# A quick overview of the C++ Standard (Template) Library

## Advanced Programming

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# Outline

# What is the standard library?

The standard library is the set of components specified by the ISO C++ standard ($\sim$ 1600 dense pages for C++17) and shipped with identical behavior (modulo performance) by every C++ implementation.

https://github.com/cplusplus/draft

# The C++ Programming Language

# The header files

| Containers | | |
|---|---|---|
| <vector> | One-dimensional resizable array | §31.4.2 |
| <deque> | Double-ended queue | §31.4.2 |
| <forward_list> | Singly-linked list | §31.4.2 |
| <list> | Doubly-linked list | §31.4.2 |
| <map> | Associative array | §31.4.3 |
| <set> | Set | §31.4.3 |
| <unordered_map> | Hashed associative array | §31.4.3.2 |
| <unordered_set> | Hashed set | §31.4.3.2 |
| <queue> | Queue | §31.5.2 |
| <stack> | Stack | §31.5.1 |
| <array> | One-dimensional fixed-size array | §34.2.1 |
| <bitset> | Array of bool | §34.2.2 |

# The header files

| General Utilities | | |
|---|---|---|
| <utility> | Operators and pairs | §35.5, §34.2.4.1 |
| <tuple> | Tuples | §34.2.4.2 |
| <type_traits> | Type traits | §35.4.1 |
| <typeindex> | Use a type_info as a key or a hash code | §35.5.4 |
| <functional> | Function objects | §33.4 |
| <memory> | Resource management pointers | §34.3 |
| <scoped_allocator> | Scoped allocators | §34.4.4 |
| <ratio> | Compile-time rational arithmetic | §35.3 |
| <chrono> | Time utilities | §35.2 |
| <ctime> | C-style date and time | §43.6 |
| <iterator> | Iterators and iterator support | §33.1 |

# The header files

| Algorithms | | |
|---|---|---|
| <algorithm> | General algorithms | §32.2 |
| <cstdlib> | bsearch(), qsort() | §43.7 |

# The header files

| Diagnostics | | |
|---|---|---|
| <exception> | Exception class | §30.4.1.1 |
| <stdexcept> | Standard exceptions | §30.4.1.1 |
| <cassert> | Assert macro | §30.4.2 |
| <cerrno> | C-style error handling | §13.1.2 |
| <system_error> | System error support | §30.4.3 |

# The header files

| Strings and Characters | | |
|---|---|---|
| <string> | String of T | Chapter 36 |
| <cctype> | Character classification | §36.2.1 |
| <cwctype> | Wide-character classification | §36.2.1 |
| <cstring> | C-style string functions | §43.4 |
| <cwchar> | C-style wide-character string functions | §36.2.1 |
| <cstdlib> | C-style allocation functions | §43.5 |
| <cuchar> | C-style multibyte characters | |
| <regex> | Regular expression matching | Chapter 37 |

# The header files

| Input/Output | | |
|---|---|---|
| **<iosfwd>** | Forward declarations of I/O facilities | §38.1 |
| **<iostream>** | Standard **iostream** objects and operations | §38.1 |
| **<ios>** | **iostream** bases | §38.4.4 |
| **<streambuf>** | Stream buffers | §38.6 |
| **<istream>** | Input stream template | §38.4.1 |
| **<ostream>** | Output stream template | §38.4.2 |
| **<iomanip>** | Manipulators | §38.4.5.2 |
| **<sstream>** | Streams to/from strings | §38.2.2 |
| **<cctype>** | Character classification functions | §36.2.1 |
| **<fstream>** | Streams to/from files | §38.2.1 |
| **<cstdio>** | **printf()** family of I/O | §43.3 |
| **<cwchar>** | **printf()**-style I/O of wide characters | §43.3 |

# The header files

| Localization | | |
|---|---|---|
| <locale> | Represent cultural differences | Chapter 39 |
| <clocale> | Represent cultural differences C-style | |
| <codecvt> | Code conversion facets | §39.4.6 |

# The header files

| Language Support | | |
|---|---|---|
| <limits> | Numeric limits | §40.2 |
| <climits> | C-style numeric scalar-limit macros | §40.2 |
| <cfloat> | C-style numeric floating-point limit macros | §40.2 |
| <cstdint> | Standard integer type names | §43.7 |
| <new> | Dynamic memory management | §11.2.3 |
| <typeinfo> | Run-time type identification support | §22.5 |
| <exception> | Exception-handling support | §30.4.1.1 |
| <initializer_list> | initializer_list | §30.3.1 |
| <cstddef> | C library language support | §10.3.1 |
| <cstdarg> | Variable-length function argument lists | §12.2.4 |
| <csetjmp> | C-style stack unwinding | |
| <cstdlib> | Program termination | §15.4.3 |
| <ctime> | System clock | §43.6 |
| <csignal> | C-style signal handling | |

# The header files

| Numerics | | |
|---|---|---|
| <complex> | Complex numbers and operations | §40.4 |
| <valarray> | Numeric vectors and operations | §40.5 |
| <numeric> | Generalized numeric operations | §40.6 |
| <cmath> | Standard mathematical functions | §40.3 |
| <cstdlib> | C-style random numbers | §40.7 |
| <random> | Random number generators | §40.7 |

# The header files

| Concurrency | | |
|---|---|---|
| <atomic> | Atomic types and operations | §41.3 |
| <condition_variable> | Waiting for an action | §42.3.4 |
| <future> | Asynchronous task | §42.4.4 |
| <mutex> | Mutual exclusion classes | §42.3.1 |
| <thread> | Threads | §42.2 |

# The header files

| C Compatibility | | |
|---|---|---|
| **<cinttypes>** | Aliases for common integer types | §43.7 |
| **<cstdbool>** | C **bool** | |
| **<ccomplex>** | **<complex>** | |
| **<cfenv>** | Floating-point environment | |
| **<cstdalign>** | C alignment | |
| **<ctgmath>** | C "type generic math": **<complex>** and **<cmath>** | |

# The header files

| Library Supported Language Features | | |
|---|---|---|
| <new> | new and delete | §11.2 |
| <typeinfo> | typeid() and type_info | §22.5 |
| <iterator> | Range-for | §30.3.2 |
| <initializer_list> | initializer_list | §30.3.1 |

# We will focus on the STL ☺

Stepanov: inventor of the Standard Template Library in 1992

# We will not see the concurrency library ☹

```
int main(){
  // f and g are independent
  f();
  g();
}
```

# We will not see the concurrency library ☹

```
#include <thread>

int main(){
  // f and g are independent
  std::thread t{ f };
  g();
  t.join();
}
```

# We will not see the concurrency library ☹

```
#include <future>

int main(){
  // f and g are independent
  auto from_f = std::async( f );
  auto from_g = g();
  ...
  complicated( from_g, from_f.get() );
}
```

# We will not see the concurrency library ☹

## Link against `pthread`

```
$ c++ test.cpp -pthread
```

```
$ c++ test.cpp -c
$ c++ test.o -pthread
```

# Containers

## Definition

A container holds a sequence of objects

## Two categories

- Sequence containers: provide access to sequences of elements
- Associative containers: provide associative lookup based on a key

## Associative containers

- Ordered
- Unordered

# Sequence containers

| Sequence Containers | |
|---|---|
| vector<T,A> | A contiguously allocated sequence of Ts; the default choice of container |
| list<T,A> | A doubly-linked list of T; use when you need to insert and delete elements without moving existing elements |
| forward_list<T,A> | A singly-linked list of T; ideal for empty and very short sequences |
| deque<T,A> | A double-ended queue of T; a cross between a vector and a list; slower than one or the other for most uses |

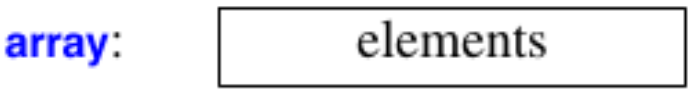
# Ordered associative containers

| Ordered Associative Containers (§iso.23.4.2)<br>C is the type of the comparison; A is the allocator type | |
|---|---|
| map<K,V,C,A> | An ordered map from K to V; a sequence of (K,V) pairs |
| multimap<K,V,C,A> | An ordered map from K to V; duplicate keys allowed |
| set<K,C,A> | An ordered set of K |
| multiset<K,C,A> | An ordered set of K; duplicate keys allowed |

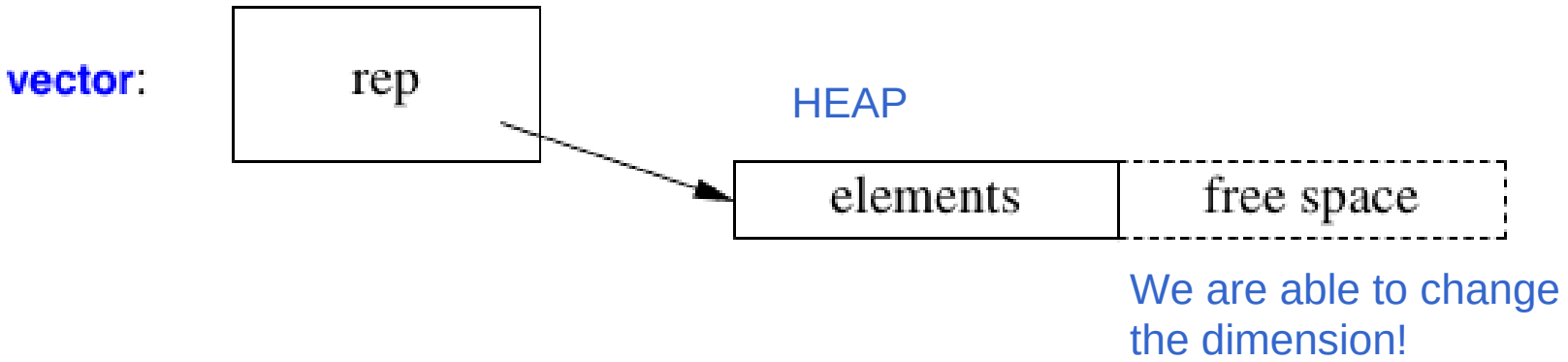
# Unordered associative containers

| Unordered Associative Containers (§iso.23.5.2)<br>H is the hash function type; E is the equality test; A is the allocator type | |
|---|---|
| unordered_map<K,V,H,E,A> | An unordered map from K to V |
| unordered_multimap<K,V,H,E,A> | An unordered map from K to V; duplicate keys allowed |
| unordered_set<K,H,E,A> | An unordered set of K |
| unordered_multiset<K,H,E,A> | An unordered set of K; duplicate keys allowed |

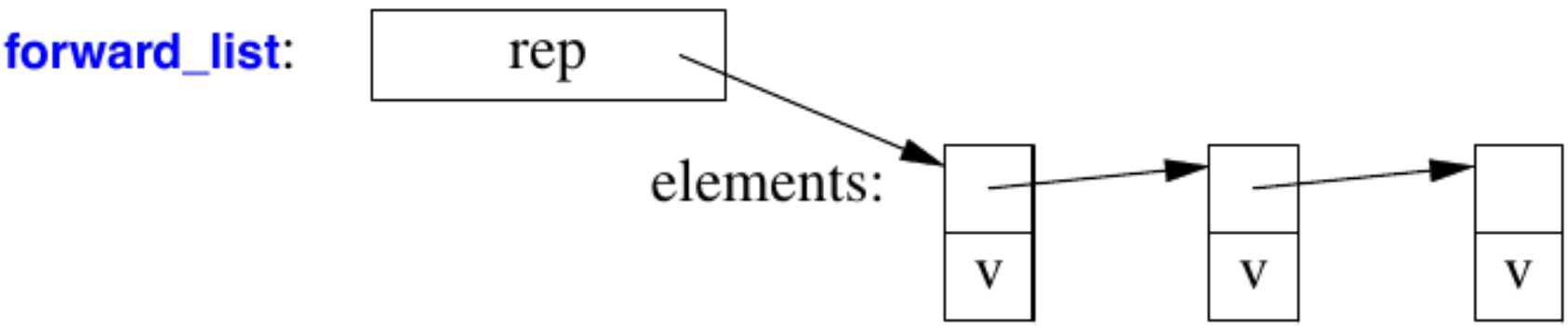
# Array



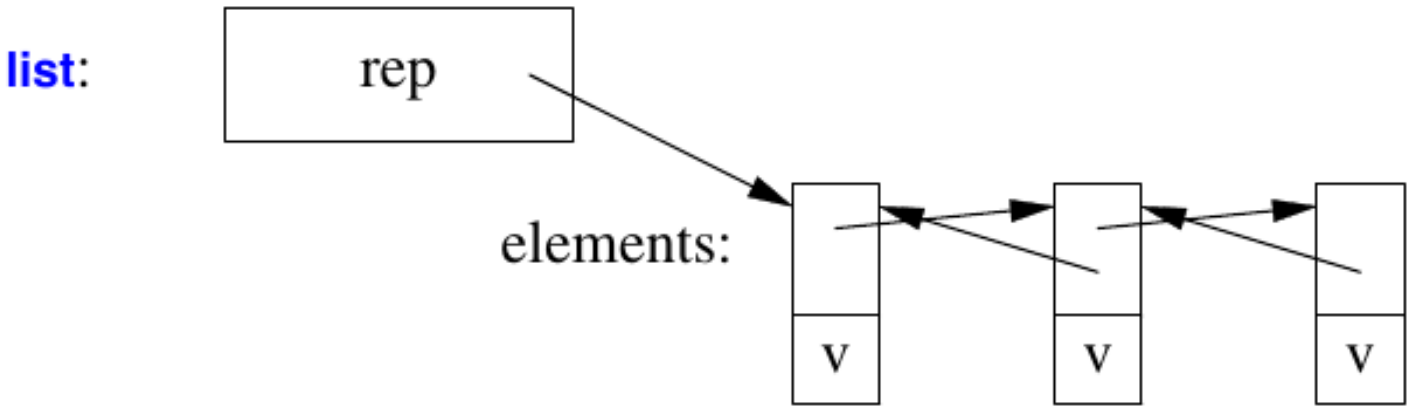
# Vector


vector:
rep
HEAP
elements
free space
We are able to change
the dimension!

# Forward list

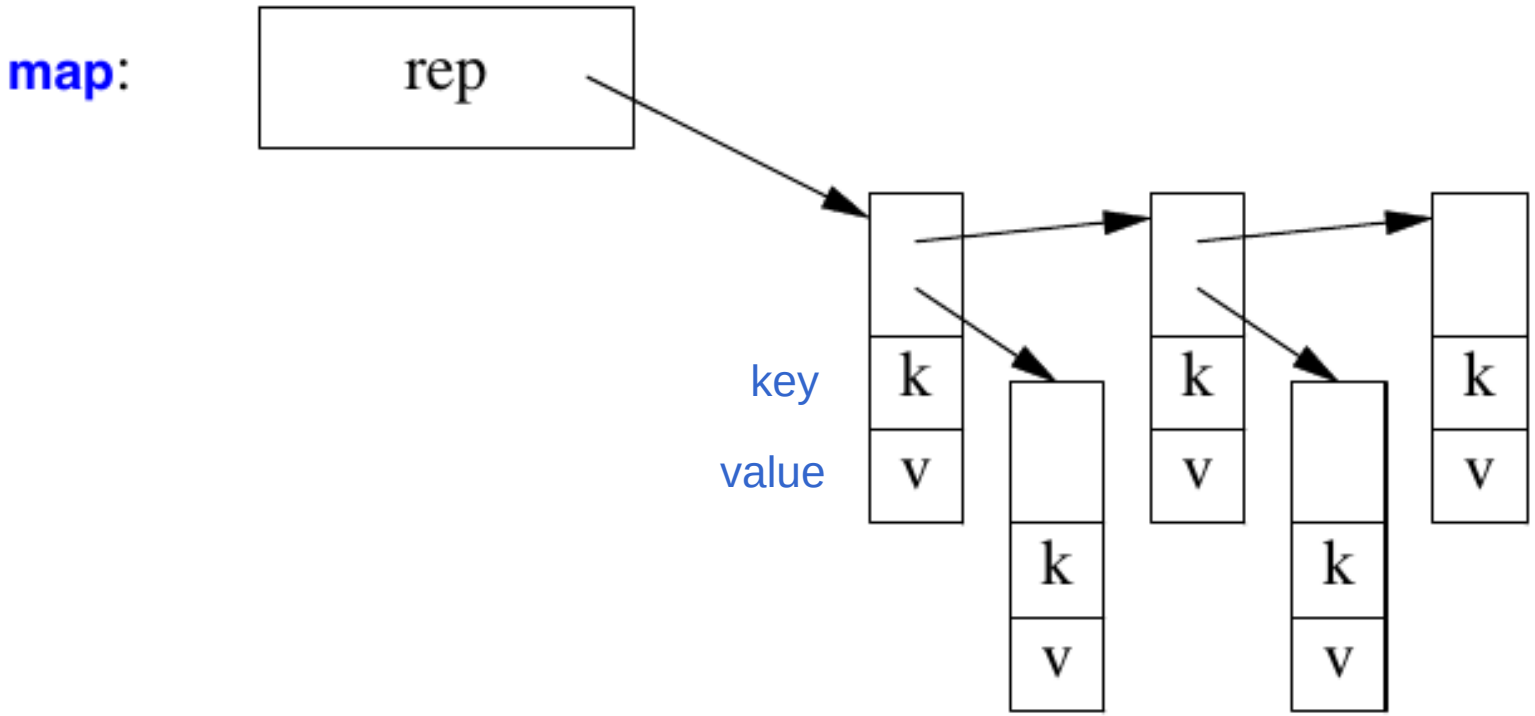


# List



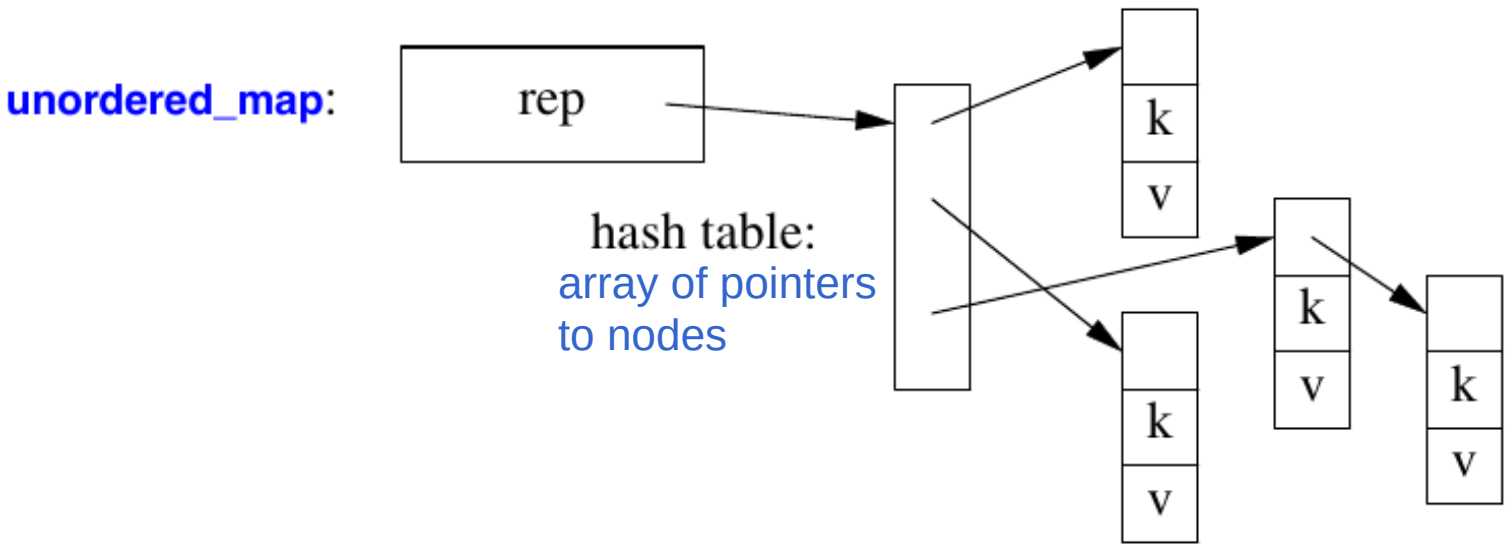
# Map

binary tree: red-balck tree

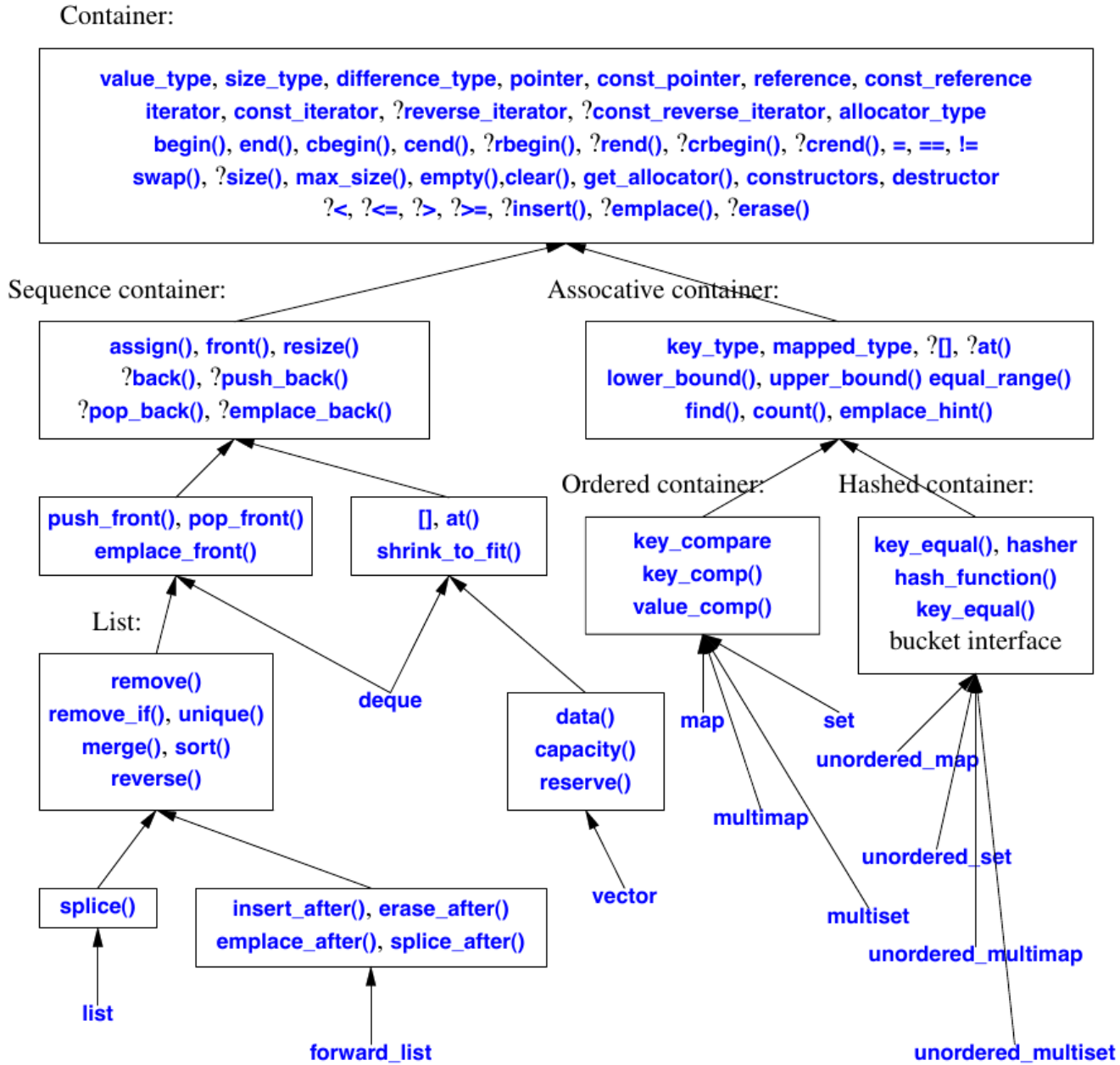



Is ordered by the key! The lower keys are on the left and the bigger keys are on the right

# Unordered map



# Operations and types



# Operation complexity

| Standard Container Operation Complexity | | | | | |
|---|---|---|---|---|---|
| | [] §31.2.2 | List §31.3.7 | Front §31.4.2 | Back §31.3.6 | Iterators §33.1.2 |
| **vector** | const | O(n)+ | | const+ | Ran |
| **list** | | const | const | const | Bi |
| **forward_list** | | const | const | | For |
| **deque** | const | O(n) | const | const | Ran |
| **stack** | | | | const | |
| **queue** | | | const | const | |
| **priority_queue** | | | O(log(n)) | O(log(n)) | |
| **map** | O(log(n)) | O(log(n))+ | | | Bi |
| **multimap** | | O(log(n))+ | | | Bi |
| **set** | | O(log(n))+ | | | Bi |
| **multiset** | | O(log(n))+ | | | Bi |
| **unordered_map** | const+ | const+ | | | For |
| **unordered_multimap** | | const+ | | | For |
| **unordered_set** | | const+ | | | For |
| **unordered_multiset** | | const+ | | | For |
| **string** | const | O(n)+ | O(n)+ | const+ | Ran |
| **array** | const | | | | Ran |
| built-in array | const | | | | Ran |
| **valarray** | const | | | | Ran |
| **bitset** | const | | | | |

log(n) in this world is always less than 64 -> 2^64 is a really big number!

# Prime numbers

```
#include <vector>

int main(){
  std::vector<int> primes;

  primes.emplace_back(2);

  for (int i=3; i<=max; ++i)
    if (is_prime(i))
      primes.emplace_back(i);

  for (const auto& x: primes)
    std::cout << x << std::endl;
}
```

# Word count

```
#include <map>

int main(){
  std::map<std::string, int> words;

  for (std::string s; std::cin>>s;)
    ++words[s];

  for (const auto& x: words)
  std::cout << x.first << ": "
            << x.second << std::endl;
}
```

# Word count

```
#include <unordered_map>

int main(){
  std::unordered_map<std::string, int> words;

  for (std::string s; std::cin>>s;)
    ++words[s];

  for (const auto& x: words)
  std::cout << x.first << ": "
            << x.second << std::endl;
}
```

# What is an Iterator?

## Design pattern [GoF]

Provide a way to access the elements of an aggregate object sequentially without exposing its underlying representation.

Unified operator!

## Stepanov

Iterator is a coordinate.

## A generalization of a pointer

- indirect access (`operator*()`, `operator->()`)
- operations for moving to point to a new element (`operator++()`, `operator--()`)

# Iterators in the STL

## Their role

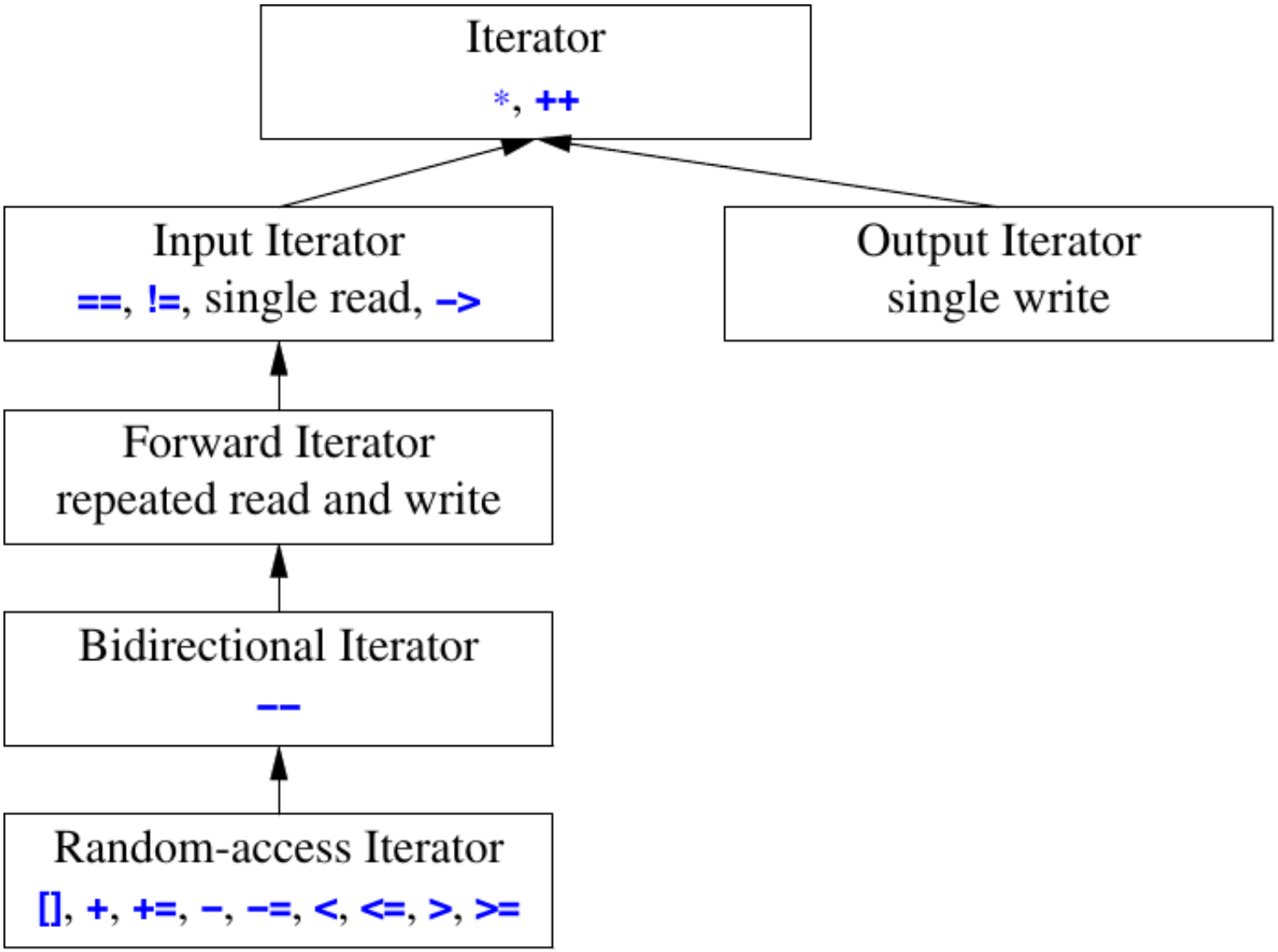
- Iterators are the glue that ties the standard-library alogorithms to their data
- Iterators are the mechanism used to minimize an algorithm's dependence on the data structures on which it operates.

## Alex Stepanov

The reason that STL containers and algorithms work so well together is that they know nothing of each other.

```
while( first != last )
```

# Iterator categories



# How to implement our own iterator?

```
template <typename T>
class List<T>::Iterator {
   ...
};
```

# How to implement our own iterator?

```
#include <iterator>
...
template <typename T>
class List<T>::Iterator{
  typename List<T>::Node current;
  public:
  using value_type = T;
  using difference_type = std::ptrdiff_t;
  using iterator_type =
    std::forward_iterator_tag;
  using reference = value_type&;
  using pointer = value_type*;
  ...
```

You don't have to say this is an Iterator class, it acts as an iterator and that's enough!

input iterator, randm access iterator, ecc...

# How to implement our own iterator?

```
    ...
    reference operator*() {
      return current->value; }
    pointer operator->() { return &**this; }
    Iterator& operator++() {
      current = current->next;
      return *this;
    }
    friend
    bool operator==(const Iterator&, const
       Iterator&);
    friend
    bool operator!=(const Iterator&, const
       Iterator&);
};
```

# STL algorithms

- about 80 algorithms in `<algorithm> and <numeric>`
- operate on *sequences*
  - pair of iterators for inputs $[b : e)$
  - single iterator for output $[b2 : b2 + (e - b))$
- can take functions or function objects
- report failure (e.g. not found) by returning the end of the sequence

# Examples

## Sequences

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

int main(){
   std::vector<double> v1;
   ...
   std::vector<double> v2(v1.size());
   std::sort(v1.begin(), v1.end());
   std::copy(v1.begin(), v1.end(), v2.begin());
}
```

# Examples

## Sequences

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

int main(){
   std::vector<double> v1;
   ...
   double sum{0};
   sum = std::accumulate(v1.begin(),v1.end(),sum);
}
```

# Examples

## User-defined functions

I have a series of detectors and I want to sum their vaules without the ones that doesn't work (they give always the value 2.2)

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

double my_f(const double& a, const double& b){
 if(std::abs(b - 2.2) < 1e-12)
  return a;
 return a+b;
}
int main(){
 std::vector<double> v1;
 ...
 double sum{0};
 sum = std::accumulate(first,last,sum,my_f);
}
```

# Examples

## Lambda functions

```
#include <numeric>
#include <vector>
int main(){
 std::vector<double> v1;
 ...
 auto my_f = [](const double& a, const double &b)
      -> double {
   return ( (std::abs(b-2.2) < 1e-12) ? a : a+b);
 };
 double sum{0};
 sum = std::accumulate(first,last,sum,my_f);
}
```

# Examples

## Generic lambdas (since C++14)

```
#include <numeric>
#include <vector>
int main(){
 std::vector<double> v1;
 ...
 auto my_f = [](const auto& a, const auto& b) {
   return ( (std::abs(b-2.2) < 1e-12) ? a : a+b);
 };
 double sum{0};
 sum = std::accumulate(first,last,sum,my_f);
}
```

# Examples

## Failure check

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

int main(){
   std::vector<double> v1;
   ...
   auto it = std::find(v1.begin(), v1.end(), 2.2);
     2.2 is present in this sequence?

   if(it != v1.end())
      std::cout << "found " << *it << std::endl;
   else
      std::cout << "not found\n";
}
```

# Function objects

calsses that has defined the call operator

- defined in `<functional>`
- comparison criteria
- predicates (functions returning `bool`)
- arithmetic operations

# Predicates

| Predicates (§iso.20.8.5, §iso.20.8.6, §iso.20.8.7) | |
|---|---|
| p=equal_to<T>(x,y) | p(x,y) means x==y when x and y are of type T |
| p=not_equal_to<T>(x,y) | p(x,y) means x!=y when x and y are of type T |
| p=greater<T>(x,y) | p(x,y) means x>y when x and y are of type T |
| p=less<T>(x,y) | p(x,y) means x<y when x and y are of type T |
| p=greater_equal<T>(x,y) | p(x,y) means x>=y when x and y are of type T |
| p=less_equal<T>(x,y) | p(x,y) means x<=y when x and y are of type T |
| p=logical_and<T>(x,y) | p(x,y) means x&&y when x and y are of type T |
| p=logical_or<T>(x,y) | p(x,y) means x\|\|y when x and y are of type T |
| p=logical_not<T>(x) | p(x) means !x when x is of type T |
| p=bit_and<T>(x,y) | p(x,y) means x&y when x and y are of type T |
| p=bit_or<T>(x,y) | p(x,y) means x\|y when x and y are of type T |
| p=bit_xor<T>(x,y) | p(x,y) means x^y when x and y are of type T |

# Arithmetic operations

| Arithmetic Operations (§iso.20.8.4) | |
|---|---|
| f=plus<T>(x,y) | f(x,y) means x+y when x and y are of type T |
| f=minus<T>(x,y) | f(x,y) means x–y when x and y are of type T |
| f=multiplies<T>(x,y) | f(x,y) means x∗y when x and y are of type T |
| f=divides<T>(x,y) | f(x,y) means x/y when x and y are of type T |
| f=modulus<T>(x,y) | f(x,y) means x%y when x and y are of type T |
| f=negate<T>(x) | f(x) means –x when x is of type T |

# Decreasing sort

```
#include <algorithm>
#include <vector>
#include <functional>

int main(){
   std::vector<double> v1;
   ...
   std::sort(v1.begin(), v1.end(),
             std::greater<double>{});
}
```

# My comparison

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

template <typename num>
struct my_comparison{
  bool operator()(const num& a, const num& b) {
     return a > b;}
};

int main(){
  std::vector<double> v1;
  ...
  std::sort(v1.begin(), v1.end(),
            my_comparison<double>{});
}
```

# Lambda

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

template <typename num>
struct my_comparison{
   bool operator()(const num& a, const num& b) {
      return a > b;}
};
int main(){
   std::vector<double> v1;
   ...
   std::sort(v1.begin(), v1.end(),
             [](const auto& a, const auto& b)
                { return a>b; } );
}
```

Sustroup and Stepanov