COMP 2012H Honors Object-Oriented Programming and Data Structures

Topic 14: Standard Template Library

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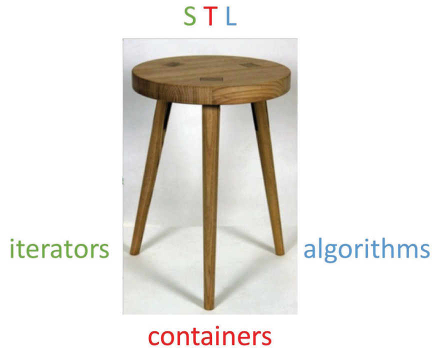
The Standard Template Library (STL)

- The STL is a collection of powerful, template-based, reusable codes.
- It implements many general-purpose containers (data structures) together with algorithms that work on them.
- To use the STL, we need an understanding of the following topics:



Part I

STL Containers

Container Classes

- A container class is a class that holds a collection of homogeneous objects — of the same type.
- Container classes are a typical use of class templates since we frequently need containers for homogeneous objects of different types at different times.
- The object types need not be known when the container class is designed.
- Let's design a sequence container that looks like an array, but that is a first-class type: so assignment and call by value is possible.
- Remark: The vector class in STL is better; so this is just an exercise for your understanding.

An Array Container Class

```
template <typename T>   /* File: arrayT.h */
class Array
{
  private:
    T* _value;
    int _size;

  public:
    Array<T>(int n = 10);      // Default and conversion constructor
    Array<T>(const Array& a); // Copy constructor
    ~Array<T>();

    int size() const { return _size; }
    void init(const T& k);

    Array& operator=(const Array<T>& a); // Copy assignment operator
    T& operator[](int i) { return _value[i]; } // lvalue
    const T& operator[](int i) const { return _value[i]; } // rvalue
};
```


An Array Container Class Too

Within the template, the typename for Array may be omitted.

```
template <typename T>   /* File: array.h */
class Array
{
  private:
    T* _value;
    int _size;

  public:
    Array(int n = 10);      // Default and conversion constructor
    Array(const Array& a); // Copy constructor
    ~Array();

    int size() const { return _size; }
    void init(const T& k);

    Array& operator=(const Array& a); // Copy assignment operator
    T& operator[](int i) { return _value[i]; } // lvalue
    const T& operator[](int i) const { return _value[i]; } // rvalue
};
```


Example: Use of Class Array

```
#include <iostream>     /* File: array-test.cpp */
using namespace std;
#include "array.h"
#include "array-constructors.h"
#include "array-op=.h"
#include "array-op-os.h"

int main()
{
    Array<int> a(3);
    a.init(98); cout << a << endl;
    a = a; a[2] = 17; cout << a << endl;

    Array<char> b(4);
    b.init('g'); b[0] = a[1]; cout << b << endl;

    const Array<char> c = b;
    // c[2] = 5; // Error: assignment of read-only location
    cout << c << endl;

    Array<int> d(a);
    cout << d << endl;
    return 0;
}
```


Constructors/Destructor of Class Array

```
template <typename T>   /* File: array-constructors.h */
Array<T>::Array(int n) : _value( new T [n] ), _size(n) { }

template <typename T>
Array<T>::Array(const Array<T>& a)
    : _size(a._size), _value( new T [a._size] )
{
    for (int i = 0; i < _size; ++i)
        _value[i] = a._value[i];
}

template <typename T>
Array<T>::~Array() { delete [] _value; }

template <typename T>
void Array<T>::init(const T& k)
{
    for (int i = 0; i < _size; ++i)
        _value[i] = k;
}
```

Assignment Operator of Class Array: Deep/Shallow Copy

```
template <typename T>   /* File: array-op=.h */
Array<T>& Array<T>::operator=(const Array<T>& a) // Deep copy
{
    if (&a != this)       // Avoid self-assignment: e.g., a = a
    {
        delete [] _value;              // First remove the old data
        _size = a._size;
        _value = new T [_size];        // Re-allocate memory

        for (int j = 0; j <_size; ++j) // Copy the new data
            _value[j] = a[j];
    }

    return (*this);
}
```


Non-member Operator≪ as a Global Function Template

- Function templates and class templates work together very well: We can use function templates to implement functions that will work on any class created from a class template.

```
template <typename T>   /* File: array-op-os.h */
ostream& operator<<(ostream& os, const Array<T>& a)
{
    os << "#elements stored = " << a.size() << endl;

    for (int j = 0; j < a.size(); ++j)
        os << a[j] << endl;

    return os;
}
```


Operator≪ as a Friend Function Template

- The Array class template may declare the operator≪ as a friend function inside the its definition as a function template.

```
template <typename T>   /* File: array-w-os-friend.h */
class Array
{
    template <typename S>
        friend ostream& operator<<(ostream& os, const Array<S>& x);
  private:
    T* _value;
    int _size;

  public:
    Array(int n = 10);     // Default or conversion constructor
    Array(const Array&);   // Copy constructor
    ~Array();

    int size() const { return _size; }
    void init(const T& k);

    Array& operator=(const Array&); // Copy assignment operator
    T& operator[](int i) { return _value[i]; } // lvalue
    const T& operator[](int i) const { return _value[i]; } // rvalue
};
```


Operator≪ as a Friend Function Template ..

- The friend operator≪ function definition may be defined outside the Array class template like other class member functions.
- Now the friend operator≪ function may access the private members of the Array class.

```
template <typename T>   /* File: array-op-os-friend.h */
ostream& operator<<(ostream& os, const Array<T>& a)
{
    os << "#elements stored = " << a._size << endl;

    for (int i = 0; i < a._size; ++i)
        os << a._value[i] << endl;

    return os;
}
```

Containers in STL

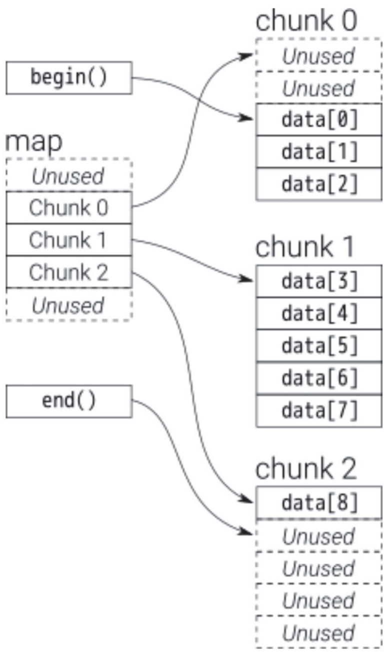
1. Sequence containers
   - Represent linear data structures
   - Start from index/location 0
2. Associative containers
   - Non-sequential containers
   - Store key/value pairs
3. Container adapters
   - Adopted containers that support a limited set of container operations
4. "Near-containers" C-like pointer-based arrays
   - Exhibit capabilities similar to those of the sequence containers, but do not support all their capabilities
   - strings, bitsets and valarrays

Containers in STL ..

Type of Container	STL Containers
Sequence	vector, list, deque
Associative	map, multimap, multiset, set
Adapters	priority_queue, queue, stack
Near-containers	bitset, valarray, string

- Containers in the same category share a set of same or similar public member functions (i.e., public interface or algorithms).
- Deque (double-ended queue)
  - Unlike STL vector, the elements of a deque are not stored contiguously;, it uses a sequence of chunks of fixed-size arrays.
  - Like STL vector, the storage of a deque is automatically expanded/contracted as needed, but deque does not require copying of *all* the existing elements.
  - Allows fast insertion and deletion at both ends.

Deque (Double-Ended QUEue)



Sequence Containers: Access, Add, Remove

Element access for all:

- front(): First element
- back(): Last element

Element access for vector and deque:

- [ ]: Subscript operator, index not checked.

Add/remove elements for all:

- push_back(): Append element.
- pop_back(): Remove last element.

Add/remove elements for list and deque:

- push_front(): Insert element at the front.
- pop_front(): Remove first element.

Sequence Containers: Other Operations

List operations are fast for list, but also available for vector and deque:

- insert(p, x): Insert an element **x** at position **p**.
- erase(p): Remove an element at position **p**.
- clear(): Erase all elements.

Miscellaneous Operations:

- size(): Returns the number of elements.
- empty(): Returns true if the sequence is empty.
- resize(int new_size): Change size of the sequence.

Comparison operators ==, !=, < etc. are also defined.

Part II

STL Iterators: Generalized Pointers

Iterators to Traverse a Sequence Container

- Iterators are generalized pointers.
- To traverse the elements of a sequence container sequentially, one may use an iterator of the container type. E.g, list<int>::iterator is an iterator for a **list** of **int**.
- const_iterator is the const version of an iterator: the object it 'points' to can't be modified.
- STL sequence containers provide the begin() and end() to set an iterator to the beginning and end of a container.
- For each kind of STL sequence container, there is an iterator type. E.g.,
  - list<int>::iterator, list<int>::const_iterator
  - vector<string>::iterator, vector<string>::const_iterator
  - deque<double>::iterator, deque<double>::const_iterator

Iterators to Traverse a Sequence Container ..

```
#include <iostream>         /* File: print-list.cpp */
using namespace std;
#include <list>             // STL list

int main()
{
    list<int> x;                    // An int STL list
    for (int j = 0; j < 5; ++j)
        x.push_back(j);             // Append items to an STL list

    list<int>::const_iterator p; // STL list iterator
    for (p = x.begin(); p != x.end(); ++p)
        cout << *p << endl;

    return 0;
}
```

Why Are Iterators So Great?

```
template <class Iterator, class T> /* File: find-template.h */
Iterator find(Iterator begin, Iterator end, const T& value)
{
    while (begin != end && *begin != value)
        ++begin;

    return begin;
}
```

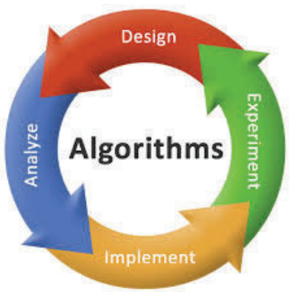
- Iterators allow us to separate algorithms from containers when they are used with templates.
- The new **find()** function template contains no information about the implementation of the container, or how to move the iterator from one element to the next.
- The same **find**() function can be used for any container that provides a suitable iterator.

Example: find() with a vector Iterator

```
#include <iostream>      /* File: find-iterator-test.cpp */
using namespace std;
#include <vector>

int main()
{
    const int SIZE = 10; vector<int> x(SIZE);
    for (int i = 0; i < x.size(); i++)
        x[i] = 2 * i;

    while (true)
    {
        cout << "Enter number: "; int num; cin >> num;
        vector<int>::iterator position = find(x.begin(), x.end(), num);

        if (position == x.end())
            cout << "Not found\n";
        else if (++position != x.end())
            cout << "Found before the item " << *position << '\n';
        else
            cout << "Found as the last element\n";
    }
}
```


Part III

STL Algorithms



STL Algorithms

- The STL does not only have container classes and iterators, but also algorithms that work with different containers.
- STL algorithms are implemented as global functions.
- E.g., STL algorithm find() searches sequentially through a sequence, and stops when an item matches its 3rd argument.
- One limitation of find() is that it requires an exact match by value.

```
template <class Iterator, class T> /* File: stl-find.cpp */
Iterator find(Iterator first, Iterator last, const T& value)
{
    while (first != last && *first != value)
        ++first;
    return first;
}
```

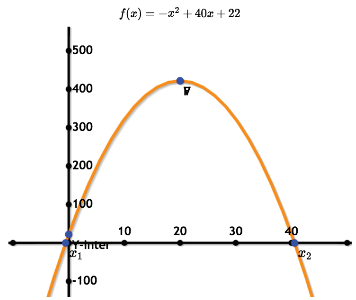
Example: Using STL find()

```
#include <iostream>     /* File: find-composer.cpp */
using namespace std;
#include <string>
#include <list>
#include <algorithm>

int main()
{
    list<string> composers;
    composers.push_back("Mozart");
    composers.push_back("Bach");
    composers.push_back("Chopin");
    list<string>::iterator p =
        find(composers.begin(), composers.end(), "Bach");

    if (p == composers.end())
        cout << "Not found." << endl;
    else if (++p != composers.end())
        cout << "Found before: " << *p << endl;
    else
        cout << "Found at the end of the list." << endl;

    return 0;
}
```


Algorithms, Iterators, and Sub-Sequences

Sequences/Sub-sequences are specified using iterators that indicate the beginning and the end for an algorithm to work on.

The following functions will be used in the following examples.




```
/* File: init.h */
inline int quadratic(int x) { return -x*x + 40*x + 22; }

template <typename T>
void my_initialization(T& x, int num_items)
{
    for (int j = 0; j < num_items; ++j)
        x.push_back( quadratic(j) ); // Can you rewrite using lambda?
}
```


Example: STL find() the 2nd Occurrence of a Value

```
#include <iostream>     /* File: find-2nd-occurrence.cpp */
using namespace std;
#include <vector>
#include <algorithm>
#include "init.h"

int main()
{
    const int search_value = 341;
    vector<int> x;
    my_initialization(x, 100);

    vector<int>::iterator p = find(x.begin(), x.end(), search_value);

    if (p != x.end())     // Value found for the first time!
    {
        p = find(++p, x.end(), search_value); // Search again
        if (p != x.end())
            cout << search_value << "appears after " << *--p << endl;
    }
    return 0;
}
```


STL find_if()

```
template <class Iterator, class Predicate> /* File: stl-find-if.cpp */
Iterator find_if(Iterator first, Iterator last, Predicate predicate)
{
    while (first != last && !predicate(*first))
        ++first;
    return first;
}
```

- find_if() is a more general algorithm than find() in that it stops when a condition is satisfied.
- The condition is called a predicate and is implemented by a boolean function.
- This allows partial match, or match by keys.
- In general, you may pass a function to another function as its argument!

STL find_if() — Search by Condition

```
#include <iostream>      /* File: find-gt350.cpp */
using namespace std;
#include <vector>
#include <algorithm>
#include "init.h"

bool greater_than_350(int value) { return value > 350; }

int main()
{
    vector<int> x;
    my_initialization(x, 100);

    vector<int>::const_iterator p =
        find_if( x.begin(), x.end(), greater_than_350 );

    if (p != x.end())
        cout << "Found element: " << *p << endl;

    return 0;
}
```


Function Pointer

- Inherited from C, C++ allows a function to be passed as argument to another function.
- Actually, we say that we pass the function pointer.
- E.g., the type of the function pointer of the template `larger()` we talked before is:

  inline const T (∗)(const T&, const T&);

- STL's `max()` is the same as our `larger()`.

Function Pointer Example: smaller() and larger()

```
#include <iostream>      /* File: fp-smaller-larger.cpp */
using namespace std;

int larger(int x, int y) { return (x > y) ? x : y; }
int smaller(int x, int y) { return (x > y) ? y : x; }

int main()
{
    int choice;
    cout << "Choice: (1 for larger; others for smaller): ";
    cin >> choice;

    int (*f)(int x, int y) = (choice == 1) ? larger : smaller;

    cout << f(3, 5) << endl;
    return 0;
}
```


Function Pointer Example: Calculator

```
#include <iostream>      /* File: fp-calculator.cpp */
using namespace std;
double add(double x, double y) { return x+y; }
double subtract(double x, double y) { return x-y; }
double multiply(double x, double y) { return x*y; }
double divide(double x, double y) { return x/y; } // No error checking

int main()
{
    double (*f[])(double x, double y) // Array of function pointers
        = { add, subtract, multiply, divide };

    int operation; double x, y;
    cout << "Enter 0:+, 1:-, 2:*, 3:/, then 2 numbers: ";
    while (cin >> operation >> x >> y)
    {
        if (operation >= 0 && operation <= 3)
            cout << f[operation](x, y) << endl; // Call + - * /
        cout << "Enter 0:+, 1:-, 2:*, 3:/, then 2 numbers: ";
    }
}
```

Example: Function Pointer as Lambda

```
#include <iostream>    /* File: fp-min-max-lambda.cpp */
using namespace std;

int main()
{
    int choice;
    cout << "Choice: (1 for my_max; others for my_min): ";
    cin >> choice;

    int (*f)(int, int);

    if(choice == 1)
       f = [] (int x, int y) { return (x > y) ? x : y; };
    else
       f = [] (int x, int y) { return (x > y) ? y : x; };

    cout << f(3, 5) << endl;
    return 0;
}
```


Function Objects

- STL function objects are a generalization of function pointers.
- An object that can be called like a function is called a function object, functoid, or functor.
- Function pointer and lambdas are just two example of function objects.
- An object can be called if it supports the operator().
- A function object must have at least the operator() overloaded; of course, they may have other member functions/data.
- Function objects are more powerful than function pointers, since they can have data members and therefore carry around information or internal states.
- A function object (or a function) that returns a boolean value (of type bool) is called a predicate.

STL find_if() with Function Object Greater_Than

```
#include <iostream>     /* File: fo-greater-than.cpp */
using namespace std;
#include <algorithm>
#include <vector>
#include "init.h"
#include "fo-greater-than.h"

int main()
{
    vector<int> x; my_initialization(x, 100);
    int limit = 0;

    while (cin >> limit)
    {
        vector<int>::const_iterator p =
            find_if(x.begin(), x.end(), Greater_Than(limit)); // Call FO

        if (p != x.end())
            cout << "Element found: " << *p << endl;
        else
            cout << "Element not found!" << endl;
    }

    return 0;
}
```


STL find_if() with Function Object Greater_Than ..

```
class Greater_Than      /* File: fo-greater-than.h */
{
  private:
    int limit;
  public:
    Greater_Than(int a) : limit(a) { }
    bool operator()(int value) { return value > limit; }
};
```

- The line with `Call FO` is the same as:

```
// Create a Greater_Than function object g
Greater_Than g(350);
p = find_if( x.begin(), x.end(), g );
```

- When find_if() examines each item, say `x[j]` in the container vector<int> x, against the temporary Greater_Than function object, it will call the FO's operator() with `x[j]` as the argument. i.e., `g(x[j]) // Or, in formal writing: g.operator()(x[j])`

STL count_if() with Function Object Greater_Than

```
#include <iostream>     /* File: fo-count.cpp */
using namespace std;
#include <vector>
#include <algorithm>
#include "fo-greater-than.h"

int main()
{
    vector<int> x;
    for (int j = -5; j < 5; ++j)
        x.push_back(j*10);

    // Count how many items are greater than 10
    cout << count_if(x.begin(), x.end(), Greater_Than(10)) << endl;

    return 0;
}
```


STL for_each() to Sum using Function Object

```
#include <iostream>     /* File: fo-sum.cpp */
using namespace std;
#include <list>
#include <algorithm>

class Sum
{
  private:
    int sum;
  public:
    Sum() : sum(0) { }
    void operator()(int value) { sum += value; }
    int result() const { return sum; }
};

int main()
{
    list<int> x;
    for (int j = 0; j < 5; ++j) x.push_back(j); // Initialize x
    Sum sum = for_each( x.begin(), x.end(), Sum() );
    cout << "Sum = " << sum.result() << endl; return 0;
}
```


STL Algorithms: for_each() and transform()

```
/* File: stl-foreach.h */
template <class Iterator, class Function>
Function for_each(Iterator first, Iterator last, Function g)
{
    for ( ; first != last; ++first )
        g(*first);
    return g; // Returning the input function!
}


/* File: stl-transform.h */
template <class Iterator1, class Iterator2, class Function>
Iterator2 transform(Iterator1 first, Iterator1 last,
                    Iterator2 result, Function g)
{
    for ( ; first != last; ++first, ++result )
        *result = g(*first);
    return result;
}
```


STL for_each() to Add using Function Object Add

```
#include <list>         /* File: fo-add.h */
#include <vector>
#include <algorithm>

class Add
{
  private:
    int data;
  public:
    Add(int i) : data(i) { }
    int operator()(int value) { return value + data; }
};

class Print
{
  private:
    ostream& os;
  public:
    Print(ostream& s) : os(s) { }
    void operator()(int value) { os << value << " "; }
};
```

STL for_each() to Add using Function Object Add ..

```
#include <iostream>     /* File: fo-add10.cpp */
using namespace std;
#include "fo-add.h"

int main()
{
    list<int> x;
    for (int j = 0; j < 5; ++j)   // Initialize x
        x.push_back(j);

    vector<int> y(x.size());
    transform( x.begin(), x.end(), y.begin(), Add(10) );

    for_each( y.begin(), y.end(), Print(cout) );
    cout << endl;

    return 0;
}
```


Other Algorithms in the STL

- min_element and max_element
- equal
- generate (Replace elements by applying a function object)
- remove, remove_if Remove elements
- reverse, rotate Rearrange sequence
- random_shuffle
- binary_search
- sort (using a function object to compare two elements)
- merge, unique
- set_union, set_intersection, set_difference

That's all!

Any questions?