Chapter 20
The STL
(containers, iterators, and algorithms)

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Based on slides by Dr. Bjarne Stroustrup

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This lecture and the next present the STL – the containers and algorithms part of the C++ standard library.

The STL is an extensible framework dealing with data in a C++ program.

First, we will discuss the general ideal, then the fundamental concepts, and finally examples of containers and algorithms.

The key notions of sequence and iterator used to tie data together with algorithms (for general processing) are also presented.
Overview

- Common tasks and ideals
- Generic programming
- Containers, algorithms, and iterators
- The simplest algorithm: find()
- Parameterization of algorithms
  - find_if() and function objects
- Sequence containers
  - vector and list
- Associative containers
  - map, set
- Standard algorithms
  - copy, sort, …
  - Input iterators and output iterators
- List of useful facilities
  - Headers, algorithms, containers, function objects
Common tasks

- Collect data into containers
- Organize data
  - For printing
  - For fast access
- Retrieve data items
  - By index (e.g., get the Nth element)
  - By value (e.g., get the first element with the value "Chocolate")
  - By properties (e.g., get the first elements where “age<64”)
- Add data
- Remove data
- Sorting and searching
- Simple numeric operations
Observation

We can (already) write programs that are very similar independent of the data type used

- Using an `int` isn’t that different from using a `double`
- Using a `vector<int>` isn’t that different from using a `vector<string>`
Ideals

• We’d like to write common programming tasks so that we don’t have to re-do the work each time we find a new way of storing the data or a slightly different way of interpreting the data
  □ Finding a value in a **vector** isn’t all that different from finding a value in a **list** or an array
  □ Looking for a **string** ignoring case isn’t all that different from looking at a **string** not ignoring case
  □ Graphing experimental data with exact values isn’t all that different from graphing data with rounded values
  □ Copying a file isn’t all that different from copying a **vector**
Ideals (continued)

- Code that’s
  - Easy to read
  - Easy to modify
  - Regular
  - Short
  - Fast

- Uniform access to data
  - Independently of how it is stored
  - Independently of its type

- ...

...
Ideals (continued)

- Type-safe access to data
- Easy traversal of data
- Compact storage of data
- Fast
  - Retrieval of data
  - Addition of data
  - Deletion of data
- Standard versions of the most common algorithms
  - Copy, find, search, sort, sum, …
Examples

- Sort a vector of strings
- Find a number in a phone book, given a name
- Find the highest temperature
- Find all values larger than 800
- Find the first occurrence of the value 17
- Sort the telemetry records by unit number
- Sort the telemetry records by time stamp
- Find the first value larger than “Petersen”?
- What is the largest amount seen?
- Find the first difference between two sequences
- Compute the pair wise product of the elements of two sequences
- What’s the highest temperatures for each day in a month?
- What’s the top 10 best-sellers?
- What’s the entry for “C++” (say, in Google)?
- What’s the sum of the elements?
Generic programming

- Generalize algorithms
  - Sometimes called “lifting an algorithm”

- The aim (for the end user) is
  - Increased correctness
    - Through better specification
  - Greater range of uses
    - Possibilities for re-use
  - Better performance
    - Through wider use of tuned libraries
    - Unnecessarily slow code will eventually be thrown away

- Go from the concrete to the more abstract
  - The other way most often leads to bloat
double sum(double array[], int n)  // one concrete algorithm (doubles in array)
{
    double s = 0;
    for (int i = 0; i < n; ++i ) s = s + array[i];
    return s;
}

struct Node { Node* next; int data; };  

int sum(Node* first)  // another concrete algorithm (ints in list)
{
    int s = 0;
    while (first) {
        s += first->data;
        first = first->next;
    }
    return s;
}
Lifting example (abstract the data structure)

// pseudo-code for a more general version of both algorithms

```cpp
int sum(data) // somehow parameterize with the data structure
{
    int s = 0;  // initialize
    while (not at end) { // loop through all elements
        s = s + get value;  // compute sum
        get next data element;
    }
    return s;  // return result
}
```

- We need three operations (on the data structure):
  - not at end
  - get value
  - get next data element
Lifting example (STL version)

// Concrete STL-style code for a more general version of both algorithms

template<class Iter, class T> // Iter should be an Input_iterator
    // T should be something we can + and =
T sum(Iter first, Iter last, T s) // T is the “accumulator type”
{
    while (first!=last) {
        s = s + *first;
        ++first;
    }
    return s;
}

- Let the user initialize the accumulator
  float a[] = { 1,2,3,4,5,6,7,8 };
  double d = 0;
  d = sum(a,a+sizeof(a)/sizeof(*a),d);
Lifting example

- Almost the standard library accumulate
  - I simplified a bit for terseness
    (see 21.5 for more generality and more details)

- Works for
  - arrays
  - vectors
  - lists
  - istreams
  - …

- Runs as fast as “hand-crafted” code
  - Given decent inlining

- The code’s requirements on its data has become explicit
  - We understand the code better
The STL

- Part of the ISO C++ Standard Library
- Mostly non-numerical
  - Only 4 standard algorithms specifically do computation
    - Accumulate, inner_product, partial_sum, adjacent_difference
  - Handles textual data as well as numeric data
    - E.g. string
  - Deals with organization of code and data
    - Built-in types, user-defined types, and data structures
- Optimizing disk access was among its original uses
  - Performance was always a key concern
The STL

- Designed by Alex Stepanov
- General aim: The most general, most efficient, most flexible representation of concepts (ideas, algorithms)
  - Represent separate concepts separately in code
  - Combine concepts freely wherever meaningful
- General aim to make programming “like math”
  - or even “Good programming is math”
  - works for integers, for floating-point numbers, for polynomials, for …
Basic model

- **Algorithms**
  - sort, find, search, copy, ...

- **Containers**
  - vector, list, map, hash_map, ...

- **Separation of concerns**
  - Algorithms manipulate data, but don’t know about containers
  - Containers store data, but don’t know about algorithms
  - Algorithms and containers interact through iterators
    - Each container has its own iterator types
The STL

- An ISO C++ standard framework of about 10 containers and about 60 algorithms connected by iterators
  - Other organizations provide more containers and algorithms in the style of the STL
    - Boost.org, Microsoft, SGI, ...
- Probably the currently best known and most widely used example of generic programming
The STL

- If you know the basic concepts and a few examples you can use the rest

- Documentation
  - SGI
  - Dinkumware
  - Rogue Wave

- More accessible and less complete documentation
  - Appendix B
Basic model

- A pair of iterators define a sequence
  - The beginning (points to the first element – if any)
  - The end (points to the one-beyond-the-last element)

- An iterator is a type that supports the “iterator operations”
  - ++ Go to next element
  - * Get value
  - == Does this iterator point to the same element as that iterator?
- Some iterators support more operations (e.g. --, +, and [ ])

begin: end:
Containers
(hold sequences in different ways)

- **vector**

- **list**
  (doubly linked)

- **set**
  (typically implemented as binary search trees)
The simplest algorithm: `find()`

```cpp
template<class In, class T>
In find(In first, In last, const T& val)
{
    while (first!=last && *first != val) ++first;
    return first;
}

void f(vector<int>& v, int x) // find an int in a vector
{
    vector<int>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found x */ }
    // ...
}
```

// Find the first element that equals a value

We can ignore ("abstract away") the differences between containers
**find()**

generic for both element type and container type

```cpp
void f(vector<int>& v, int x)  // works for vector of ints
{
    vector<int>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found x */ }
    // ...
}

void f(list<string>& v, string x)  // works for list of strings
{
    list<string>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found x */ }
    // ...
}

void f(set<double>& v, double x)  // works for set of doubles
{
    set<double>::iterator p = find(v.begin(),v.end(),x);
    if (p!=v.end()) { /* we found x */ }
    // ...
}
```
Algorithms and iterators

- An iterator points to (refers to, denotes) an element of a sequence
- The end of the sequence is “one past the last element”
  - *not* “the last element”
  - That’s necessary to elegantly represent an empty sequence
  - One-past-the-last-element isn’t an element
    - You can compare an iterator pointing to it
    - You can’t dereference it (read its value)
- Returning the end of the sequence is the standard idiom for “not found” or “unsuccessful”
Simple algorithm: **find_if()**

- Find the first element that matches a criterion (predicate)
  - Here, a predicate takes one argument and returns a **bool**

```cpp
template<class In, class Pred>
In find_if(In first, In last, Pred pred)
{
    while (first!=last && !pred(*first)) ++first;
    return first;
}

void f(vector<int>& v)
{
    vector<int>::iterator p = find_if(v.begin(),v.end(),odd());
    if (p!=v.end()) { /* we found an odd number */ }
    // ...
}
```
Predicates

- A predicate (of one argument) is a function or a function object that takes an argument and returns a bool

- For example
  - A function
    ```cpp
    bool odd(int i) { return i%2; } // % is the remainder (modulo) operator
    odd(7); // call odd: is 7 odd?
    ```
  - A function object
    ```cpp
    struct Odd {
      bool operator()(int i) const { return i%2; }
    };
    Odd odd; // make an object odd of type Odd
    odd(7); // call odd: is 7 odd?
    ```
A concrete example using state

```cpp
template<class T> struct Less_than {
    T val;    // value to compare with
    Less_than(int x) :val(x) {} 
    bool operator()(const T& x) const { return x < val; }
};
```

// find x<43 in vector<int> :
```
p=find_if(v.begin(), v.end(), Less_than(43));
```

// find x<“perfection” in list<string>:
```
q=find_if(ls.begin(), ls.end(), Less_than("perfection"));
```
Function objects

- A very efficient technique
  - inlining very easy
    - and effective with current compilers
  - Faster than equivalent function
    - And sometimes you can’t write an equivalent function
- The main method of policy parameterization in the STL
- Key to emulating functional programming techniques in C++
Whenever you have a useful algorithm, you eventually want to parameterize it by a “policy”.

For example, we need to parameterize sort by the comparison criteria:

```cpp
struct Record {
    string name; // standard string for ease of use
    char addr[24]; // old C-style string to match database layout
    // ...
};

vector<Record> vr;

// ...

sort(vr.begin(), vr.end(), Cmp_by_name()); // sort by name
sort(vr.begin(), vr.end(), Cmp_by_addr()); // sort by addr
```
Comparisons

// Different comparisons for Rec objects:

struct Cmp_by_name {
    bool operator()(const Rec& a, const Rec& b) const
    { return a.name < b.name; }  // look at the name field of Rec
};

struct Cmp_by_addr {
    bool operator()(const Rec& a, const Rec& b) const
    { return strncmp(a.addr, b.addr, 24)<0; }  // !?!
};

// note how the comparison function objects are used to hide ugly
// and error-prone code
template<typename T> class vector {
    T* elements;
    // ...

typedef ??? iterator; // the type of an iterator is implementation defined
    // and it (usefully) varies (e.g. range checked iterators)
    // a vector iterator could be a pointer to an element

typedef ??? const_iterator;

iterator begin();                  // points to first element
const_iterator begin() const;
iterator end();                    // points one beyond the last element
const_iterator end() const;

iterator erase(iterator p);        // remove element pointed to by p
iterator insert(iterator p, const T& v); // insert a new element v before p
};
**insert() into vector**

```cpp
vector<int>::iterator p = v.begin(); ++p; ++p; ++p;
vector<int>::iterator q = p; ++q;
```

![Diagram showing vector and iterators](image)

- Note: q is invalid after the `insert()`
- Note: Some elements moved; all elements could have moved

```cpp
p = v.insert(p, 99); // leaves p pointing at the inserted element
```

![Diagram showing updated vector and iteratros](image)
erase() from vector

p = v.erase(p);  // leaves p pointing at the element after the erased one

- vector elements move when you insert() or erase()
- Iterators into a vector are invalidated by insert() and erase()
template<class T> class list {
    Link* elements;
    // …
    typedef ??? iterator; // the type of an iterator is implementation defined
    // and it (usefully) varies (e.g. range checked iterators)
    // a list iterator could be a pointer to a link node
    typedef ??? const_iterator;

    iterator begin(); // points to first element
    const_iterator begin() const;
    iterator end(); // points one beyond the last element
    const_iterator end() const;

    iterator erase(iterator p); // remove element pointed to by p
    iterator insert(iterator p, const T& v); // insert a new element v before p
};
`list<int>::iterator p = v.begin(); ++p; ++p; ++p;`

`list<int>::iterator q = p; ++q;`

**v:**

```
   6
```

**p:**

```
-----
```

**q:**

```
-----
```

```
0 --1 --2 --3 --4 --5
```

```
p = v.insert(p,99); // leaves p pointing at the inserted element
```

**v:**

```
    7
```

**p:**

```
-----
```

**q:**

```
-----
```

```
0 --1 --2 --3 --4 --5
```

```
99
```

- Note: q is unaffected
- Note: No elements moved around
erase() from list

\[ p = v.\text{erase}(p); \quad \text{// leaves } p \text{ pointing at the element after the erased one} \]

- Note: list elements do not move when you insert() or erase()
Ways of traversing a vector

```cpp
for(int i = 0; i<v.size(); ++i)   // why int?
    // do something with v[i]

for(vector<int>::size_type i = 0; i<v.size(); ++i) // longer but always correct
    // do something with v[i]

for(vector<int>::iterator p = v.begin(); p!=v.end(); ++p)
    // do something with *p
```

- know both ways (iterator and subscript)
  - The subscript style is used in essentially every language
  - The iterator style is used in C (pointers only) and C++
  - The iterator style is used for standard library algorithms
  - The subscript style doesn’t work for lists (in C++ and in most languages)
- use either way for vectors
  - There are no fundamental advantage of one style over the other
  - But the iterator style works for all sequences
  - Prefer `size_type` over plain `int`
    - pedantic, but quiets compiler and prevents rare errors
Some useful standard headers

- `<iostream>` I/O streams, cout, cin, …
- `<fstream>` file streams
- `<algorithm>` sort, copy, …
- `<numeric>` accumulate, inner_product, …
- `<functional>` function objects
- `<string>`
- `<vector>`
- `<map>`
- `<list>`
- `<set>`
Next lecture

- Map, set, and algorithms