << f();  // 5
cout << y;    // 1
```

```
auto f = [i=0]() mutable {
  ++i;  return i;
};
cout << f();  // 1
cout << f();  // 2
```

## Generic Lambdas

C++14

```
auto print = [](auto const& x){ std::cout << x; };
print(5); ✓
print(std::string{"it works!"}); ✓
```

```
[](auto value, auto const& cref, auto& ref){ … }
[](auto... args){ return g(args...); }
```

### Perfect Forwarding

preserving constness, l/r-valueness

```
[](auto&& x){ g( std::forward<decltype(x)>(x) ); }
[](auto&&... args){
   g( std::forward<decltype(args)>(args)... ); }
```

### Constrained auto Parameters

C++20

```
#include <concepts>
[](std::copyable auto x){ … }
```

### Explicit Template Parameters

C++20

```
[]<typename T>(T x, T y){ … }
```

v1.0

# Итераторы

# Итераторы (начало)

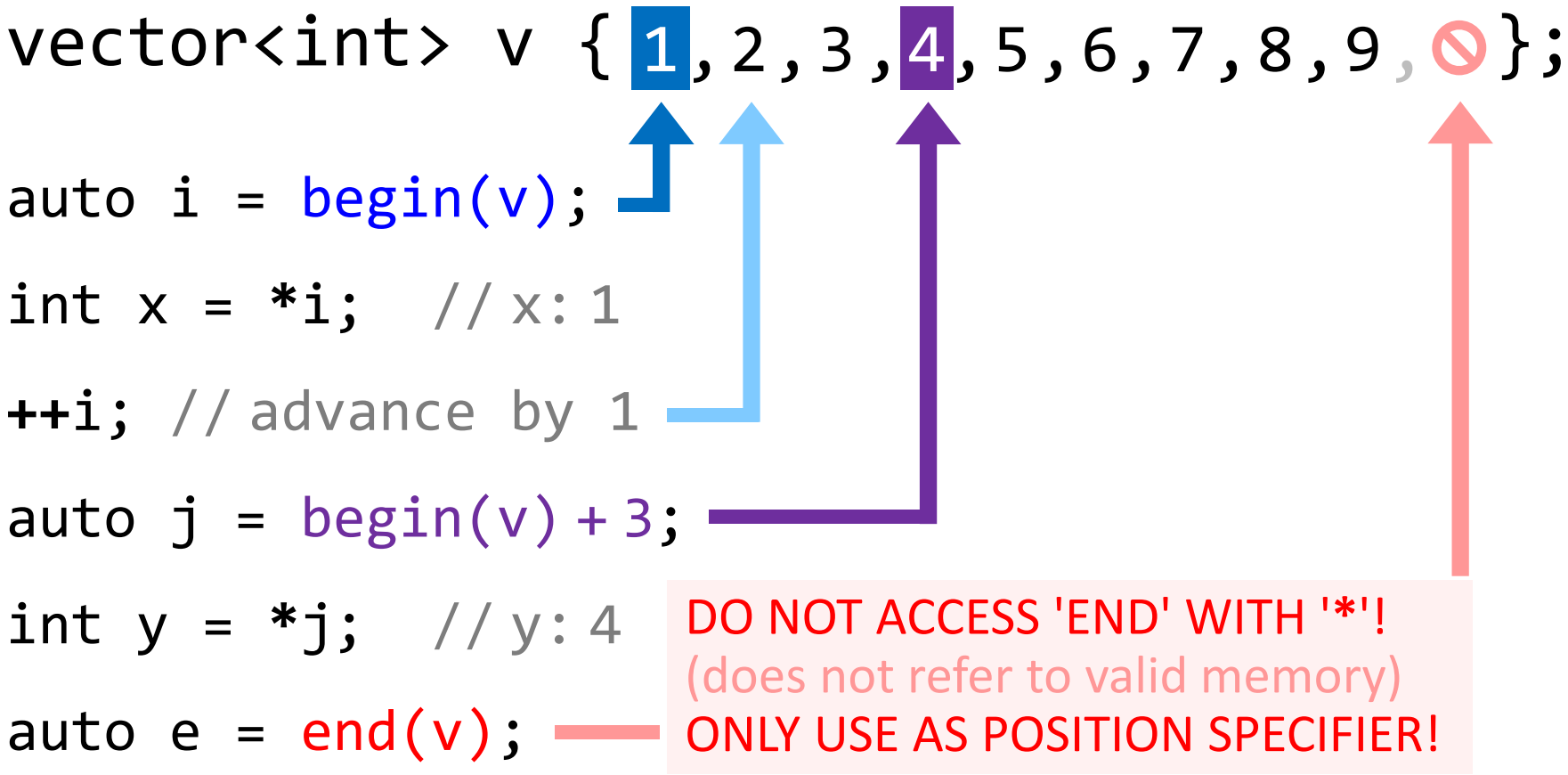
Итератор — это структура данных, предназначенная, для того чтобы перебирать элементы контейнера (последовательности), при этом не задумываясь, с каким именно контейнером происходит работа.

Получить итераторы у контейнера можно через:

- методы `begin()` и `end()`: `array.begin();`
- одноимённые функции: `begin(array);`

Чтобы ходить по контейнеру в обратном направлении используются реверс-итераторы: `rbegin()` и `rend()`.

# Итераторы на примере vector

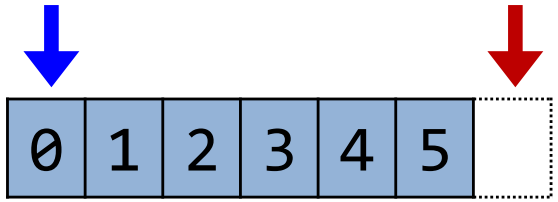


```
std::vector<int> v {0, 1, 2, 3, 4, 5};
```

---

`begin(v), end(v)`

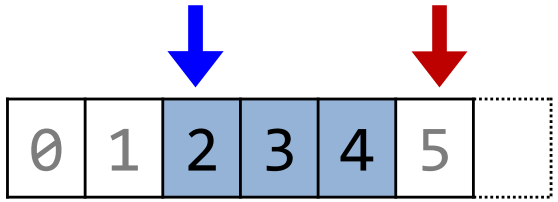
6 elements




---

`begin(v)+2, begin(v)+5`

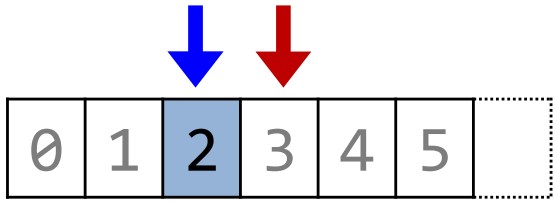
3 elements




---

`begin(v)+2, begin(v)+3`

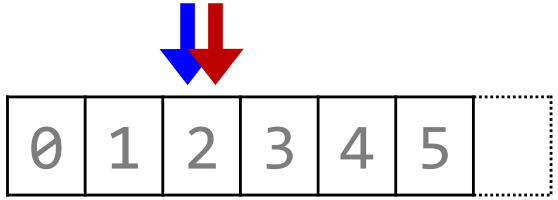
1 element



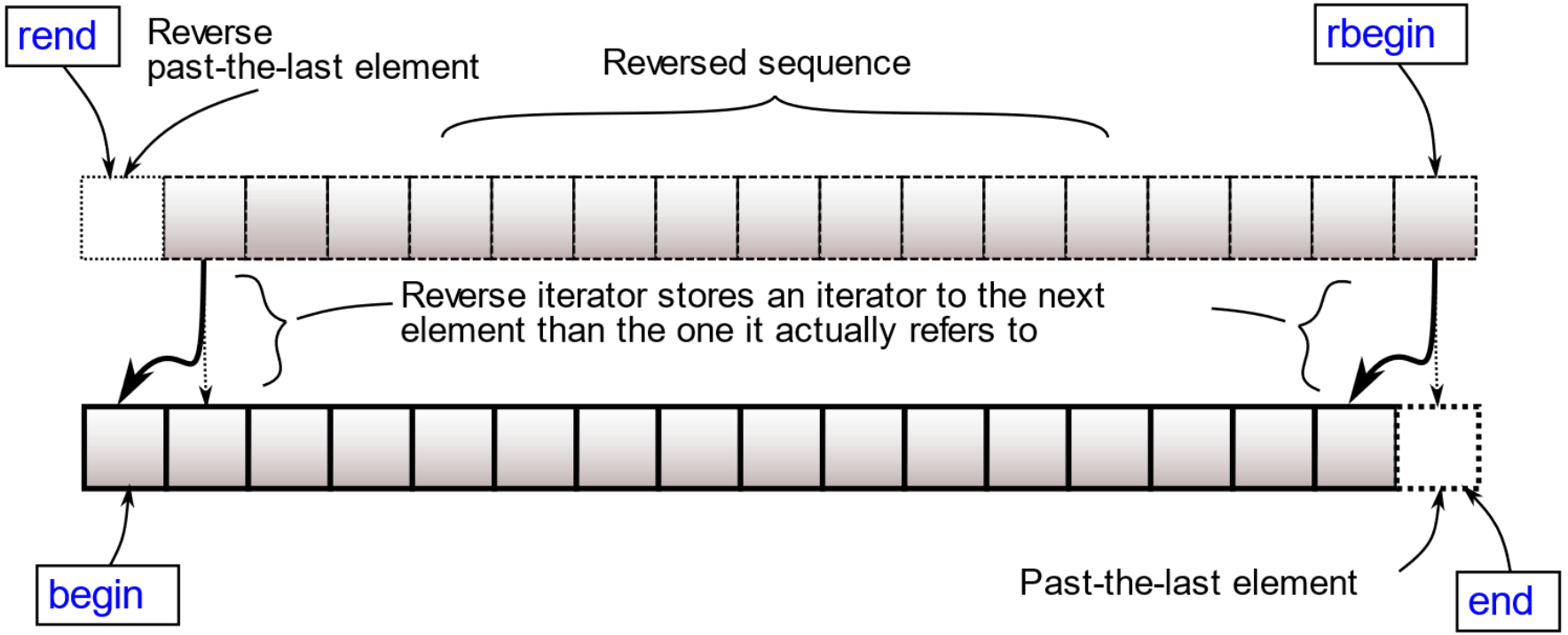

---

`begin(v)+2, begin(v)+2`

empty range



# Реверс итераторы



# Стандартные алгоритмы

Шпаргалки по стандартным алгоритмам: https://hackingcpp.com/cpp/std/algorithms.html

105 STL Algorithms in Less Than an Hour: https://youtu.be/bXkWuUe9V2I