STL Algorithms
Principles and Practice

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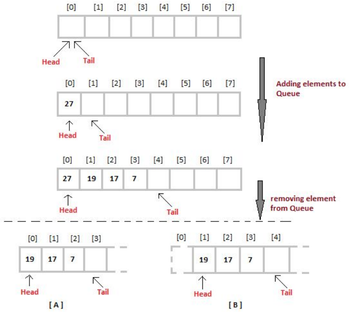
March 2019

Agenda

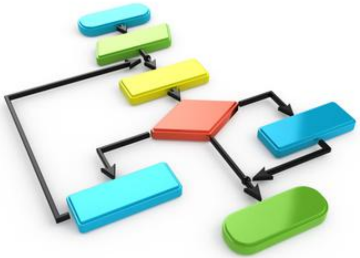
Part 0: STL Background

Part 1: Containers and Iterators



Part 2: STL Function Objects and Utilities

Part 3-4: STL Algorithms Principles and Practice



Introduction to Algorithms

Thomas H. Cormen
Charles E. Leiserson
Ronald L. Rivest
Clifford Stein

March, 1990

A classic, priceless book, nearly 30 years after publication.

We have some books for you, now...

Generic Programming Drawbacks

- abstraction penalty
- implementation in the interface
- early binding
- horrible error messages (*no formal specification* of interfaces, **yet**)
- duck typing
- algorithm could work on some data types, but fail to work/compile on some other new data structures (different iterator category, no copy semantics, etc)

We need to fully specify **requirements** on algorithm types => `Concepts`

Named Requirements

Some examples from **STL**:

- `DefaultConstructible`, `MoveConstructible`, `CopyConstructible`
- `MoveAssignable`, `CopyAssignable`,
- `Destructible`
- `EqualityComparable`, `LessThanComparable`
- `Predicate`, `BinaryPredicate`
- `Compare`
- `FunctionObject`
- `Container`, `SequenceContainer`, `ContiguousContainer`, `AssociativeContainer`
- `Iterator`
    - `InputIterator`, `OutputIterator`
    - `ForwardIterator`, `BidirectionalIterator`, `RandomAccessIterator`

https://en.cppreference.com/w/cpp/named_req

Named Requirements

Named requirements are used in the normative text of the C++ standard to define the expectations of the standard library.

Some of these requirements are being formalized in **C++20** using **`concepts`**.

Until then, the burden is on the programmer to ensure that library templates are instantiated with template arguments that satisfy these requirements.

https://en.cppreference.com/w/cpp/named_req

C++20

What Is A `Concept`, Anyway ?

Formal specification of concepts makes it possible to **verify** that template arguments satisfy the expectations of a template or function during overload resolution and template specialization (requirements).

Each concept is a **predicate**, evaluated at *compile time*, and becomes a part of the interface of a template where it is used as a constraint.

https://en.cppreference.com/w/cpp/language/constraints

What's the Practical Upside ?

If I'm not a library writer □,
Why Do I Care ?

C++20

What's the Practical Upside ?

Using STL algorithms & data structures

Designing & exposing your own vocabulary types
(interfaces, APIs)

Compare Concept

Why is this one special ?
Because ~50 STL facilities (algorithms & data structures) expect a *Compare* type.

```
template< class RandomIt, class Compare >
void sort( RandomIt first, RandomIt last, Compare comp );
```

Concept relations:

Compare << *BinaryPredicate* << *Predicate* << *FunctionObject* << *Callable*

Compare Concept

What are the requirements for a `Compare` type ?

Compare << *BinaryPredicate* << *Predicate* << *FunctionObject* << *Callable*

```
bool comp(*iter1, *iter2);
```

But what kind of **ordering** relationship is needed for the ***elements*** of the collection ?

https://en.cppreference.com/w/cpp/named_req/Compare

Compare Concept

But what kind of ***ordering*** relationship is needed □

Irreflexivity	∀ a, **comp**(a,a)==**false**
Antisymmetry	∀ a, b, **if** **comp**(a,b)==**true** **=>** **comp**(b,a)==**false**
Transitivity	∀ a, b, c, **if** **comp**(a,b)==**true** **and** **comp**(b,c)==**true** **=>** **comp**(a,c)==**true**

https://en.wikipedia.org/wiki/Partially_ordered_set

{ partial ordering }

Compare Examples

```
vector<string> v = { ... };

sort(v.begin(), v.end());

sort(v.begin(), v.end(), less<>());

sort(v.begin(), v.end(), [](const string & s1, const string & s2)
{
  return s1 < s2;
});

sort(v.begin(), v.end(), [](const string & s1, const string & s2)
{
  return stricmp(s1.c_str(), s2.c_str()) < 0;
});
```

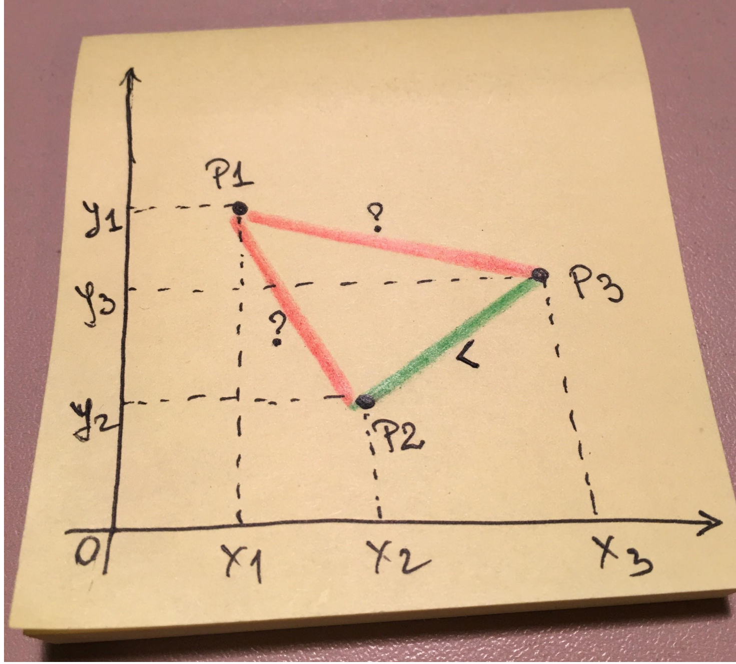
Compare Examples

```
struct Point { int x; int y; };
vector<Point> v = { ... };

sort(v.begin(), v.end(), [](const Point & p1, const Point & p2)
{
  return (p1.x < p2.x) && (p1.y < p2.y);
});
```

Is this a good *Compare* predicate for 2D points ?

Compare Examples



Definition:

```
if comp(a,b)==false && comp(b,a)==false
```

=> **a** and **b** are **equivalent**

```
Let { P1, P2, P3 }
x1 < x2; y1 > y2;
x1 < x3; y1 > y3;
x2 < x3; y2 < y3;
```

=>

```
P2 and P1 are unordered (P2 ?P1) comp(P2,P1)==false && comp(P1,P2)==false
P1 and P3 are unordered (P1 ?P3) comp(P1,P3)==false && comp(P3,P1)==false
P2 and P3 are ordered   (P2 <P3) comp(P2,P3)==true  && comp(P3,P2)==false
```

=>

```
P2 is equivalent to P1
P1 is equivalent to P3
P2 is less than P3
```

`Compare` Concept

Partial ordering relationship is not enough :(

`Compare` needs a **stronger** constraint

Strict weak ordering = ***Partial ordering*** + **Transitivity of Equivalence**

where:

```
equiv(a,b) : comp(a,b)==false && comp(b,a)==false
```

Strict weak ordering

Partial ordering relationship: *Irreflexivity* + *Antisymmetry* + *Transitivity*

Strict weak ordering relationship: ***Partial ordering*** + *Transitivity of Equivalence*

Total ordering relationship: ***Strict weak ordering*** + **equivalence** must be the same as **equality**

Irreflexivity	`∀ a,     comp(a,a)==false`
Antisymmetry	`∀ a, b, if comp(a,b)==true => comp(b,a)==false`
Transitivity	`∀ a, b, c, if comp(a,b)==true and comp(b,c)==true => comp(a,c)==true`
Transitivity of equivalence	`∀ a, b, c, if equiv(a,b)==true and equiv(b,c)==true => equiv(a,c)==true`

where:

```
equiv(a,b) : comp(a,b)==false && comp(b,a)==false
```

https://en.wikipedia.org/wiki/Weak_ordering#Strict_weak_orderings

Compare Examples

```
struct Point { int x; int y; };
vector<Point> v = { ... };

sort(v.begin(), v.end(), [](const Point & p1, const Point & p2)
{
  return (p1.x * p1.x + p1.y * p1.y) <
         (p2.x * p2.x + p2.y * p2.y);
});
```

Is this a good Compare predicate for 2D points ?

Compare Examples

```
struct Point { int x; int y; };
vector<Point> v = { ... };

sort(v.begin(), v.end(), [](const Point & p1, const Point & p2)
{
  if (p1.x < p2.x) return true;
  if (p2.x < p1.x) return false;

  return p1.y < p2.y;
});
```

Is this a good Compare predicate for 2D points ?

Compare Examples

The general idea is to pick an **order** in which to compare ***elements/parts*** of the object.
(in our example we first compared by **x** coordinate, and then by **y** coordinate for equivalent **x**)

This strategy is analogous to how a **dictionary** works, so it is often called *"dictionary order"*, or *“lexicographical order”*.

The STL implements dictionary ordering in at least three places:

std::pair<T, U> - defines the six comparison operators in terms of the corresponding operators of the pair's components

std::tuple< ... Types> - generalization of pair

std::lexicographical_compare() algorithm

- Two ranges are compared element by element
- The first mismatching element defines which range is lexicographically *less* or *greater* than the other
- ...

STL Algorithms - Principles and Practice

“Show me the code”

A common task...

Remove elements matching a predicate.

Given:

```
std::vector<int> v = { 1, 2, 3, 4, 5, 6, 7 };
```

How do we remove all **even** numbers ?

A common task...

Remove elements matching a predicate.

https://en.cppreference.com/w/cpp/container/vector/erase

```
iterator vector::erase(const_iterator first, const_iterator last);
```

https://en.cppreference.com/w/cpp/algorithm/remove

```
template< class ForwardIt, class UnaryPredicate >
ForwardIt std::remove_if(ForwardIt first, ForwardIt last, UnaryPredicate p);
```

Erase-Remove Idiom

```
std::vector<int> v = { 1, 2, 3, 4, 5, 6, 7 };

v.erase( std::remove_if(v.begin(), v.end(),
                        [] (int i) { return (i & 1) == 0; }),
         v.end() );
```

How do you think this works ?

"remove_if() moves all the elements you want to remove to the **end** of the vector, then the erase gets rid of them."

```
v = { 1, 3, 5, 7, 2, 4, 6 }
```

WRONG !

Erase-Remove Idiom

```
std::vector<int> v = { 1, 2, 3, 4, 5, 6, 7 };

v.erase( std::remove_if(v.begin(), v.end(),
                        [] (int i) { return (i & 1) == 0; }),
         v.end() );
```

This **isn't** what `std::remove_if()` does !

If it did that – which is ***more work*** than it does – it would in fact be `std::partition()`.

What `std::remove()` does is move the elements that **won't** be removed **to the beginning**.

Erase-Remove Idiom

```
std::vector<int> v = { 1, 2, 3, 4, 5, 6, 7 };

v.erase( std::remove_if(v.begin(), v.end(),
                        [] (int i) { return (i & 1) == 0; }),
         v.end() );
```

What about the elements at the **end** of the vector ?

GARBAGE !

They get *overwritten* in the process of `std::remove()` algorithm.

Before `erase()` is called: `v = { 1, 3, 5, 7, 5, 6, 7 }`

`where the iterator` **`returned`** `by remove_if() points`

Prefer Member Functions To Similarly Named Algorithms

The following member functions are available for ***associative containers***:

- `.count()`
- `.find()`
- `.equal_range()`
- `.lower_bound() // only for ordered containers`
- `.upper_bound() // only for ordered containers`

The following member functions are available for **`std::list`**

- `.remove()`   `.remove_if()`
- `.unique()`
- `.sort()`
- `.merge()`
- `.reverse()`

These member functions are always **faster** than their similarly named generic algorithms.

Why? They can leverage the ***implementation details*** of the underlying data structure.

Prefer Member Functions To Similarly Named Algorithms

std::list<> specific algorithms

`std::sort()` doesn't work on lists (Why ?)
=> call `.sort()` member function

`.remove()` and `.remove_if()` don't need to use the **erase/remove idiom**.
They directly remove matching elements from the list.

`.remove()` and `.remove_if()` are more efficient than the generic algorithms,
because they just relink nodes with the need to copy or move elements.

Prefer Member Functions To Similarly Named Algorithms

```
std::set<string> s = {...}; // 1 million elements

// worst case: 1 million comparisons
// average:    ½ million comparisons
auto it = std::find(s.begin(), s.end(), “stl”);
if (it != s.end()) {...}


// worst case: 40 comparisons
// average:    20 comparisons
auto it = s.find(“stl”);
if (it != s.end()) {...}
```

Why ?

Don’t Trust Your Intuition: Always Benchmark !

```
static void StdFind(benchmark::State & state)
{
  std::set<std::string> items;
  for (int i = COUNT_ELEM; i >= 0; --i)
    items.insert("string #" + std::to_string(i));

  // Code before the loop is not measured
  for (auto _ : state)
  {
    auto it = std::find(items.begin(), items.end(), "STL");
    if (it != items.end())
      std::cout << "Found: " << *it << std::endl;

  }
}

BENCHMARK(StdFind);
```

```
static void SetFind(benchmark::State & state)
{
  std::set<std::string> items;
  for (int i = COUNT_ELEM; i >= 0; --i)
    items.insert("string #" + std::to_string(i));

  // Code before the loop is not measured
  for (auto _ : state)
  {
    auto it = items.find("STL");
    if (it != items.end())
      std::cout << "Found: " << *it << std::endl;
  }
}

BENCHMARK(SetFind);
```

http://quick-bench.com

Try increasing values for `COUNT_ELEM` : `500` >>> `500’000` >>> ...

Don’t Trust Your Intuition: Always Benchmark !

```
static void ListFind(benchmark::State & state)
{
  std::list<std::string> items;
  for (int i = COUNT_ELEM; i >= 0; --i)
    items.push_back("string #" + std::to_string(i));

  // Code before the loop is not measured
  for (auto _ : state)
  {
    auto it = std::find(items.begin(), items.end(), "STL");
    if (it != items.end())
      std::cout << "Found: " << *it << std::endl;

  }
}

BENCHMARK(ListFind);
```

```
static void VectorFind(benchmark::State & state)
{
  std::vector<std::string> items;
  for (int i = COUNT_ELEM; i >= 0; --i)
    items.push_back("string #" + std::to_string(i));

  // Code before the loop is not measured
  for (auto _ : state)
  {
    auto it = std::find(items.begin(), items.end(), "STL");
    if (it != items.end())
      std::cout << "Found: " << *it << std::endl;
  }
}

BENCHMARK(VectorFind);
```

http://quick-bench.com

Try increasing values for `COUNT_ELEM` : `500` >>> `500’000` >>> ...

Binary search operations (on *sorted* ranges)

```
binary_search() // helper (incomplete interface - Why ?)
lower_bound()   // returns an iter to the first element not less than the given value
upper_bound()   // returns an iter to the first element greater than the certain value

equal_range() = { lower_bound(), upper_bound() }

// properly checking return value
auto it = lower_bound(v.begin(), v.end(), 5);
if ( it != v.end() && (*it == 5) )
{
  // found item, do something with it
}
else // not found, insert item at the correct position
{
  v.insert(it, 5);
}
```

*Why do we need to check the **value** we searched for ?*

Binary search operations (on *sorted* ranges)

Counting elements equal to a given value

```
vector<string> v = { … }; // sorted collection
size_t num_items = std::count(v.begin(), v.end(), “stl”);
```

Instead of using **`std::count()`** generic algorithm, use **binary search** instead.

```
auto range = std::equal_range(v.begin(), v.end(), “stl”);
size_t num_items = std::distance(range.first, range.second);
```

Extend STL With Your Generic Algorithms

Eg.

```
template<class Container, class Value>
bool name_this_algorithm(Container & c, const Value & v)
{
  return std::find(begin(c), end(c), v) != end(c);
}
```

Extend STL With Your Generic Algorithms

Eg.

```
template<class Container, class Value>
void name_this_algorithm(Container & c, const Value & v)
{
  if ( std::find(begin(c), end(c), v) == end(c) )
    c.emplace_back(v);
}
```

Extend STL With Your Generic Algorithms

Eg.

```
template<class Container, class Value>
bool name_this_algorithm(Container & c, const Value & v)
{
  auto found = std::find(begin(c), end(c), v);
  if (found != end(v))
  {
    c.erase(found); // call 'erase' from STL container
    return true;
  }
  return false;
}
```

Consider Adding Range-based Versions of STL Algorithms

```
namespace range {   // our <algorithm_range.h> has ~150 wrappers for std algorithms

  template< class InputRange, class T > inline
  typename auto find(InputRange && range, const T & value)
  {
    return std::find(begin(range), end(range), value);
  }

  template< class InputRange, class UnaryPredicate > inline
  typename auto find_if(InputRange && range, UnaryPredicate pred)
  {
    return std::find_if(begin(range), end(range), pred);
  }

  template< class RandomAccessRange, class BinaryPredicate > inline
  void sort(RandomAccessRange && range, BinaryPredicate comp)
  {
    std::sort(begin(range), end(range), comp);
  }

}
```

Until C++20

Consider Adding Range-based Versions of STL Algorithms

Eg.

```
vector<string> v = { … };

auto it = range::find(v, "stl");
string str = *it;

auto chIt = range::find(str, 't');

auto it2 = range::find_if(v, [](const auto & val) { return val.size() > 5; });

range::sort(v);

range::sort(v, [](const auto & val1, const auto & val2)
               { return val1.size() < val2.size(); } );
```

Until C++20

Student solutions for Homeworks

NONE :(

You can still send us your solutions until March, 27

Email solutions to gabriel.diaconita@caphyon.com

Fun with STL algorithms: What does it print ?

Homework

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

#define 🚗  const auto
#define 🤹  std::accumulate
#define 🔢  std::sort
#define 🏳️  empty()
#define 📏  size()
#define 👉  begin()
#define 👈  end()
#define 🔱  []

using 📜 = std::string;
template<typename T>
using 💰 = std::vector<T>;
```

```cpp
🚗 🛠️ = "algorithms";
🚗 🔗 = " ";
🚗 💔 = "really love";
🚗 🎶 = "!";

🚗 🏹(💰<📜> & 📦)
{
    🔢(📦.👉, 📦.👈, 🔱(🚗 & 💚, 🚗 & 💜)
    {
        return 💚.📏 < 💜.📏;
    });

    return 🤹(📦.👉, 📦.👈, 📜(),
                🔱(🚗 & 🤓🤓, 🚗 & 🙄)
                {
                    return (🤓🤓.🏳️ ? 🙄 : (🤓🤓 + 🔗)) + 🙄;
                });
}

int main()
{
    💰<📜> 😃😃😃 = { 🛠️, 💔, 🎶 };
    std::cout << 🏹(😃😃😃) << std::endl;
    return 0;
}
```

Homework

Server Nodes

We have a huge network of server nodes.
Each server node contains a copy of a particular ***data*** `Value` (not necessarily unique).

`class Value` is a ***Regular*** type.

{ Assignable + Constructible + EqualityComparable + LessThanComparable }

The network is constructed in such a way that the nodes are ***sorted ascending*** with respect to their `Value` but their sequence might be **rotated** (left) by some offset.

Eg.

For the ***ordered*** node values:
`{ A, B, C, D, E, F, G, H }`

The **actual network** configuration might look like:
`{ D, E, F, G, H, A, B, C }`

Email solutions to gabriel.diaconita@caphyon.com

Homework

Server Nodes

The network exposes the following APIs:

```
// gives the total number of nodes -  O(1)
size_t Count() const;

// retrieves the data from a given node -  O(1)
const Value & GetData(size_t index) const;

// iterator interface for the network nodes
vector<Value>::const_iterator BeginNodes() const;
vector<Value>::const_iterator EndNodes() const;
```

☞Implement a new API for the network, that efficiently finds a server node (address) containing a given data `Value`.

```
size_t GetNode(const Value & data) const
{
   // implement this
}
```

STL for Competitive Programming and Software Development

Coding Test

- Test CAPHYON (March 27, 5:30pm)
- Test NETROM (April 3rd, 5:30pm)
- max 3h
- open-books, internet
- bring your laptop
- your assigned homeworks will help prepare you for this

Demo: Time for coding fun!

Solve these two `Advent of Code` challenges, using constructs presented in this course (STL data structures, algorithms, lambda functions, range-for, etc):

https://adventofcode.com/2018/day/9 EASY

https://adventofcode.com/2018/day/13 MEDIUM

Take it away, Gabi !

// FIN