CSE 333

Lecture 12 - templates, STL

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Administrivia

New exercise out today. Due before class Wednesday.

HW2 due Thursday night, 11 pm.

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;
}
```

functiontemplate.cc

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;  // bug!
  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:

nontypeparameter.cc

```
#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;
}
```

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.cc

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 con, or copy $$)?
    - you can insert a wrapper object with a pointer to the object
    - we'll learn about these "smart pointers" later

http://www.cplusplus.com/reference/stl/vector/vector/

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

http://www.cplusplus.com/reference/algorithm/

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 vectoralgos.cc

http://www.cplusplus.com/reference/stl/list/

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

http://www.cplusplus.com/reference/stl/map/

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(word number), y-axis: log(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 Wednesday!