

CSE 333

Lecture 12 - templates, STL

Hal Perkins

Department of Computer Science & Engineering

University of Washington



Administrivia

HW2 due Thursday night, 11 pm.

- <panic>if not started yet</panic> <celebrate>if done</celebrate>
- **BE SURE TO CHECK YOUR WORK** (git clone/checkout, make, tests, ...)

Exam Monday, in class

- Closed book, no notes — exam questions can be more straightforward that way; reference info on test as needed
- Topics: everything from lectures, exercises, project, etc. up to HW2 & basics of C++ (including references, const, classes, constructors, destructors, new/delete, nothing after that)
- Old exams and topic list on the web now
- Review Sunday, 2 pm, location TBA

No more exercises until (right) after the exam

Today's goals

Templates and type-independent code

C++'s standard library

- STL containers, iterators, algorithms
 - A few core ones only - see docs & Primer for others

Suppose that...

You want to write a function to compare two ints:

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
int compare(const int &value1, const int &value2) {
    if (v1 < v2) return -1;
    if (v2 < v1) return 1;
    return 0;
}
```

Suppose that...

You want to write a function to compare two ints, and you also want to write a function to compare two strings:

```
// note the cool use of function overloading!  
  
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise  
int compare(const int &value1, const int &value2) {  
    if (value1 < value2) return -1;  
    if (value2 < value1) return 1;  
    return 0;  
}  
  
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise  
int compare(const string &value1, const string &value2) {  
    if (value1 < value2) return -1;  
    if (value2 < value1) return 1;  
    return 0;  
}
```

Hmm....

The two implementations of compare are nearly identical.

- we could write a compare for every comparable type
 - ▶ but, that's obviously a waste; lots of redundant code!

Instead, we'd like to write "generic code"

- code that is **type-independent**
- code that is **compile-time polymorphic** across types

C++: parametric polymorphism

C++ has the notion of **templates**

- a function or class that accepts a **type** as a parameter
 - ▶ you implement the function or class once, in a type-agnostic way
 - ▶ when you invoke the function or instantiate the class, you specify (one or more) types, or values, as arguments to it
- at **compile-time**, when C++ notices you using a template...
 - ▶ the compiler generates specialized code using the types you provided as parameters to the template

Function template

You want to write a function to compare two things:

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

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <class T>
int compare(const T &value1, const T &value2) {
    if (value1 < value2) return -1;
    if (value2 < value1) return 1;
    return 0;
}

int main(int argc, char **argv) {
    std::string h("hello"), w("world");
    std::cout << compare<std::string>(h, w) << std::endl;
    std::cout << compare<int>(10, 20) << std::endl;
    std::cout << compare<double>(50.5, 50.6) << std::endl;
    return 0;
}
```


Function template

Same thing, but letting the compiler infer the types:

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

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <class T>
int compare(const T &value1, const T &value2) {
    if (value1 < value2) return -1;
    if (value2 < value1) return 1;
    return 0;
}

int main(int argc, char **argv) {
    std::string h("hello"), w("world");
    std::cout << compare(10, 20) << std::endl;
    std::cout << compare("Hello", "World") << std::endl; // hmmm...
    std::cout << compare(h, w) << std::endl; // ok
    return 0;
}
```

functiontemplate_infer.cc

Function template

You can use non-types (constant values) in a template:

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

template <class T, int N>
void printmultiple(const T &value1) {
    for (int i = 0; i < N; ++i)
        std::cout << value1 << std::endl;
}

int main(int argc, char **argv) {
    std::string h("hello");
    printmultiple<std::string, 3>(h);
    printmultiple<const char *, 4>("hi");
    printmultiple<int, 5>(10);
    return 0;
}
```

nontypeparameter.cc

What's going on underneath?

The compiler doesn't generate any code when it sees the templated function

- it doesn't know what code to generate yet, since it doesn't know what types are involved

When the compiler sees the function being used, then it understands what types are involved

- it generates the instantiation of the template and compiles it
 - ▶ the compiler generates template instantiations for each type used as a template parameter
 - ▶ kind of like macro expansion

This creates a problem...

```
#ifndef _COMPARE_H_
#define _COMPARE_H_

template <class T>
int comp(const T& a, const T& b);

#endif // COMPARE_H_
compare.h
```

```
#include "compare.h"

template <class T>
int comp(const T& a, const T& b) {
    if (a < b) return -1;
    if (b < a) return 1;
    return 0;
}
compare.cc
```

```
#include <iostream>
#include "compare.h"

using namespace std;

int main(int argc, char **argv) {
    cout << comp<int>(10, 20);
    cout << endl;
    return 0;
}
main.cc
```

One solution

```
#ifndef _COMPARE_H_
#define _COMPARE_H_

template <class T>
int comp(const T& a, const T& b) {
    if (a < b) return -1;
    if (b < a) return 1;
    return 0;
}

#endif // COMPARE_H_ compare.h
```

```
#include <iostream>
#include "compare.h"

using namespace std;

int main(int argc, char **argv) {
    cout << comp<int>(10, 20);
    cout << endl;
    return 0;
}

main.cc
```

Another solution

```
#ifndef _COMPARE_H_
#define _COMPARE_H_

template <class T>
int comp(const T& a, const T& b);

#include "compare.cc"

#endif // COMPARE_H_ compare.h
```

```
template <class T>
int comp(const T& a, const T& b) {
    if (a < b) return -1;
    if (b < a) return 1;
    return 0;
} compare.cc
```

```
#include <iostream>
#include "compare.h"

using namespace std;

int main(int argc, char **argv) {
    cout << comp<int>(10, 20);
    cout << endl;
    return 0;
} main.cc
```

Class templates

Templating is useful for classes as well! Imagine we want a class that holds a pair of things

- we want to be able to:
 - ▶ set the value of the first thing, second thing
 - ▶ get the value of the first thing, second thing
 - ▶ reverse the order of the things
 - ▶ print the pair of things

Pair class

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

template <class Thing> class Pair {
public:
    Pair() { };

    Thing &get_first() { return first_; }
    Thing &get_second();
    void set_first(Thing &copyme);
    void set_second(Thing &copyme);
    void Reverse();

private:
    Thing first_, second_;
};

#include "Pair.cc"
```

Pair.h

Pair class

```
template <class Thing> Thing &Pair<Thing>::get_second() {  
    return second_;  
}  
  
template <class Thing> void Pair<Thing>::set_first(Thing &copyme) {  
    first_ = copyme;  
}  
  
template <class Thing> void Pair<Thing>::set_second(Thing &copyme) {  
    second_ = copyme;  
}  
  
template <class Thing> void Pair<Thing>::Reverse() {  
    // makes *3* copies  
    Thing tmp = first_;  
    first_ = second_;  
    second_ = tmp;  
}
```

Pair class

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

#include "Pair.h"

int main(int argc, char **argv) {
    Pair<std::string> ps;
    std::string x("foo"), y("bar");

    ps.set_first(x);
    ps.set_second(y);
    ps.Reverse();
    std::cout << ps.get_first() << std::endl;

    return 0;
}
```

main.cc

C++'s standard library

Consists of four major pieces:

- the entire C standard library
- C++'s input/output stream library
 - ▶ `std::cin`, `std::cout`, `stringstreams`, `fstreams`, etc.
- C++'s standard template library (**STL**)
 - ▶ containers, iterators, algorithms (sort, find, etc.), numerics
- C++'s miscellaneous library
 - ▶ strings, exceptions, memory allocation, localization

STL :)

Containers!

- a container is an object that stores (in memory) a collection of other objects (elements)
 - ▶ implemented as class templates, so hugely flexible
- several different classes of container
 - ▶ sequence containers (vector, deque, list)
 - ▶ associative containers (set, map, multiset, multimap, bitset)
- differ in algorithmic cost, supported operations

STL :(

STL containers store by value, not by reference

- when you insert an object, the container makes a copy
- if the container needs to rearrange objects, it makes copies
 - ▶ e.g., if you sort a vector, it will make many many copies
 - ▶ e.g., if you insert into a map, that may trigger several copies
- what if you don't want this (disabled copy ctr, or copy is \$\$)?
 - ▶ you can insert a wrapper object with a pointer to the object
 - ▶ we'll learn about these "smart pointers" later

STL vector

A generic, dynamically resizable array

- elements are stored in contiguous memory locations
 - ▶ elements can be accessed using pointer arithmetic if you like
 - ▶ random access is $O(1)$ time
- adding / removing from the end is cheap (constant time)
- inserting / deleting from middle or start is expensive ($O(n)$)

Example

see Tracer.cc, Tracer.h, vectorfun.cc

STL iterator

Each container class has an associated iterator class

- used to iterate through elements of the container (duh!)
- some container iterators support more operations than others
 - ▶ all can be incremented (++ operator), copied, copy-cons'ed
 - ▶ some can be dereferenced on RHS (e.g., `x = *it;`)
 - ▶ some can be dereferenced on LHS (e.g., `*it = x;`)
 - ▶ some can be decremented (-- operator)
 - ▶ some support random access (`[]`, `+`, `-`, `+=`, `-=`, `<`, `>` operators)

Example

see [vectoriterator.cc](#)

Type inference [C++11]

the **'auto'** keyword can be used to infer types

- simplifies your life if, for example, functions return complicated types
- the expression using auto must contain explicit initialization for it to work

```
// Calculate and return a vector  
// containing all factors of n  
std::vector<int> Factors(int n);  
  
void foo(void) {  
    // Manually identified type  
    std::vector<int> facts1 =  
        Factors(324234);  
  
    // Inferred type  
    auto facts2 = Factors(12321);  
  
    // Compiler error here  
    auto facts3;  
}
```

Type inference [C++11]

Auto and iterators

- life becomes much simpler!

```
for (vector<Tracer>::iterator it = vec.begin(); it < vec.end(); it++) {  
    cout << *it << endl;  
}
```



```
for (auto it = vec.begin(); it < vec.end(); it++) {  
    cout << *it << endl;  
}
```

Range “for” statements [C++11]

Syntactic sugar that emulates Java’s “foreach”

- works with any sequence-y type
 - ▶ strings, initializer lists, arrays with an explicit length defined, STL containers that support iterators

```
// Prints out a string, one  
// character per line  
std::string str("hello");  
for (auto c : str) {  
    std::cout << c << endl;  
}
```

Combining auto with range for

see [vectoriterator_2011.cc](#)

STL algorithms

A set of functions to be used on ranges of elements

- range: any sequence that can be accessed through iterators or pointers, like arrays or some of the containers
- algorithms operate directly on values using assignment or copy constructors, rather than modifying container structure
- some do not modify elements
 - ▶ find, count, for_each, min_element, binary_search, etc.
- some do modify elements
 - ▶ sort, transform, copy, swap, etc.

Example

see vectoralgorithms.cc

STL list

A generic doubly-linked list

- elements are **not** stored in contiguous memory locations
 - ▶ does not support random access (cannot do `list[5]`)
- some operations are much more efficient than vectors
 - ▶ constant time insertion, deletion anywhere in list
 - ▶ can iterate forward or backwards
- has a built-in sort member function
 - ▶ no copies; manipulates list structure instead of element values

Example

see listexample.cc

STL map

A key/value table, implemented as a tree

- elements stored in sorted order
 - ▶ key value must support less-than operator
- keys must be unique
 - ▶ multimap allows duplicate keys
- efficient lookup ($O(\log n)$) and insertion ($O(\log n)$)

Example

see [mapexample.cc](#)

New in C++ 11

unordered_map, unordered_set

- and related classes: unordered_multimap, unordered_multiset
- average case for key access is $O(1)$
 - ▶ But range iterators can be less efficient than ordered map/set
- See C++ Primer, online references for details

Exercise 1

Take one of the books from HW2's test_tree, and:

- read in the book, split it into words (you can use your HW2)
- for each word, insert the word into an STL map
 - ▶ the key is the word, the value is an integer
 - ▶ the value should keep track of how many times you've seen the word, so each time you encounter the word, increment its map element
 - ▶ thus, build a histogram of word count
- print out the histogram in order, sorted by word count
- bonus: plot the histogram on a log/log scale (use excel, gnuplot, ...)
 - ▶ xaxis: $\log(\text{word number})$, y-axis: $\log(\text{word count})$

Exercise 2

Using the `Tracer.cc/.h` file from lecture:

- construct a vector of lists of Tracers
 - ▶ i.e., a vector container, each element is a list of Tracers
- observe how many copies happen. :)
 - ▶ use the “sort” algorithm to sort the vector
 - ▶ use the “list.sort()” function to sort each list

See you on Friday!