Basic C++

Standard Template Library

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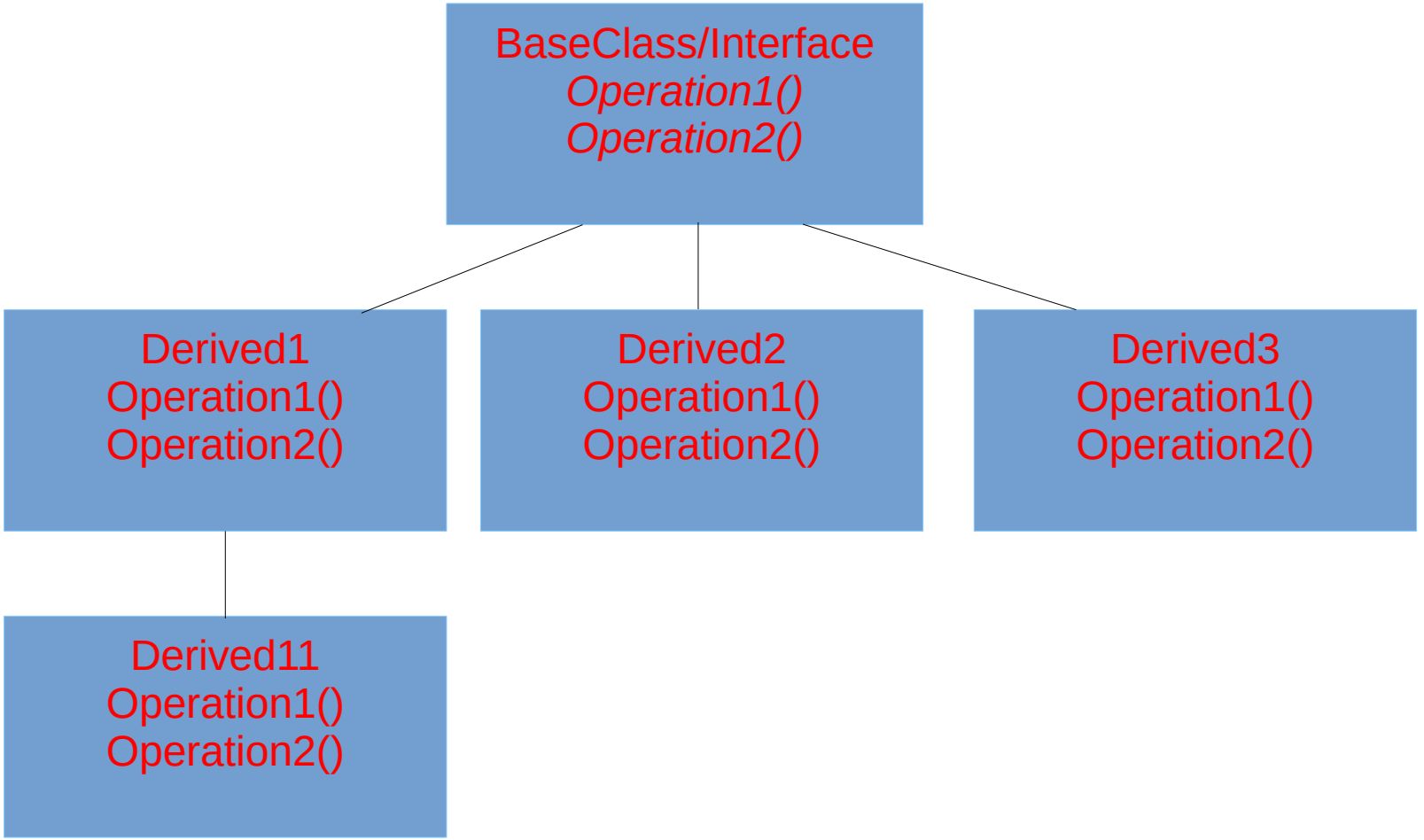
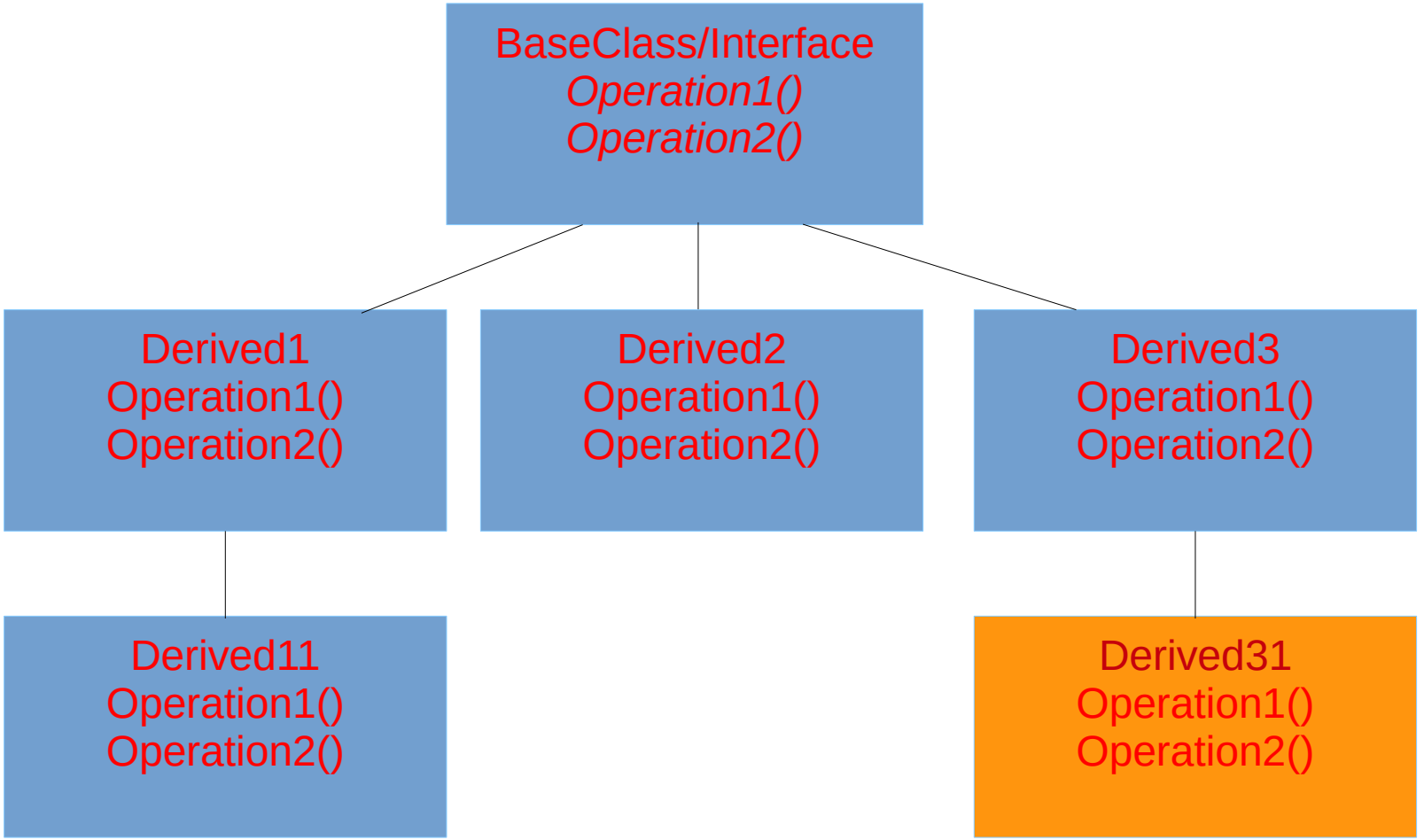
STL

- Expression problem
- Generic programming
- An example – inserters, iterator-adapters, functors
- Efficiency
- Memory consumption characteristics
- Array and forward_list in C++11
- Unordered containers in C++11
- Traps and pitfalls

The expression problem



The expression problem



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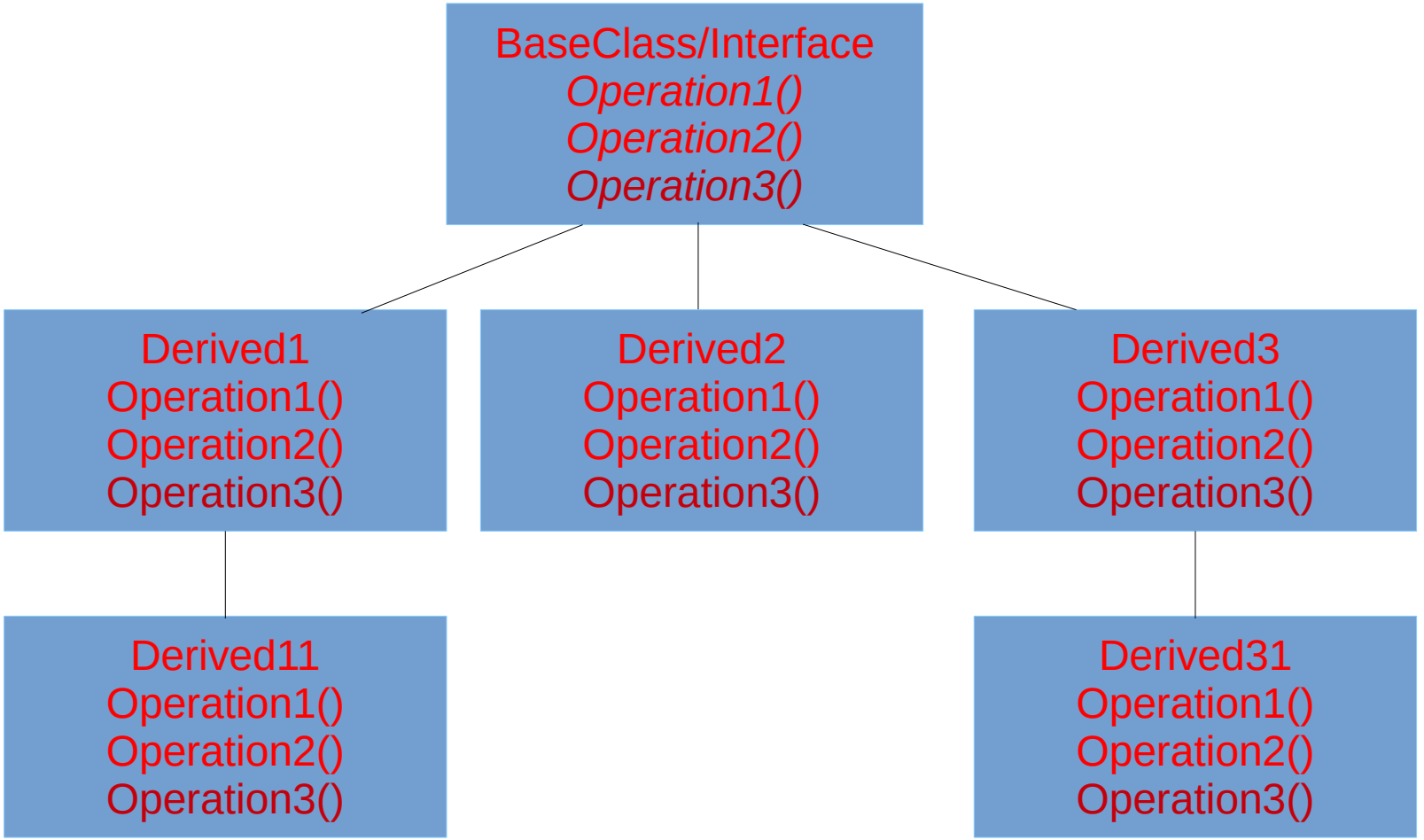

The expression problem

- Philip Wadler: expression problem mail, 1990
- Shriram Krishnamurthi, Matthias Felleisen, Daniel P. Friedman: "Synthesizing Object-Oriented and Functional Design to Promote Re-Use", 1998

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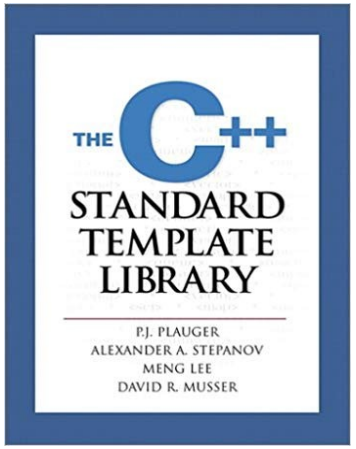
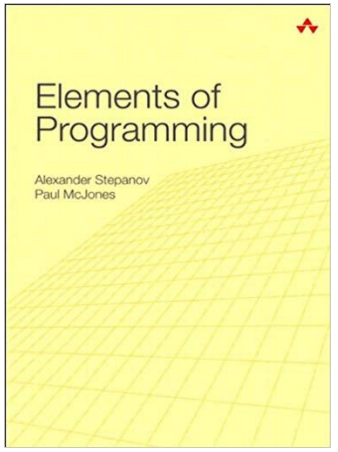
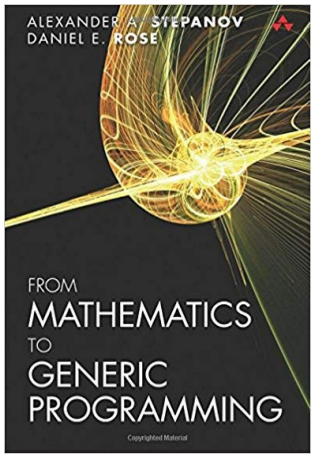
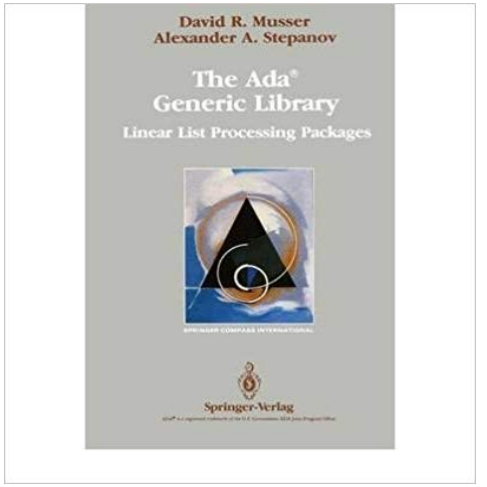
- Aleksey Stepanov: generic programmig, 1985

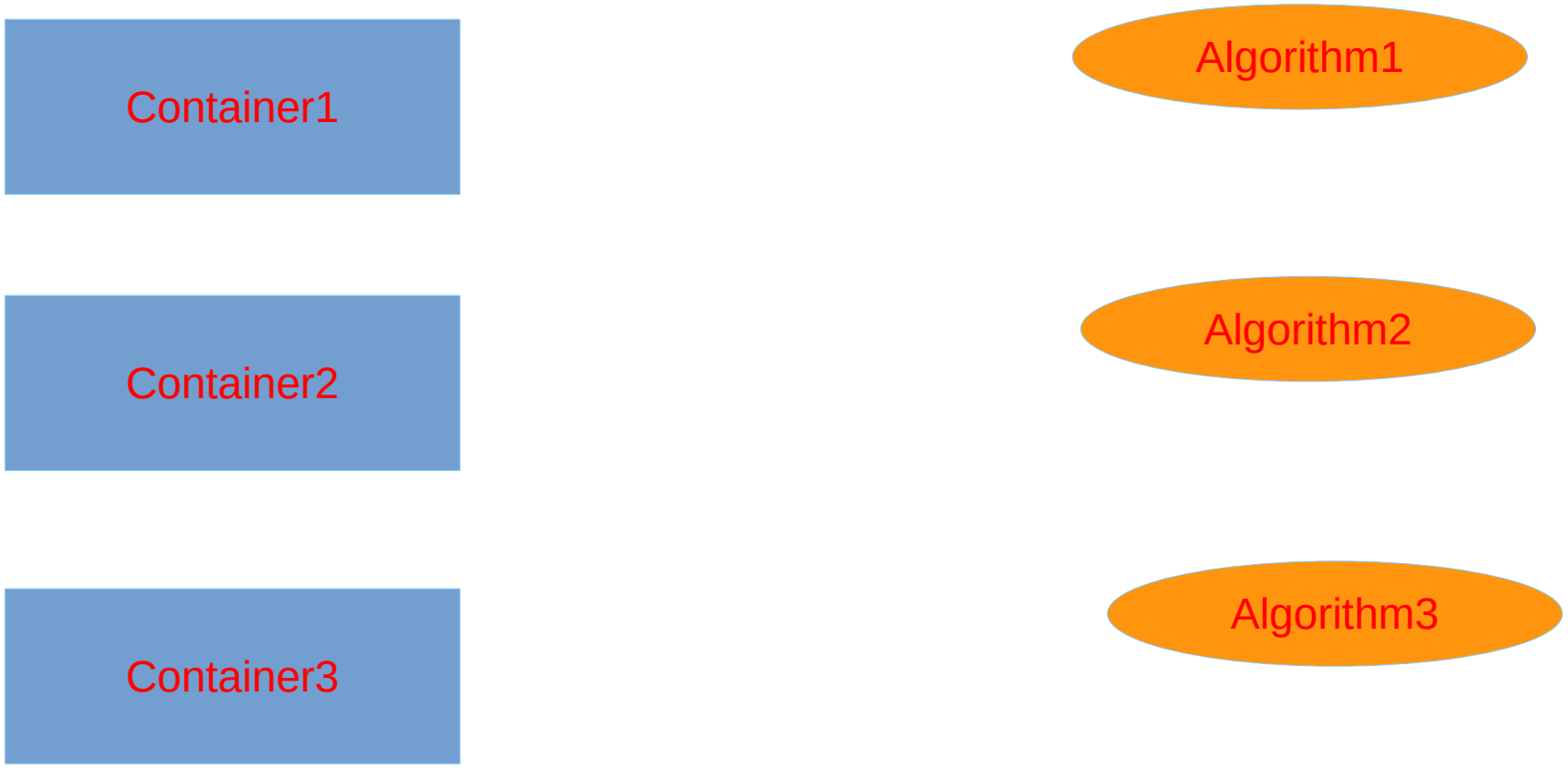








The STL solution



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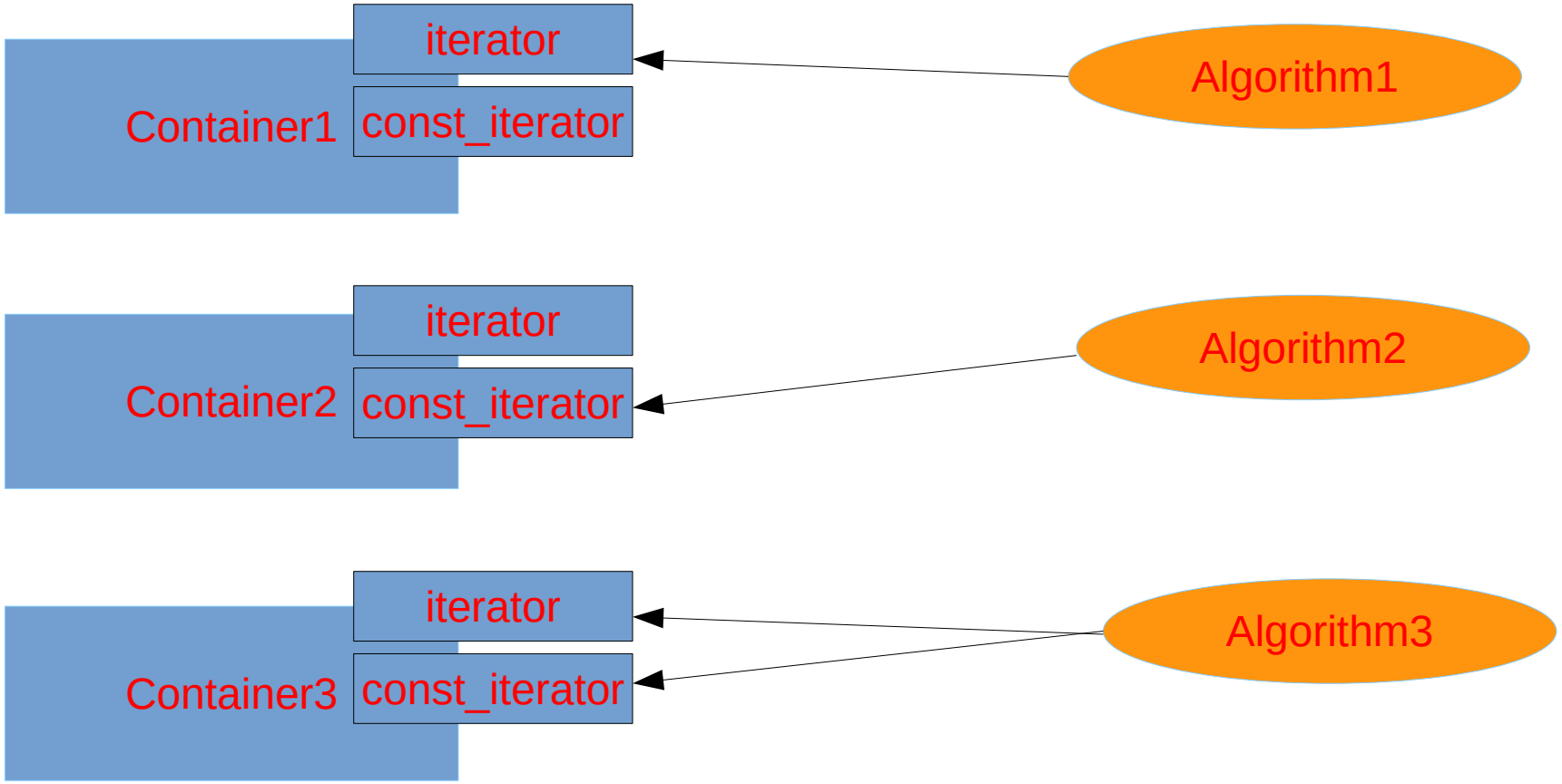

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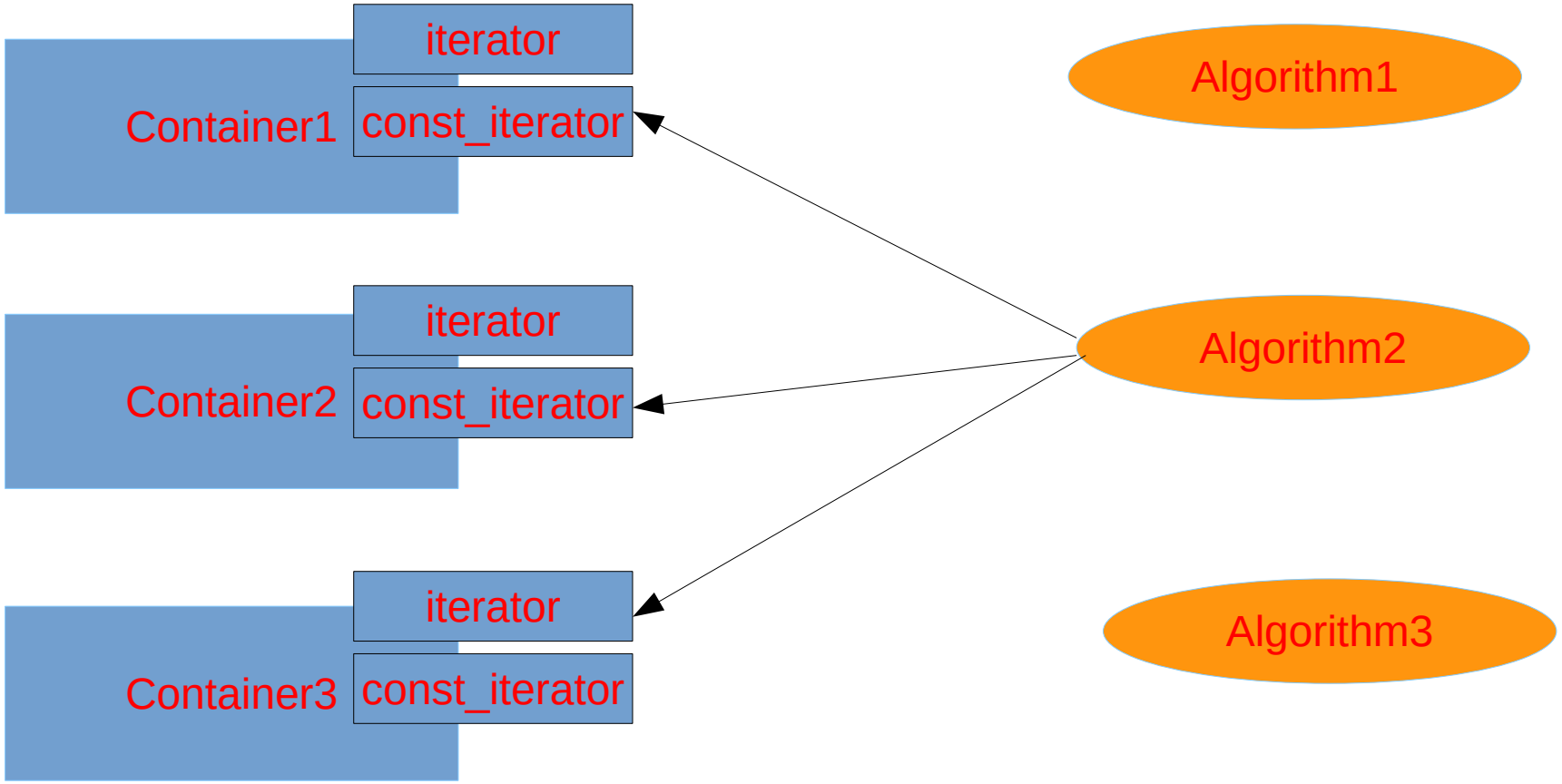
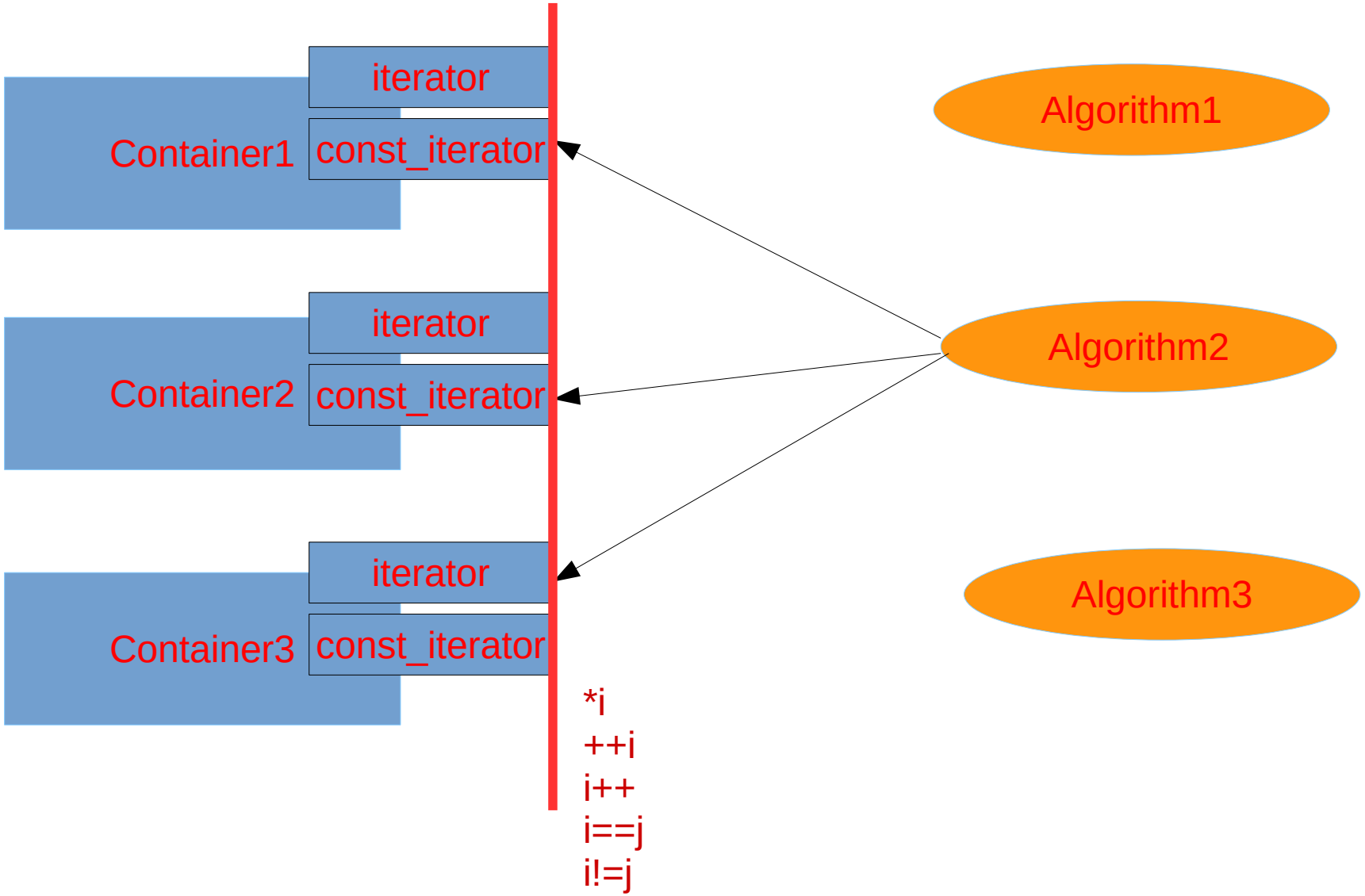


The STL solution



How to implement

```
int t[] = { 1, 3, 5, ... };

// find the first occurrence of value 55
int *pi = find( t, t+sizeof(t)/sizeof(t[0]), 55);

if ( pi )
{
  *pi = 56
}

// a very specific algorithm: works only on integer arrays
int *find( int *begin, int *end, int x)
{
  while ( begin != end )
  {
    if ( *begin == x )
    {
      return begin;
    }
    ++begin;
  }
  return nullptr;
}
```

Simple solution

```
int t[] = { 1, 3, 5, ... };

// find the first occurrence of value 55
int *pi = find( t, t+sizeof(t)/sizeof(t[0]), 55);

if ( pi )
{
  *pi = 56
}
```

Template based

```
double t[] = { 1.0, 3.14, 5.55, ... };

// find the first occurrence of a value
double *pi = find( t, t+sizeof(t)/sizeof(t[0]), 55.5);

if ( pi )
{
  *pi = 56.5
}

// Templated algorithm
template <typename T>
T *find( T *begin, T *end, const T& x)
{
  while ( begin != end )
  {
    if ( *begin == x )
    {
      return begin;
    }
    ++begin;
  }
  return nullptr;
}
```

Iterator based

```
std::list<int> li = { 1, 3, 5, ... };

// find the first occurrence of value 55
auto it = find( li.begin(), li.end(), 55);

if ( li.end() != it )
{
  *it = 56
}

// Iterator based algorithm
template <typename It, typename T>
It find( It begin, It end, const T& x)
{
  while ( begin != end )
  {
    if ( *begin == x )
    {
      return begin;
    }
    ++begin;
  }
  return end;  // not nullptr
}
```

Universal usage

```
std::list<int> li = { 1, 3, 5, ... };
std::vector<double> vd = { 1.0, 3.3, 5.5, ... };

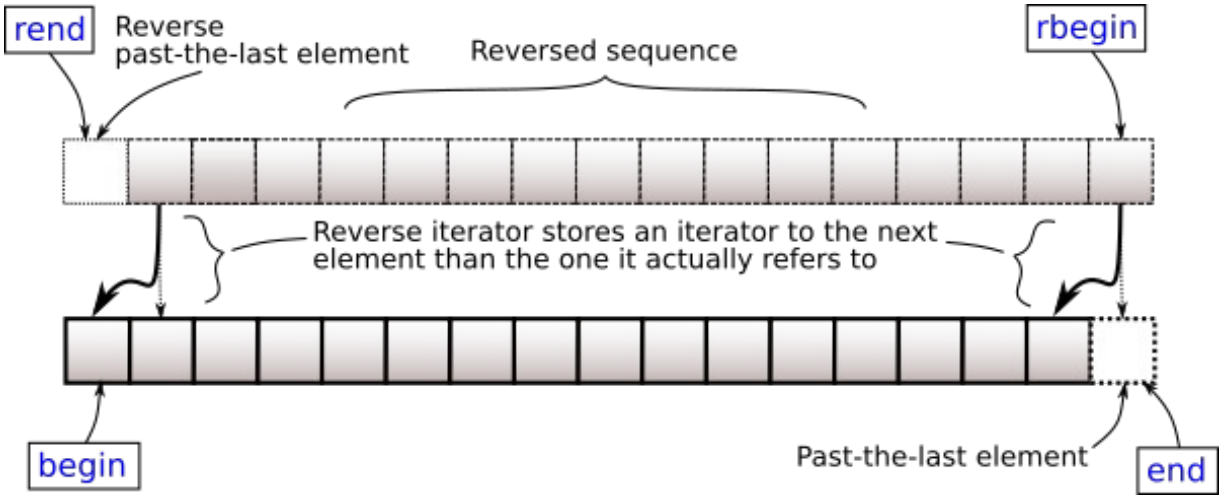
template <typename Container>
auto generic_find( const Container& c, typename Container::value_type& v)
{
  return std::find( c.begin(), c.end(), v);
}
```

- ```
  template<class C>
  typename C::value_type generic_sum(const C& c)
  {
    typename C::value_type s{};                  // value construct
    typename C::const_iterator it = c.begin();   // auto it = c.begin()

    while ( it != c.end() )
    {
      s += *it;          // requires operator+= on C::value_type
      ++it;
    }
    return s;
  }

  auto i = generic_find(li, 5);
  auto d = generic_sum(vd);
  ```
  ```

Reverse iterator




```
template<class C>
typename C::iterator find_last(C& c, const typename C::value_type& v)
{
  typename C::reverse_iterator p = c.rbegin(); // view sequence in revers
  while ( p != c.rend() )
  {
    if ( *p == v )
    {
      typename C::iterator i = p.base();
      return --i;
    }
    ++p;              // note: increment, not decrement (--)
  }
  return c.end();   // use c.end() to indicate "not found”
}
```

Iterators are const safe

```
//  C++11
std::vector<int>  v1 = { 1, 2, 3, 4, ... };
auto i = std::find( v1.begin(), v1.end(), 3);
// i is vector::iterator

const std::vector<int>  v2 = { 1, 2, 3, 4, ... };
auto j = std::find( v2.begin(), v2.end(), 3);
// j is vector::const_iterator

auto k = std::find( v1.cbegin(), v1.cend(), 3);
// k is vector::const_iterator


auto j2 = std::find( std::begin(v1), std::end(v1), 3);
// j2 is vector::iterator

auto k2 = std::find( std::cbegin(v1), std::cend(v1), 3);
// k2 is vector::const_iterator
```

STL is const safe

```
template <typename It, typename T>
It find( It begin, It end, const T& t)
{
    while (begin != end) {
        if ( *begin == t )
            return begin;
        ++begin;
    }
    return end;
}

const char t[] = { 1, 2, 3, 4, 5 };
const char *p = std::find( t, t+sizeof(t), 3)
if ( p != t+sizeof(t) )
{
    std::cout << *p; // ok to read
    // syntax error: *p = 6;
}
const std::vector<int>  v(t, t+sizeof(t));
std::vector<int>::const_iterator i = std::find( v.begin(), v.end(), 3);
if ( v.end() != i )
{
     std::cout << *i; // ok to read
    // syntax error: *i = 6;
}
```

Functors

```
std::list<int> li = { 1, 3, 5, ... };

// find the third occurrence of value less than 55
auto it = find_if( li.begin(), li.end(), ?);

if ( li.end() != it )
{
  *it = 56
}

// Iterator based algorithm
template <typename It, typename Pred>
It find_if( It begin, It end, Pred p)
{
  while ( begin != end )
  {
    if ( p(*begin) )
    {
      return begin;
    }
    ++begin;
  }
  return end;
}
```

Functors

```
std::list<int> li = { 1, 3, 5, ... };

// find the third occurrence of value less than 55
bool less55_3rd(int x)
{
  static int cnt = 0;
  if ( x < 55 )    ++cnt;
  return 3 == cnt;
}

// Iterator based algorithm
template <typename It, typename Pred>
It find_if( It begin, It end, Pred p)
{
  while ( begin != end )
  {
    if ( p(*begin) )  // calls less55_3rd(*begin)
    {
      return begin;
    }
    ++begin;
  }
  return end;
}
```

Functors

```
std::list<int> li = { 1, 3, 5, ... };


bool less55_3rd(int x)
{
  static int cnt = 0;
  if ( x < 55 )    ++cnt;
  return 3 == cnt;
}

// find the third occurrence of value less than 55
auto it = find_if( li.begin(), li.end(), less55_3rd);

if ( li.end() != it )
{
  *it = 56;

}
```

Functors

```
std::list<int> li = { 1, 3, 5, ... };


bool less55_3rd(int x)
{
  static int cnt = 0;
  if ( x < 55 )    ++cnt;
  return 3 == cnt;
}

// find the third occurrence of value less than 55
auto it = find_if( li.begin(), li.end(), less55_3rd);

if ( li.end() != it )
{
  *it = 56;
   it = find_if( ++it, li.end(), less55_3rd);  // works?
}
```

Functors

```
struct less55_3rd
{
  less55_3rd() : cnt(0) { }
  bool operator()(int x)
  {
    if ( x < 55 )    ++cnt;
    return 3 == cnt;
  }
private:
  int cnt;
};

template <typename It, typename Pred>
It find_if( It begin, It end, Pred p)
{
  while ( begin != end )
  {
    if ( p(*begin) )  // calls p.operator()(*begin)
    {
      return begin;
    }
    ++begin;
  }
  return end;
}
```

Functors

```
struct less55_3rd
{
  less55_3rd() : cnt(0) { }
  bool operator()(int x)
  {
    if ( x < 55 )    ++cnt;
    return 3 == cnt;
  }
private:
  int cnt;
};

// find the third occurrence of value less than 55
auto it = find_if( li.begin(), li.end(), less55_3rd{});


if ( li.end() != it )
{
  *it = 56;
   it = find_if( ++it, li.end(), less55_3rd{});  // new object, cnt = 0
}
```

Functors

```
struct less55_3rd
{
  less55_3rd() : cnt(0) { }
  bool operator()(int x)
  {
    if ( x < 55 )    ++cnt;
    return 3 == cnt;
  }
private:
  int cnt;
};

// find the third occurrence of value less than 55
auto it = find_if( li.begin(), li.end(), [](int x) { static int cnt = 0;
                                                     if(x < 55) ++cnt;
                                                     return 3 == cnt;} );

if ( li.end() != it )
{
  *it = 56;
   it = find_if( ++it, li.end(), [](int x) { ... }); // new lambda, cnt = 0
}
```

Functors

```
struct less55_3rd
{
  less55_3rd() : cnt(0) { }
  bool operator()(int x)
  {
    if ( x < 55 )    ++cnt;
    return 3 == cnt;
  }
private:
  int cnt;
};

// find the third occurrence of value less than 55
auto it = find_if( li.begin(), li.end(), [cnt=0](int x) { // since C++14
                                                          if(x < 55) ++cnt;
                                                          return 3 == cnt;} );

if ( li.end() != it )
{
  *it = 56;
   it = find_if( ++it, li.end(), [cnt=0](int x) { ... }); // new lambda
}
```

Functors

```
template <typename T>
struct less_Nth
{
  less_Nth(const T& t, int n) : value(t), nth(n), cnt(0) { }
  bool operator()(const T& x)
  {
    if ( x < value )    ++cnt;
    return nth == cnt;
  }
private:
  T   value;
  int nth;
  int cnt;
};

// find the fifth occurrence less than value 3.14
auto it = find_if( li.begin(), li.end(), less_Nth<double>{3.14,5});

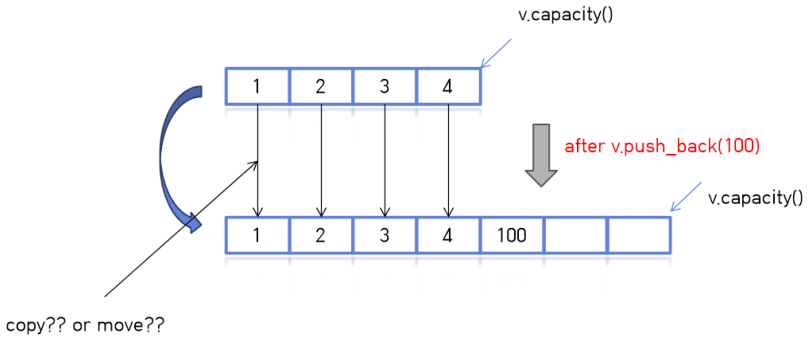
if ( li.end() != it )
{
  *it = 2.178;
   it = find_if( ++it, li.end(), less_Nth<double>{99.9,7});
}
```

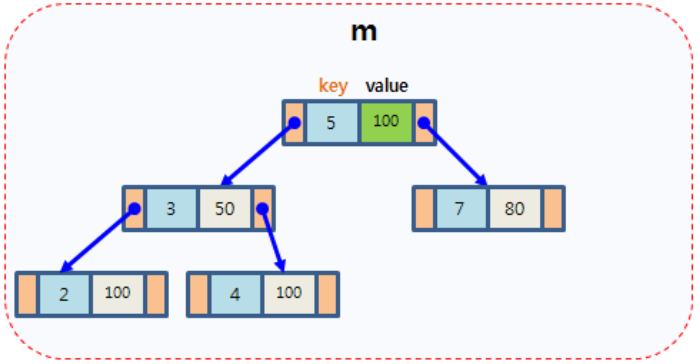
Standard containers

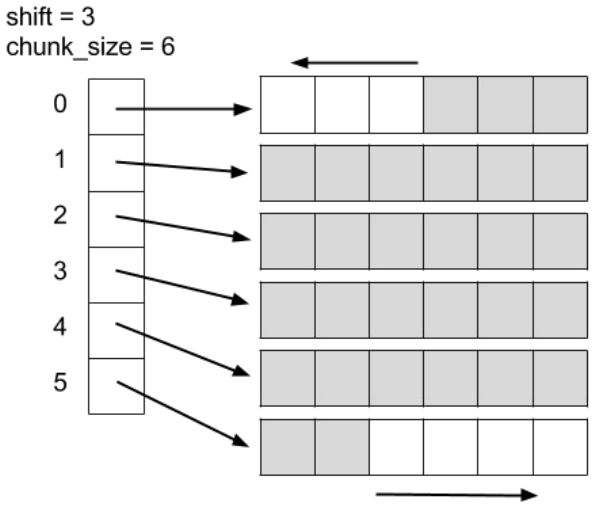
- Sequential containers
  - array, vector, deque, forward_list, list, basic_string*
- Associative containers
  - set, map, multiset, mutimap
- Unordered associative (hash) containers
  - unordered_map, ..._set, ..._multimap, ..._multiset
- Container adaptors
  - stack, queue, priority_queue
- Views
  - span, basic_string_view*

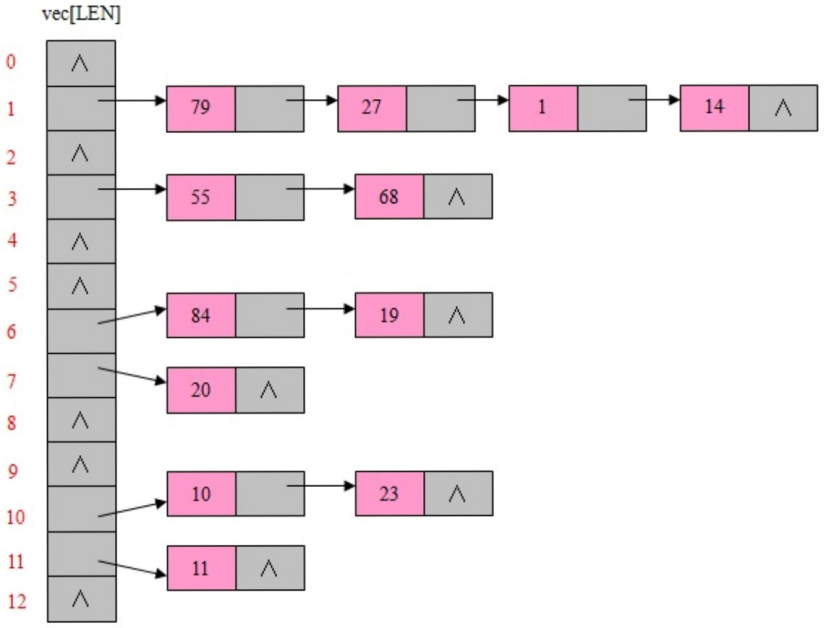
*officially not container, but very much behaves like it

Typical container implementations









Std::array

```
#include <string>
#include <iterator>
#include <iostream>
#include <algorithm>
#include <array>

int main()
{
    // construction uses aggregate initialization
    std::array<int, 3> a1{ {1, 2, 3} }; // double-braces required in C++11 (not in C++14)
    std::array<int, 3> a2 = {1, 2, 3};  // never required after =
    std::array<std::string, 2> a3 = { std::string("a"), "b" };

    // container operations are supported
    std::sort(a1.begin(), a1.end());
    std::reverse_copy(a2.begin(), a2.end(), std::ostream_iterator<int>(std::cout, " "));

    std::cout << '\n';

    // ranged for loop is supported
    for(const auto& s: a3)
        std::cout << s << ' ';

    std::array  a1{"foo"};          // C++17 CTAD: std::array<const char*,1>{"foo"}
    auto a2 = std::to_array{"foo"}; // std::array<char,4>{'f','o','o','\0'};
}
```

Std::vector

```
#include <iterator>
#include <iostream>
#include <cassert>
#include <vector>

int main()
{
    std::vector<int> v0;                // 0 element vector of int
    std::vector<int> v5 = {1,2,3,4,5}; // 5 element vector of int
    std::vector<int> v9(9,42);          // 9 element vector of int 42

    assert( v0.empty() && v0.size() == 0 && std::size(v0) && std::ssize(v0) == 0 )

    v0.push_back(1);              // cheap O(1) insertion to the back
    v0.emplace_back(2);           // cheap O(1) creation at the back

    assert( !v0.empty() && v0.size() == 2 && std::size(v0) && std::ssize(v0) == 2 );

    v0::value_type               i1 = v0.front();  // 1 first element
    std::vector<int>::value_type i2 = v0.back();   // 2 last element

    v0.pop_back();        // remove last item 2
    v0.pop_back();        // remove last item 1
    v0.pop_back();        // undefined behavior, v0.empty() == true

    return v2 == v1;      // lexicographical comparision, similarly !=, <, <=, ...
}
```

Std::vector

```
#include <iterator>
#include <iostream>
#include <cassert>
#include <algorithm>
#include <vector>

void f(std::vector<int> v)
{
    v.at(3) = 42;    // throws std::out_of_range if v.size() < 4
    v[3] = 43;       // does not throw, undefined behavior if v.size() < 4

    std::vector<int>  v2{v1}  // copy elements, v2 == v1

    for ( auto a : v2 )  {  std::cout << a << ", " }
    for ( auto it = v2.begin(); it != v2.end(); ++it) { std::cout << *it << ", " }
    for ( auto it = std::begin(v2); it != std::end(v2); ++it) { std::cout << *it << ", " }

    v2::iterator i = std::begin(v2)+4;
    v2.insert( i, 42); // insert into the middle, shift elements back, may resise
    *i = 43; //  oops, iterator may be invalidated

    v2.erase( std::begin(v2), std::begin(v2)+2);        // erase v2[0], v2[1] from v2
    i = std::find( std::begin(v2), std::end(v2), 42);   // find first occurance of 42
    if ( i != v2.end() )  // found
        *i = 43;
    v2.push_back(44); // may resize
        *i = 45;      //  oops, iterator may be invalidated
```

Std::vector

```
#include <iterator>
#include <iostream>
#include <cassert>
#include <vector>


int f()
{
    std::vector<int>  v;
    std::cout << v.size() << '\n'   // 0

    v.reserve(1000);   // pre-allocate buffer with >= 1000 capacity
    std::cout << v.capacity() << '\n'   // >= 1000

    v.resize(1000);    // add 1000 default int: 0
    std::cout << v.size() << '\n'   // 1000

    v.resize(10);    // erase the last 990 elements
    std::cout << v.size() << '\n'   // 10
    std::cout << v.capacity() << '\n'   // >= 1000

    v.shrink_to_fit();   // reallocate buffer, invalidates iterators!
    std::cout << v.capacity() << '\n'   // >= 1000

    v.clear(); // erase all elements
}
```

Std::deque

```
#include <iterator>
#include <iostream>
#include <cassert>
#include <algorithm>
#include <deque>


void f()
{
    // similar interface as for vector
    std::deque<int>  d;

    // but no reserve and capacity
    d.reserve(1000);   // pre-allocate buffer with >= 1000 capacity
    std::cout << d.capacity() << '\n'   // >= 1000

    // but O(1) operations on front too
    d.push_front(42);
    d.emplace_front(43);

    d.pop_front();

    d.resize(1000);    // add 1000 default int: 0
    std::cout << d.size() << '\n'   // 1000
}
```

Std::list

```
#include <iterator>
#include <iostream>
#include <cassert>
#include <algorithm>
#include <list>

void f()
{
    // similar interface as for deque
    std::list<int>  lst;

    lst.resize(1000);    // add 1000 default int: 0
    std::cout << d.size() << '\n'   // 1000

    // but no direct access to random element
    std::cout << lst[5] << lst.at(2) << '\n';

    // O(1) operations on front and end
    lst.push_front(42);
    lst.emplace_front(43);
    lst.push_back(42);
    lst.emplace_back(43);

    lst.pop_front();
    lst.pop_back();
}
```

Std::list

```
#include <iterator>
#include <iostream>
#include <cassert>
#include <algorithm>
#include <list>

void f(std::list<int> &other)
{
    std::list<int>  lst;  // similar interface as for deque

    lst.push_front(42);
    lst.emplace_back(43);

    auto it = find( lst.begin(), lst.end(), 42);
    insert( it+2, 44);   // iterator is bidirectional not random access iterator

    // list specific operations
    lst.merge(other);         // merge elements from other list (sorted)
    lst.splice( it, other);   // move elements from other list

    lst.reverse();        // reverse elements
    lst.sort();           // sort elements

    lst.remove(42);       // removes all 42, not the algorithm, really erase elements
    lst.unique(42);       // removes consecutive duplicate elements, erases too
}
```

Std::forward_list

```
template <typename T, typename Alloc = allocator<T> >
class forward_list
{
public:
    void clear();
    iterator insert_after(const_iterator pos, const T& value); // +move, +interval
    iterator emplace_after(const_iterator pos, Args&&... args);
    iterator erase_after(const_iterator pos); // +interval
    void push_front(const T& value);          // +move
    void emplace_front( Args&&... args );
    void pop_front();
    void resize(size_type count);
    void resise(size_type count, const T& value);
    void swap(forward_list& other);
    bool empty();

    iterator before_begin();  // cbefore_begin()
    iterator begin();         // cbegin()
    iterator end();           // cend()

    void merge(forward_list&& other, Compare comp);
    void splice_after(const_iterator pos, forward_list& other);
    void remove(const T& value);
    void remove_if(UnaryPredicate p);
    void reverse();
    void unique(BinaryPredicate p);
    void sort(Compare comp);  // sort()

     // no reverse iteration
     // no back() or push_back()
     // no size()
};
```

Std::stack

```
#include <stack>

void f()
{
    // stack is a container adaptor
    // stack can be defined on anything having: back(), push_back(), pop_back()
    std::stack<int,vector>  sv;   // stack over vector
    std::stack<int>  st;          // stack is by default over deque

    // usual accessors: empty(), size()

    // stack interface
    st.push(42);          // at top
    st.emplace(43);       // at top

    auto val = st.top;    // read the top element
    st.top = 44;          // write the top element

    st.pop();             // remove the top element

    // the underlying container is a protected member,
    // accessible if one inherits from stack
}
```

Std::queue

```
#include <queue>

void f()
{
    // queue is a container adaptor
    // queue can be defined on anything having: back(), push_back(), pop_back()
    std::queue<int,list>  qv;     // queue over vector
    std::queue<int>  q;           // queue is by default over deque

    // usual accessors: empty(), size()

    // queue interface
    q.push(42);           // insert to the end
    q.emplace(43);        // create at the end

    auto first = q.front();   // read the first element
    auto last  = q.back();    // read the last element

    q.pop();              // remove the first element

    // the underlying container is a protected member,
    // accessible if one inherits from stack
}
```

Std::priority_queue

```
#include <queue>

void f()
{
    // queue is a container adaptor
    // queue can be defined on anything having: back(), push_back(), pop_back()
    std::priority_queue<int,deque> pv;    // priority queue over deque
    std::priority_queue<int>       pq;    // priority queue is by default over vector

    // usual accessors: empty(), size()

    // queue interface
    pq.push(42);     // insert into the priority_queue, keep heap invariant, O(log(n))
    pq.emplace(43);  // create at the end then maintain heap invariant, O(log(n))

    auto first = pq.top();    // read the first element, O(1)
    pq.top() = 42;            // cannot write the top element
    q.pop();                 // remove the top element, keep heap invariant, O(log(n))

    // the underlying container is a protected member,
    // accessible if one inherits from stack
}
```

Std::set

```
#include <set>

void f()
{
    // set is an associative container, ordered by key (the whole object by default)

    std::set<std::string> s;           // empty set of strings, comparator is std::less
    std::set<std::string,mycomp<std::string>> s2;  // empty set of strings, custom comp.
    std::multiset<std::string> ms;     // empty set of strings, duplicates allowed

    // usual empty() size()
    s.insert(42);    // insert into the set, keep ordering, O(log(n))
    s.insert(42);    // insert the same key into the set fails, O(log(n))

    ms.insert(42);   // insert into the multiset, keep ordering, O(log(n))
    ms.insert(42);   // insert the same into the multiset works, neighbours, O(log(n))

    s.erase(42);     // erase the only element with key 42 if any
    ms.erase(42);    // erase one element with key 42 if any

    s.erase(s.begin());  // erase the first, smallest element
    ms.erase(--s.end()); // erase the last, largest element
}
```

Std::map

```
#include <map>

void f()
{
    // map is an associative container of key+mapped type, ordered by key

    std::map<std::string,long,mycomp<std::string>> m;  // map (string,long) custom comp.
    std::multimap<std::string> mm; // empty map of (string,long), key duplicates allowed

    // map specific interface
    m.insert({"Gabor"s, 12L});  // insert into map, keep ordering, O(log(n))
    m.insert({"Gabor"s, 13L});  // insert into map fails due key duplicate, O(log(n))
    mm.insert({"Gabor"s, 14L}); // insert into multimap ok, keep ordering, O(log(n))
    mm.insert({"Gabor"s, 15L}); // insert into multimap ok, keep ordering, O(log(n))

    // similar operations as set/multiset
    int n1 = m.count("Gabor"s);   // 0 or 1 elements with the key
    bool b = m.contains("Gabor"s);// C++20
    auto it = m.find("Gabor"s);   // return iterator to element 42 or end()
    auto [lb,ub] = mm.equal_range("Gabor"s); // return pair of iterator
    if ( lb != mm.end() )
        mm.erase(lb,ub);     // erase all 42s
}
```

Std::map

```
#include <map>

void f()
{
    // map is an associative container of key+mapped type, ordered by key

    std::map<std::string,long,mycomp<std::string>> m;   // map (string,long) custom comp.

    m.insert({"Gabor"s, 12L});  // insert into map, keep ordering, O(log(n))
    m.insert({"Gabor"s, 13L});  // insert into map fails due key duplicate, O(log(n))

    // only on map (not even multimap!)
    long l1 = m.at("Gabor"s); // return reference to the mapped value
                              // or throw std::out_of_range
    m.at("Gabor"s) = 43L;

    long l2 = m["Gabor"s];    // return reference to the mapped value, if there where no
                              //     such key, creates with default value of mapped type
    long l3 = m["Zoltan"s];   // maybe 0L

    m["Bjarne"s] = 42L;       // insert or overwrite
}
```

std::unordered_map

```cpp
#include <unordered_map>
#include <string>

using namespace std;

int main()
{
    unordered_map<string, string> hashtable;
    hashtable.emplace("www.zolix.hu", "212.92.23.158");
    hashtable.insert(make_pair("www.elte.hu", "212.92.23.159"));

    cout << "IP Address: " << hashtable["www.zolix.com"] << endl;

    for (auto &obj : hashtable)
    {
        cout << obj.first << ": " << obj.second << endl;
    }

    // returns std::unordered_map<std::string,double>::const_iterator
    auto it = hashtable.find("www.elte.com");
    if (hashtable.end() != it)   // hashtable.count(“www.elte.com”) > 0
    {
        cout << it->first << ": " << it->second << endl;
    }
    return 0;
}
```

std::unordered_map

```
#include <unordered_map>
#include <string>

class MyClass
{
    std::string name;
    int         age;
public:
    Bool operator==(const MyClass& rhs) { ... }   // should be reflexive
    // ...
};
class MyClassHash
{
public:
    size_t operator()(const MyClass& m) const
    {
        return std::hash<std::string>()(m.name) ^ hash<int>()(m.age);
    }
};
int main()
{
    MyClass jim(...), joe(...);
    unordered_map<MyClass, double> salary;
    hashtable.emplace( jim, 20000);
    hashtable.emplace( joe, 22000);
    // ...
}
```

Load factor

- Average insert/find is constant
- Worst-case: linear in container size
- Iterators are invalidated only on rehash
- Load factor == size() / bucket_count() // default 1.0
- Control of buckets:
  - size_type bucket_count() const; // #of buckets
  - float max_load_factor() const; // get max load factor
  - void max_load_factor(float z); // set max load factor
  - size_type bucket_size (size_type n) const; // #of bucket n
  - size_type bucket(const key_t& key) const; // where key goes?
  - void rehash(size_type n); // sets #of buckets

std::unordered_map

```cpp
// unordered_map::bucket_count
#include <iostream>
#include <string>
#include <unordered_map>

int main ()
{
  std::unordered_map<std::string,std::string> mymap = {
       {"house","maison"},{"apple","pomme"},{"tree","arbre"},
       {"book","livre"},{"door","porte"},{"grapefruit","pamplemousse"}
  };
  unsigned n = mymap.bucket_count();
  std::cout << "mymap has " << n << " buckets.\n";

  for (unsigned i=0; i<n; ++i) {
    std::cout << "bucket #" << i << " contains: ";
    for (auto it = mymap.begin(i); it!=mymap.end(i); ++it)
      std::cout << "[" << it->first << ":" << it->second << "] ";
    std::cout << "\n";
  }
}
```

```
mymap has 7 buckets.
bucket #0 contains: [book:livre] [house:maison]
bucket #1 contains:
bucket #2 contains:
bucket #3 contains: [grapefruit:pamplemousse] [tree:arbre]
bucket #4 contains:
bucket #5 contains: [apple:pomme]
bucket #6 contains: [door:porte]
```

Load factor

```
// unordered_map::max_load_factor
int main ()
{
  std::unordered_map<std::string,std::string> mymap = {
    {"Au","gold"},{"Ag","Silver"},{"Cu","Copper"},{"Pt","Platinum"}
  };

  std::cout << "current max_load_factor: " << mymap.max_load_factor() << std::endl;
  std::cout << "current size: " << mymap.size() << std::endl;
  std::cout << "current bucket_count: " << mymap.bucket_count() << std::endl;
  std::cout << "current load_factor: " << mymap.load_factor() << std::endl;

  float z = mymap.max_load_factor();
  mymap.max_load_factor ( z / 2.0 );

  std::cout << "new max_load_factor: " << mymap.max_load_factor() << std::endl;
  std::cout << "new size: " << mymap.size() << std::endl;
  std::cout << "new bucket_count: " << mymap.bucket_count() << std::endl;
  std::cout << "new load_factor: " << mymap.load_factor() << std::endl;
  return 0;
}
current max_load_factor: 1
current size: 4
current bucket_count: 5
current load_factor: 0.8
new max_load_factor: 0.5
new size: 4
new bucket_count: 11
new load_factor: 0.363636
```

Std::unordered_multi...

```
// unordered_multiset::equal_range

#include <iostream>
#include <string>
#include <unordered_set>

int main ()
{
  std::unordered_multiset<std::string> myums =
                        {"cow","pig","pig","chicken","pig","chicken"};

  auto myrange = myums.equal_range("pig");

  std::cout << "These pigs were found:";

  while ( myrange.first != myrange.second ) {
      std::cout << " " << *myrange.first++;
  }
  std::cout << std::endl;

  return 0;
}
```

Example: merge two files

```
#include <iostream>
#include <fstream>
#include <string>

using namespace std;

int main()   // simple merge:
{
    string s1, s2;
    ifstream f1("file1.txt");
    ifstream f2("file2.txt");

    f1 >> s1; f2 >> s2;
    while (f1 || f2)
    {
        if (f1 && ((s1 <= s2) || !f2))
        {
            cout << s1 << endl;
            f1 >> s1;
        }
        if (f2 && ((s1 >= s2) || !f1))
        {
            cout << s2 << endl;
            f2 >> s2;
        }
    }
    return 0;
}
```

Example: naïve STL usage

```
#include <iostream>
#include <fstream>
#include <string>
#include <algorithm>    // merge( b1, e1, b2, e2, b3 [,opc_rend])
#include <vector>

using namespace std;
int main()
{
    ifstream if1("file1.txt");
    ifstream if2("file2.txt");

    string s;
    vector<string> v1;
    while ( if1 >> s ) v1.push_back(s); // do we have enough memory?
    vector<string> v2;
    while ( if2 >> s ) v2.push_back(s); // do we have enough memory?

    // allocate the elements for the result, do we have enough memory?
    vector<string> v3(v1.size() + v2.size());   // constructs empty strings...

    // *b3++ = *b1 < *b2 ? *b1++ : *b2++
    merge( v1.begin(),v1.end(),v2.begin(),v2.end(),v3.begin());

    for ( int i = 0; i < v3.size(); ++i)
        cout << v3[i] << endl;

    return 0;
}
```

std::merge

```
template<class InputIt1, class InputIt2, class OutputIt>
OutputIt merge(InputIt1 first1, InputIt1 last1,
               InputIt2 first2, InputIt2 last2,
               OutputIt d_first)
{
    for (; first1 != last1; ++d_first) {
        if (first2 == last2) {
            return std::copy(first1, last1, d_first);
        }
        if (*first2 < *first1) {
            *d_first = *first2;
            ++first2;
        } else {
            *d_first = *first1;
            ++first1;
        }
    }
    return std::copy(first2, last2, d_first);
}
```

std::merge

```
template<class InputIt1, class InputIt2, class OutputIt>
OutputIt merge(InputIt1 first1, InputIt1 last1,
               InputIt2 first2, InputIt2 last2,
               OutputIt d_first, Compare comp)
{
    for (; first1 != last1; ++d_first) {
        if (first2 == last2) {
            return std::copy(first1, last1, d_first);
        }
        if ( comp(*first2,*first1) ) {
            *d_first = *first2;
            ++first2;
        } else {
            *d_first = *first1;
            ++first1;
        }
    }
    return std::copy(first2, last2, d_first);
}
```

Example: inserters

```
#include <iostream>
#include <fstream>
#include <string>
#include <algorithm>
#include <vector>

using namespace std;

int main()
{
    ifstream if1("file1.txt");
    ifstream if2("file2.txt");

    string s;
    vector<string> v1;
    while ( if1 >> s ) v1.push_back(s);
    vector<string> v2;
    while ( if2 >> s ) v2.push_back(s);
    vector<string> v3;
    v3.reserve( v1.size() + v2.size() ); // alloc buffer but do not construct, size == 0

    merge(v1.begin(),v1.end(),v2.begin(),v2.end(),back_inserter(v3)); // v3.push_back(*c)

    for ( int i = 0; i < v3.size(); ++i)
        cout << v3[i] << endl;

    return 0;
}
```

Example: inserters

```
#include <iostream>
#include <fstream>
#include <string>
#include <algorithm>
#include <vector>

using namespace std;

int main()
{
    ifstream if1("file1.txt");
    ifstream if2("file2.txt");

    string s;
    vector<string> v1;
    while ( if1 >> s ) v1.push_back(s);
    vector<string> v2;
    while ( if2 >> s ) v2.push_back(s);
    vector<string> v3;
    v3.reserve( v1.size() + v2.size() ); // alloc buffer but do not construct, size == 0

    merge(v1.begin(),v1.end(),v2.begin(),v2.end(),back_inserter(v3)); // v3.push_back(*c)

    for ( int i = 0; i < v3.size(); ++i)
        cout << v3[i] << endl;

    return 0;
}
```

```
template<typename _Cont>
class back_insert_iterator : public
      iterator<output_iterator_tag,void,void,void,void>
{
  back_insert_iterator&
  operator=(const typename _Cont::value_type& __value)
  {   // same overloaded to reference and rvalue ref
    container->push_back(__value);
    return *this;
  }
  back_insert_iterator& operator*()   { return *this; }
  back_insert_iterator& operator++()  { return *this; }
  back_insert_iterator operator++(int){ return *this; }
protected:
  _Cont* container;
};
```

Example: stream iterators

```
#include <iostream>
#include <fstream>
#include <string>
#include <algorithm>
#include <iterator>     // input- and output-iterators

using namespace std;

int main()
{
    ifstream if1("file1.txt");
    ifstream if2("file2.txt");

    // istream_iterator(if1) -> if1 >> *current
    // istream_iterator() -> EOF
    // ostream_iterator(of,x) -> of << *current << x
    merge( istream_iterator<string>(if1), istream_iterator<string>(),
           istream_iterator<string>(if2), istream_iterator<string>(),
           ostream_iterator<string>(cout,"\n") );

    return 0;
}
```

Example: comparator

```
#include <iostream>
#include <fstream>
#include <string>
#include <cctype>
#include <algorithm>
#include <iterator>

struct my_less  // function object: "functor"
{
    bool operator()(const std::string& s1, const std::string& s2)  {
        std::string us1 = s1;
        std::string us2 = s2;
        transform( s1.begin(), s1.end(), us1.begin(), toupper);  // TODO: use <locale>
        transform( s2.begin(), s2.end(), us2.begin(), toupper);
        return us1 < us2;
    }
};

int main()
{
    ifstream if1("file1.txt");
    ifstream if2("file2.txt");

    merge( istream_iterator<string>(if1), istream_iterator<string>(),
           istream_iterator<string>(if2), istream_iterator<string>(),
           ostream_iterator<string>(cout,"\n"), my_less() );
    return 0;
}
```

Example: template comparator

```
template <typename T>
class distr
{
public:
    distr(int l, int r, bool fl = true) : left_(l), right_(r), from_left_(fl), cnt_(0) { }
    // formal reasons: "compare" has two parameters of type T
    bool operator()( const T&, const T&)   {
        bool ret = from_left_;   // from_left_ is “smaller” currently
        const int max = from_left_ ? left_ : right_;
        if ( ++cnt_ == max )
        {
            cnt_ = 0;
            from_left_ = ! from_left_;
        }
        return ret;
    }
private:
    const int left_;  // read left_ element from left
    const int right_; // read right_ element from right
    int from_left_;   // start from left
    int cnt_;
};
```

```
   // ...
   istream_iterator<string>(if2), istream_iterator<string>(),
   ostream_iterator<string>(cout,"\n"), distr<std::string>(left,right) );
   // ...
```

Vector vs Associative containers

```
#include <iostream>
#include <string>
#include <algorithm>
#include <set>
using namespace std;

int main()   /* print unique sorted elems  */
{
    set<string> coll( istream_iterator<string>(cin), istream_iterator<string>());
    copy( coll.begin(), coll.end(), ostream_iterator<string>(cout, "\n"));
}
```

```
#include <iostream>
#include <string>
#include <algorithm>
#include <vector>
using namespace std;

int main()   /* print unique sorted elems  */
{
    vector<string> coll( istream_iterator<string>(cin), istream_iterator<string>());
    sort (coll.begin(), coll.end());   // sort elements
    unique_copy (coll.begin(), coll.end(), ostream_iterator<string>(cout, "\n"));
}
```

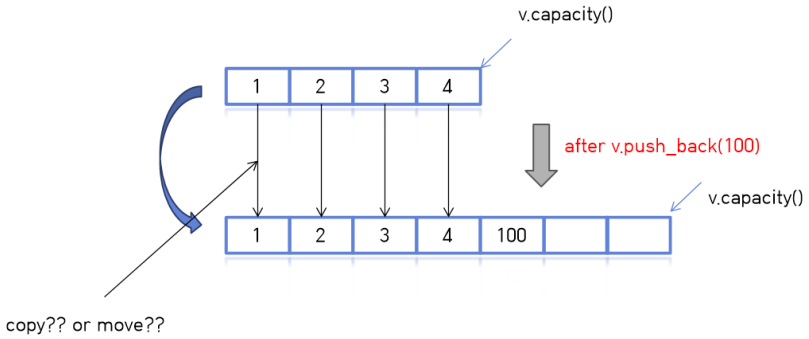
Vector vs Associative containers

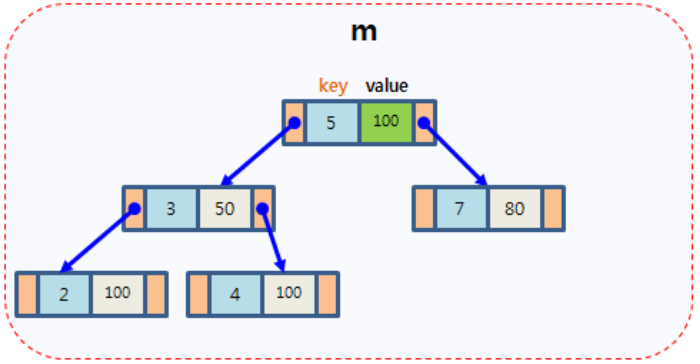
```
#include <iostream>
#include <string>
#include <algorithm>
#include <set>
using namespace std;

int main()   /* print unique sorted elems  */
{
    set<string> coll( istream_iterator<string>(cin), istream_iterator<string>());
    copy( coll.begin(), coll.end(), ostream_iterator<string>(cout, "\n"));
}
```

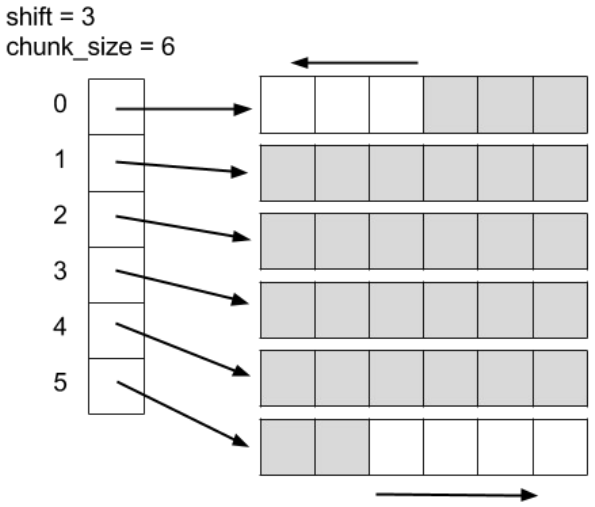
```
#include <iostream>
#include <string>
#include <algorithm>
#include <vector>
using namespace std;

int main()   /* print unique sorted elems  */
{
    vector<string> coll( istream_iterator<string>(cin), istream_iterator<string>());
    sort (coll.begin(), coll.end());   // sort elements
    unique_copy (coll.begin(), coll.end(), ostream_iterator<string>(cout, "\n"));
}
```

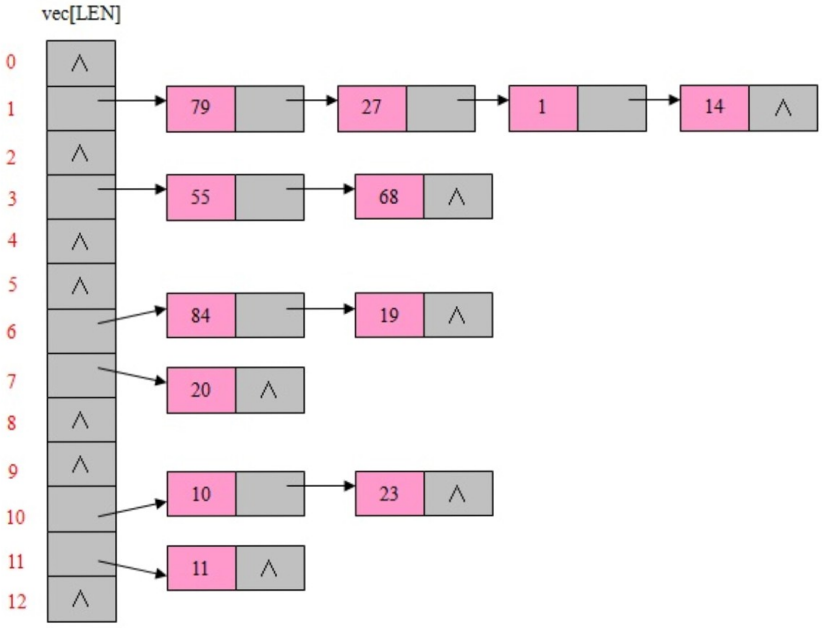
```
        //  150.000 string:  vector solution is better with 10%
        //       + reserve:                                 15%
        // multiset + copy:                                 40%
```

Typical container implementations

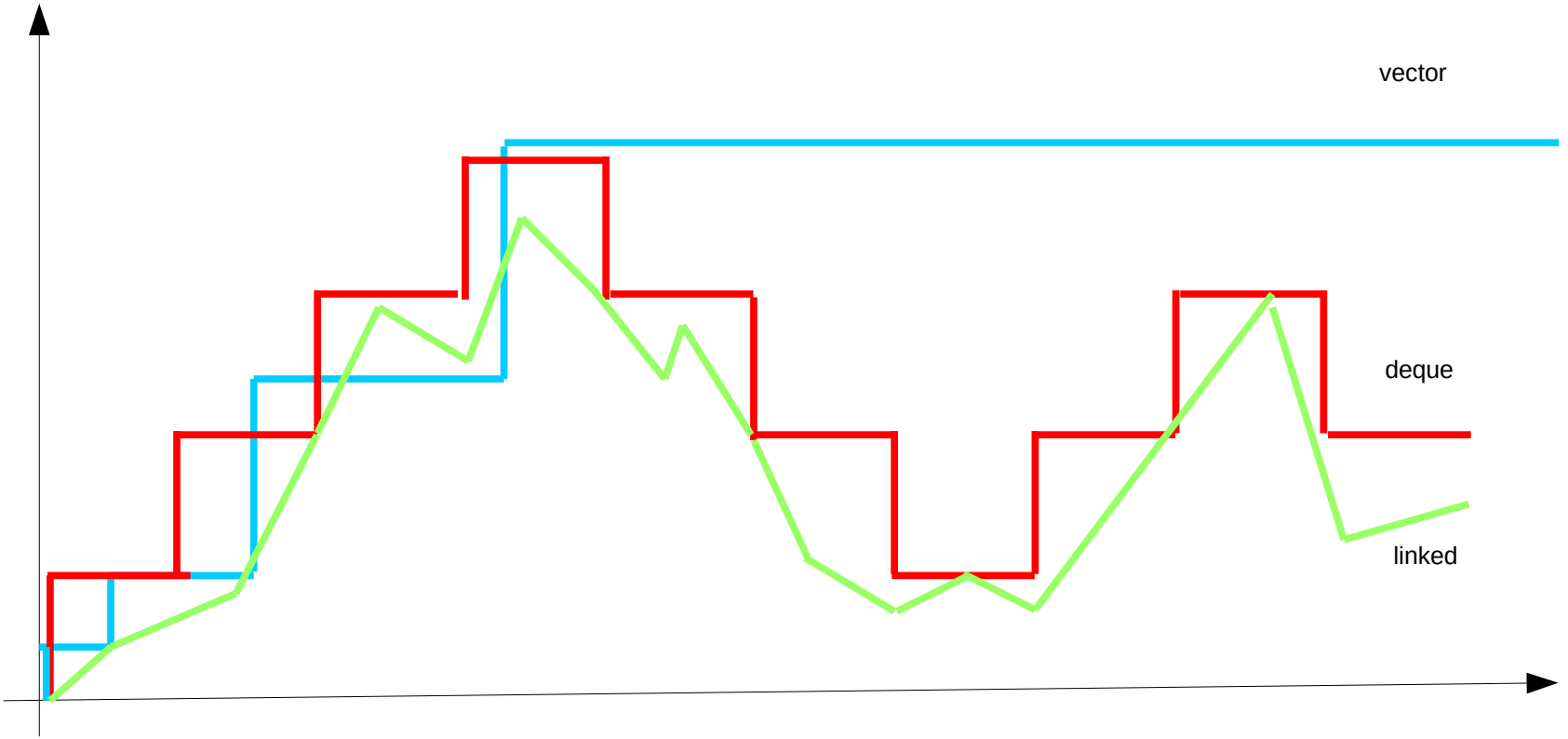








Memory consumption



Vector size and capacity

```
int main()
{
    std::vector<int> v;
    std::cout << "Default-constructed capacity is " << v.capacity() << '\n';

    v.resize(100);
    std::cout << "Capacity of a 100-element vector is " << v.capacity() << '\n';

    v.clear();
    std::cout << "Capacity after clear() is " << v.capacity() << '\n';

    // std::vector<int>(v).swap(v); // C++98

    v.shrink_to_fit(); // C++11
    std::cout << "Capacity after shrink_to_fit() is " << v.capacity() << '\n';
}
```

```
Default-constructed capacity is 0
Capacity of a 100-element vector is 100
Capacity after clear() is 100
Capacity after shrink_to_fit() is 0
```

Iterator invalidation

Category	Container	After **insertion**, are...		After **erasure**, are...		Conditionally
		iterators valid?	**references** valid?	**iterators** valid?	**references** valid?	
Sequence containers	`array`	N/A		N/A		
	`vector`	No		N/A		Insertion changed capacity
		Yes		Yes		Before modified element(s) (for insertion only if capacity didn't change)
		No		No		At or after modified element(s)
	`deque`	No	Yes	Yes, except erased element(s)		Modified first or last element
			No	No		Modified middle only
	`list`	Yes		Yes, except erased element(s)		
	`forward_list`	Yes		Yes, except erased element(s)		
Associative containers	`set` `multiset` `map` `multimap`	Yes		Yes, except erased element(s)		
Unordered associative containers	`unordered_set` `unordered_multiset`	No	Yes	N/A		Insertion caused rehash
	`unordered_map` `unordered_multimap`	Yes		Yes, except erased element(s)		No rehash

From: https://en.cppreference.com/w/cpp/container

STL traps

```
void f(std::vector<int> &v; int del)
{
    std::remove( v.begin(), v.end(), del);   // remove elements equal del ?
}
```

STL traps

```
void f(std::vector<int> &v; int del)
{
    std::remove( v.begin(), v.end(), del);   // remove elements equal del ?
}
```

```
void f(std::vector<int> &v; int del)
{
    auto it = std::remove( v.begin(), v.end(), del);
    v.erase( it, v.end() );                  // remove elements equal del
}
```

STL traps

```
void f(std::vector<int> &v)
{
    std::unique( v.begin(), v.end(), del);   // remove duplicates ?
}
```

STL traps

```
void f(std::vector<int> &v)
{
    std::unique( v.begin(), v.end(), del);   // remove duplicates ?
}


void f(std::vector<int> &v; int del)
{

    auto it = std::unique( v.begin(), v.end());
    v.erase( it, v.end() );                  // remove duplicates
}
```

STL traps

```
void f(std::vector<int> &v)
{
    std::unique( v.begin(), v.end(), del);   // remove duplicates ?
}


void f(std::vector<int> &v; int del)
{
    std::sort( v.begin(), v.end());           // unique requires sorted input
    auto it = std::unique( v.begin(), v.end());
    v.erase( it, v.end() );                   // remove duplicates
}
```

STL traps

```
bool f(std::map<std::string, int> &m, std::string key)
{
    return m[i] == key ? true : false;   // check whether containes key ?
}
```

STL traps

```
bool f(std::map<std::string, int> &m, std::string key)
{
    return m[i] == key ? true : false;   // check whether containes key ?
}


bool f(std::map<std::string, int> &m, std::string key)
{
    return m.end() != m.find(key) ? true : false;// check whether containes key
}

bool f(std::map<std::string, int> &m, std::string key)
{
    return m.count(key) == 1 ? true : false;  // check whether containes key
}
```

STL traps

```
bool f(std::map<std::string, int> &m, std::string key)
{
    return m[i] == key ? true : false;   // check whether containes key ?
}


bool f(std::map<std::string, int> &m, std::string key)
{
    return m.end() != m.find(key); // check whether containes key
}

bool f(std::map<std::string, int> &m, std::string key)
{
    return m.count(key) == 1;  // check whether containes key
}
```

STL traps

```
bool f(std::map<std::string, int> &m, std::string key)
{
    return m[i] == key ? true : false;   // check whether containes key ?
}


bool f(std::multimap<std::string, int> &m, std::string key)
{
    return m.end() != m.find(key); // check whether containes key
}

bool f(std::multimap<std::string, int> &m, std::string key)
{
    return m.count(key) > 0;  // check whether containes key
}
```

STL traps

```
bool f(std::list<std::string> &lst, std::string key)
{
    for ( auto it = lst.begin(); it != lst.end(); ++it)
    {
        if ( *it == key )
            lst.erase(it);          // erase all elements equal to key ?
    }
}
```

STL traps

```
bool f(std::list<std::string> &lst, std::string key)
{
    for ( auto it = lst.begin(); it != lst.end(); ++it)
    {
        if ( *it == key )
            lst.erase(it);          // erase all elements equal to key ?
    }
}
bool f(std::list<std::string> &lst, std::string key)
{
    for ( auto it = lst.begin(); it != lst.end(); )
    {
        if ( *it == key )
            lst.erase(it++);        // erase all elements equal to key
        else
            ++it;
    }
}
```

STL traps

```
bool f(std::list<std::string> &lst, std::string key)
{
    for ( auto it = lst.begin(); it != lst.end(); ++it)
    {
        if ( *it == key )
            lst.erase(it);          // erase all elements equal to key ?
    }
}
bool f(std::list<std::string> &lst, std::string key)
{
    for ( auto it = lst.begin(); it != lst.end(); )
    {
        if ( *it == key )
            lst.erase(it++);        // erase all elements equal to key
        else
            ++it;
    }
}
bool f(std::list<std::string> &lst, std::string key)
{
    auto it = std::remove(lst.begin(), lst.end(); key);
    lst.erase( it, lst.end() );   // erase all elements equal to key
}
```

STL traps

```
#include <string>
#include <vector>
#include <algorithm>


std::string f(std::vector<std::string> &v1,std::vector<std::string> &v2,int i)
{
    std::vector<std::vector> v3;
    v3.resize( v1.size()+v2.size() );

    std::merge( v1.begin(), v2.end(), v2.begin(), v1.end(), v3.begin());
    return v3.at(i);   // return the i.th lement of the merged vectors
}

$ g++ -Wextra merge.cpp
$ ./a.out
Segmentation fault (core dumped)
```

STL traps

```
#include <string>
#include <vector>
#include <algorithm>


std::string f(std::vector<std::string> &v1,std::vector<std::string> &v2,int i)
{
    std::vector<std::vector> v3;
    v3.resize( v1.size()+v2.size() );

    std::merge( v1.begin(), v2.end(), v2.begin(), v1.end(), v3.begin());
    return v3.at(i);   // return the i.th lement of the merged vectors
}

$ g++ -Wextra merge.cpp
$ ./a.out
Segmentation fault (core dumped)
```

Ranges

- Ranges are representing an iterable sequence
- In form of [first, sentinel]
  - Containers: [first, last)
  - Arrays: [first, size)
  - Streams: [first, predicate) (EOF)
  - Generators: [first, …)
- Range algorithms
  - Applied eagerly
- Range adaptors
  - Applied to views lazily
  - Can be composed

Ranges

```
#include <iostream>
#include <string>
#include <vector>
#include <algorithm>
#include <ranges>

std::string f(std::vector<std::string> &v1,std::vector<std::string> &v2,int i)
{
  std::vector<std::string> v3;
  v3.resize( v1.size()+v2.size() );

  std::ranges::merge( v1, v2, v3.begin());
  return v3.at(i); // return the i.th lement of the merged vectors
}
int main()
{
  std::vector<std::string> v1={"Hello","world"};
  std::vector<std::string> v2={"Hallo","welt"};
  std::cout << f(v1,v2,1);

  return 0;
}
$ g++ -Wextra merge.cpp
$ ./a.out
Hello
```

Ranges

```
#include <iostream>
#include <string>
#include <vector>
#include <algorithm>

int main()
{
  std::vector<std::string> v1={"Hello","world","Hallo","welt"};

  std::sort( v1.begin(), v1.end());

  for ( auto s: v1 )
    std::cout << s << ' ';
  std::cout << '\n';

  return 0;
}

$ g++ -Wextra merge.cpp
$ ./a.out
Hallo Hello welt world
```

Ranges

```
#include <iostream>
#include <string>
#include <vector>
#include <algorithm>

int main()
{
  std::vector<std::string> v1={"Hello","world","Hallo","welt"};

  std::ranges::sort(v1);   //std::sort( v1.begin(), v1.end());

  for ( auto s: v1 | std::views::take(3) )
    std::cout << s << ' ';
  std::cout << '\n';

  return 0;
}

$ g++ -Wextra merge.cpp
$ ./a.out
Hallo Hello welt
```

Ranges

```
#include <iostream>
#include <string>
#include <vector>
#include <algorithm>

int main()
{
  std::vector<std::string> v1={"Hello","world","Hallo","welt"};
  auto len5 = [](std::string s) { return s.length() == 5; };

  std::ranges::sort( v1);

  for ( auto s: v1 | std::views::filter(len5) )
    std::cout << s << ' ';
  std::cout << '\n';

  return 0;
}

$ g++ -Wextra merge.cpp
$ ./a.out
Hallo Hello world
```

Ranges

```
#include <iostream>
#include <string>
#include <vector>
#include <algorithm>

int main()
{
  std::vector<std::string> v1={"Hello","world","Hallo","welt"};
  auto len5 = [](std::string s) { return s.length() == 5; };

  std::ranges::sort( v1);

  for ( auto s: v1 | std::views::drop(1)
                   | std::views::take(3)
                   | std::views::filter(len5) )
    std::cout << s << ' ';
  std::cout << '\n';

  return 0;
}

$ g++ -Wextra merge.cpp
$ ./a.out
Hello world
```

Example: word counter

```
#include <cctype>
#include <iterator>
#include <iostream>
#include <vector>
#include <algorithm>



int main()
{
  std::vector<char> v{};
  std::cin >> std::noskipws;
  std::copy( std::istream_iterator<char>{std::cin},
             std::istream_iterator<char>{}, std::back_inserter(v));
  int  cnt = 0;
  char prev = '\n';  // the imaginary char on -1 position is a white space.

  for ( char curr : v )
  {
    if ( std::isspace(prev) && !std::isspace(curr) )  // new word starts
      ++cnt;
    prev = curr;
  }
  std::cout << cnt << '\n';
}
```

Example: word counter

```
#include <cctype>
#include <iterator>
#include <iostream>
#include <vector>
#include <algorithm>
#include <numeric>


int main()
{
  std::vector<char> v{};
  std::cin >> std::noskipws;
  std::copy( std::istream_iterator<char>{std::cin},
             std::istream_iterator<char>{}, std::back_inserter(v));
  int cnt = 0;
  if ( ! v.empty() )
  {
    cnt = std::transform_reduce(
      std::begin(v), std::end(v)-1, std::begin(v)+1, !std::isspace(v[0])?1:0, std::plus{},
      [](char curr, char next){ return std::isspace(curr) && !std::isspace(next); } );


    std::cout << cnt << '\n';
}
```

Example: word counter

```
#include <cctype>
#include <iterator>
#include <iostream>
#include <vector>
#include <algorithm>
#include <numeric>
#include <execution>

int main()
{
  std::vector<char> v{};
  std::cin >> std::noskipws;
  std::copy( std::istream_iterator<char>{std::cin},
             std::istream_iterator<char>{}, std::back_inserter(v));
  int cnt = 0;
  if ( ! v.empty() )
  {
    cnt = std::transform_reduce( std::execution::par,
      std::begin(v), std::end(v)-1, std::begin(v)+1, !std::isspace(v[0])?1:0, std::plus{},
      [](char curr, char next){ return std::isspace(curr) && !std::isspace(next); } );


    std::cout << cnt << '\n';
}
```

Example: word counter

```
#include <cctype>
#include <iterator>
#include <iostream>
#include <vector>
#include <algorithm>
#include <numeric>
#include <execution>

int main()
{
  std::vector<char> v{};
  std::cin >> std::noskipws;
  std::copy( std::istream_iterator<char>{std::cin},
             std::istream_iterator<char>{}, std::back_inserter(v));
  int cnt = 0;
  if ( ! v.empty() )
  {
    cnt = std::transform_reduce( std::execution::par,
      std::begin(v), std::end(v)-1, std::begin(v)+1, 0, std::plus{},
      [](char curr, char next){ return std::isspace(curr) && !std::isspace(next); } )
      + !std::isspace(v[0]?1:0);

    std::cout << cnt << '\n';
}
```

par_algorithms (C++17)

- Based on Intel's Threading Building Blocks (TBB)
- Extends STL algorithms with execution policy
  - std::execution::seq Sequential execution
  - std::execution::par Parallel execution
  - std::execution::par_unseq Parallel SIMD execution
  - std::execution::unseq Sequential SIMD execution
- These policies are permissions not obligations. Implementation may choose what can be parallelized
- Minimal requirement: forward iterator
- The programmer's task to ensure that element access functions will not cause dead lock or data race
- In case of paralellization and vectorization access must not use any blocking synchronization

Vectorization

```
std::vector<int> v {1,2, ... };

int sum { std::accumulate(v.begin(), v.end(), 0) };


int sum = 0;
for ( size_t i = 0; i < v.size(); ++i)
{
    sum += v[i];
}



int sum = 0;
for ( size_t i = 0; i < v.size() / 4; i+=4)
{
    sum += v[i] + v[i+1] + v[i+2] + v[i+3];   // most CPU supports this
}
// handle if (v.size()/4) is not 0
```

Parallel STL

```
// Example from Stroustrup

template<class T, class V>
struct Accum     // simple accumulator function object
{
    T* b;
    T* e;
    V val;
    Accum(T* bb, T* ee, const V& vv) : b{bb}, e{ee}, val{vv} {}
    V operator() () { return std::accumulate(b,e,val); }
};

double comp(vector<double>& v)   // spawn many tasks if v is large enough
{
    if (v.size()<10000) return std::accumulate(v.begin(),v.end(),0.0);

    auto f0 {async(Accum{&v[0],&v[v.size()/4],0.0})};
    auto f1 {async(Accum{&v[v.size()/4],&v[v.size()/2],0.0})};
    auto f2 {async(Accum{&v[v.size()/2],&v[v.size()*3/4],0.0})};
    auto f3 {async(Accum{&v[v.size()*3/4],&v[v.size()],0.0})};

    return f0.get()+f1.get()+f2.get()+f3.get();
}
```

Parallel STL

```
// Example from cppreference

template<class T, class V>
struct Accum     // simple accumulator function object
{
    T* b;
    T* e;
    V val;
    Accum(T* bb, T* ee, const V& vv) : b{bb}, e{ee}, val{vv} {}
    V operator() () { return std::accumulate(b,e,val); }
};

double comp(vector<double>& v)
{
    // non-deterministic if binary_op is not associative or not commutative
    double res = std::reduce(std::execution::par, v.begin(), v.end(), 0.0);
    return res;
}
```

Dynamic policy

```
std::size_t threshold= ...;  // some value

template <class ForwardIt>
void quicksort(ForwardIt first, ForwardIt last)
{
  if(first == last) return;
  std::size_t distance= std::distance(first,last);
  auto pivot = *std::next(first, distance/2);

  std::parallel::execution_policy exec_pol = std::parallel::par;
  if ( distance < threshold ) exec_pol = std::parallel_execution::seq;

  ForwardIt middle1 = std::partition(exec_pol, first, last,
                      [pivot](const auto& em){ return em < pivot; });
  ForwardIt middle2 = std::partition(exec_pol, middle1, last,
                      [pivot](const auto& em){ return !(pivot < em); });
  quicksort(first, middle1);
  quicksort(middle2, last);
}
```

Algorithms with execution policy

- std::adjacent_difference
- std::adjacent_find
- std::all_of
- std::any_of
- std::copy
- std::copy_if
- std::copy_n
- std::count
- std::count_if
- std::equal
- std::fill
- std::fill_n
- std::find
- std::find_end
- std::find_first_of
- std::find_if
- std::find_if_not
- std::generate
- std::generate_n
- std::includes
- std::inner_product
- std::inplace_merge
- std::is_heap
- std::is_heap_until
- std::is_partitioned
- std::is_sorted
- std::is_sorted_until
- std::lexicographical_compare
- std::max_element
- std::merge
- std::min_element
- std::minmax_element
- std::mismatch
- std::move
- std::none_of
- std::nth_element
- std::partial_sort
- std::partial_sort_copy
- std::partition
- std::partition_copy
- std::remove
- std::remove_copy
- std::remove_copy_if
- std::remove_if
- std::replace
- std::replace_copy
- std::replace_copy_if
- std::replace_if
- std::reverse
- std::reverse_copy
- std::rotate
- std::rotate_copy
- std::search
- std::search_n
- std::set_difference
- std::set_intersection
- std::set_symmetric_difference
- std::set_union
- std::sort
- std::stable_partition
- std::stable_sort
- std::swap_ranges
- std::transform
- std::uninitialized_copy
- std::uninitialized_copy_n
- std::uninitialized_fill
- std::uninitialized_fill_n
- std::unique
- std::unique_copy

… and a few new algorithms

```
std::for_each
std::for_each_n
std::exclusive_scan
std::inclusive_scan
std::transform_exclusive_scan
std::transform_inclusive_scan
std::reduce
std::transform_reduce
```

Protection?

```
int numComp= 0;

std::vector<int> vec={1,3,8,9,10};

std::sort(std::executon::par, vec.begin(), vec.end(),
          [&numComp](int fir, int sec){ numComp++; return fir < sec; });
```

Protection?

```
int numComp= 0;

std::vector<int> vec={1,3,8,9,10};

std::sort(std::parallel::vec, vec.begin(), vec.end(),
          [&numComp](int fir, int sec){ numComp++; return fir < sec; });
```

Race condition == Undefined behavior

Protection?

```
int numComp= 0;

std::vector<int> vec={1,3,8,9,10};

std::sort(std::parallel::vec, vec.begin(), vec.end(),
          [&numComp](int fir, int sec){ numComp++; return fir < sec; });
```

Race condition == Undefined behavior

Also: must not use blocking mutexes

accumulate() vs reduce()

```
#include <iostream>
#include <vector>

int main()
{
  std::vector<long long> v1;
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4}); // creates 50 elements
  }

  long long sum = 0;
  for ( std::size_t i = 0; i < v1.size(); ++i) // summa x^2  x in [0..49]
  {
    sum += v1[i]*v1[i];
  }

  std::cout << sum << '\n';

  return 0;
}


$ ./a.out
300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>


std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});  // creates 50 elements
  }

  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);  // classical STL



  std::cout << sum1 << '\n';
  return 0;
}


$ ./a.out
300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>


std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});  // creates 50 elements
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);  // classical STL



  std::cout << sum1 << '\n';
  return 0;
}


$ ./a.out
300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 10; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << “, “ << sum2 << '\n';
  return 0;
}


$ ./a.out
300, 300
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 1000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << “, “ << sum2 << '\n';
  return 0;
}


$ ./a.out
30000, 30000
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 1000000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << “, “ << sum2 << '\n';
  return 0;
}


$ ./a.out
30000000, 59820950156796
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>

std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };  // not commutative

int main()
{
  for ( int i = 0; i < 1000000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  // reduce can work parallel
  auto sum2 = std::reduce(std::execution::par, v1.begin(), v1.end(), 0LL, sqrsum);

  std::cout << sum1 << “, “ << sum2 << '\n';
  return 0;
}


$ ./a.out
30000000, 59820950156796
```

accumulate() vs reduce()

```
#include <iostream>
#include <numeric>
#include <vector>
#include <execution>
#include <functional>
std::vector<long long> v1;
auto sqrsum = [] (auto s, auto val) { return s + val * val; };

int main()
{
  for ( int i = 0; i < 1000000; ++i)
  {
    v1.insert( v1.end(), {0,1,2,3,4});
  }
  // accumulate is guaranteed left associative
  auto sum1 = std::accumulate(v1.begin(), v1.end(), 0LL, sqrsum);
  auto sum2 = std::transform_reduce(std::execution::par,  // map-reduce
          v1.begin(), v1.end(), 0LL,
          std::plus<>(),
          [](auto v) { return v*v; });
  std::cout << sum1 << “, “ << sum2 << '\n';
  return 0;
}

$ ./a.out
30000000, 30000000
```