C++ Templates and the STL
CSE 333

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Administrivia

- Homework 2 due **tomorrow night** (7/18)
  - File system crawler, indexer, and search engine
  - Don't forget to clone your repo to double-/triple-/quadruple-check compilation, execution, and tests!
    - If your code won't build or run when we clone it, well … you should have caught that …

Lecture Outline

- **Templates**
- The C++ Standard Template Library

Suppose that…

- You want to write a function to compare two ints
- You want to write a function to compare two doubles
  - 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 double &value1, const double &value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}
```

Hm…

- The two implementations of `compare` are nearly identical!
  - What if we wanted a version of `compare` for *every* comparable type?
  - We could write (many) more functions, but that's obviously wasteful and redundant

- What we'd prefer to do is write "*generic code*"
  - Code that is type-independent

C++ Parametric Polymorphism

- C++ has the notion of templates
  - A function or class that accepts a ***type*** as a parameter
  - You define 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

Function Templates

- Template to **compare** two "things":

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

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename T>   // <...> can also be written <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<int>(10, 20) << std::endl;
  std::cout << compare<double>(50.5, 50.6) << std::endl;
  std::cout << compare<std::string>(h, w) << std::endl;
  return EXIT_SUCCESS;
}
```

functiontemplate.cc

Compiler Inference

- 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 <typename 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; // ok
  std::cout << compare(h, w) << std::endl;   // ok
  std::cout << compare("Hello", "World") << std::endl;  // hm…
  return EXIT_SUCCESS;
}
```

functiontemplate_infer.cc

How Do Templates Work?

```
#include "compare.h"

int main(int argc, char **argv) {
  std::cout << compare(10, 20)
  std::cout << std::endl;
  return EXIT_SUCCESS;
}

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

```
int comp(const int& a, const int& b) {
  if (a < b) return -1;
  if (b < a) return 1;
  return 0;
}
```

- At ***compile-time***, the compiler will generate the "specialized" code from your template using the types you provided

How Do Templates Work?

- At ***compile-time***, the compiler will generate the "specialized" code from your template using the types you provided
  - Your template definition is NOT runnable code
  - Code is *only* generated if you use your template
  - Code is specialized for the specific types of data used in the template instance (e.g.: code for < on ints differs from code for < on strings)

How Do Templates Work?

- The compiler doesn't generate any code when it sees the template 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 (kind of like macro expansion)
    - The compiler generates template instantiations for *each* type used as a template parameter

```
compare.h: In instantiation of 'int comp(const T&, const T&) [with T
= Pair<int>]':
main.cc:10:26:   required from here
   10 |   cout << comp<Pair<int>>(Pair<int>(), Pair<int>());
      |           ~~~~~~~~~~~~~~~^~~~~~~~~~~~~~~~~~~~~~~~~
compare.h:6:9: error: no match for 'operator<' (operand types are
'const Pair<int>' and 'const Pair<int>')
    6 |   if (a < b) return -1;
      |       ~~^~~
compare.h:7:9: error: no match for 'operator<' (operand types are
'const Pair<int>' and 'const Pair<int>')
    7 |   if (b < a) return 1;
      |       ~~^~~
```

Template Instantiation Creates a Problem

```
#ifndef COMPARE_H_
#define COMPARE_H_

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

#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 EXIT_SUCCESS;
```

```
undefined reference to
`int comp<int>(int const&, int const&)
```

```
#include "compare.h"

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

compare.cc

Solution #1 (Google Style Guide prefers)

```
#ifndef COMPARE_H_
#define COMPARE_H_

template <typename 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 EXIT_SUCCESS;
}
```

main.cc

Solution #2 (you'll see this sometimes)

```
#ifndef COMPARE_H_
#define COMPARE_H_

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

#include "compare.cc"

#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 EXIT_SUCCESS;
}
```

main.cc

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

compare.cc

Pretty much the only time you'll see a #include of anything that's not a .h

Template Non-types

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

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

// return pointer to new N-element heap array filled with val
// (not entirely realistic, but shows what's possible)
template <typename T, int N>
T* varray(const T &val) {
  T* a = new T[N];
  for (int i = 0; i < N; ++i)
    a[i] = val;
  return a;
}

int main(int argc, char **argv) {
  int *ip = varray<int, 10>(17);
  string *sp = varray<string, 17>("hello");
  ...
}
```

The compiler can unroll this loop! It's a constant length in every instantiation

valtemplate.cc

Class Templates

- Templates are useful for classes as well
  - (In fact, that was one of the main motivations for templates!)

- Imagine we want a class that holds a pair of things that we can:
  - Set the value of the first thing
  - Set the value of the second thing
  - Get the value of the first thing
  - Get the value of the second thing
  - Swap the values of the things
  - Print the pair of things

Pair Class Definition

Pair.h

```
#ifndef PAIR_H_
#define PAIR_H_

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

  Thing get_first() const { return first_; }
  Thing get_second() const { return second_; }
  void set_first(const Thing &copyme);
  void set_second(const Thing &copyme);
  void Swap();

 private:
  Thing first_, second_;
};

#include "Pair.cc" // or put entire template def here

#endif  // PAIR_H_
```

Pair Function Definitions

Pair.cc

```
template <typename Thing>
void Pair<Thing>::set_first(const Thing &copyme) {
  first_ = copyme;
}

template <typename Thing>
void Pair<Thing>::set_second(const Thing &copyme) {
  second_ = copyme;
}

template <typename Thing>
void Pair<Thing>::Swap() {
  Thing tmp = first_;
  first_ = second_;
  second_ = tmp;
}

template <typename T>
std::ostream &operator<<(std::ostream &out, const Pair<T>& p) {
  return out << "Pair(" << p.get_first() << ", "
             << p.get_second() << ")";
}
```

Using Pair

usepair.cc

```
#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.Swap();
  std::cout << ps << std::endl;

  return EXIT_SUCCESS;
}
```

More Flexible Pair Class Definition

Pair.h

```
#ifndef PAIR_H_
#define PAIR_H_

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

  Thing get_first() const { return first_; }
  Stuff get_second() const { return second_; }
  void set_first(const Thing &copyme);
  void set_second(const Stuff &copyme);
  void Swap();

 private:
  Thing first_;
  Stuff second_;
};

#include "Pair.cc" // or put entire template def here

#endif  // PAIR_H_
```

Class Template Notes (look in *Primer* for more)

- `Thing` is replaced with template argument when class is instantiated
  - The class template parameter name is in scope of the template class definition and can be freely used there
- Class template member functions are template functions with template parameters that match those of the class template
  - These member functions must be defined as template function outside of the class template definition (if not written inline)
    - The template parameter name does *not* need to match that used in the template class definition, but really should
- Only template methods that are actually called in your program are instantiated

Lecture Outline

- Templates
- **The C++ Standard Template Library**
  - **Containers: vector**
  - Iterators

C++'s Standard Library

- C++'s Standard Library consists of four major pieces:

1) The entire C standard library

2) C++'s input/output stream library
   - std::cin, std::cout, stringstreams, fstreams, etc.

3) C++'s miscellaneous library
   - Strings, exceptions, memory allocation, localization

4) C++'s standard template library (**STL**) ☞
   - Containers, iterators, algorithms (sort, find, etc.), numerics

STL Containers ☺

- A container is an object that stores (in memory) a collection of other objects (elements)
  - Implemented as class templates, so hugely flexible
  - More info in *C++ Primer* §9, 11

- Several different classes of container
  - Sequence containers (`vector`, `deque`, `list`, `...`)
  - Associative containers (`set`, `map`, `multiset`, `multimap`, `bitset`, `...`)
  - Differ in algorithmic cost and supported operations

STL Containers ☹️

- 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 constructor or copying is expensive)?
    - You can insert a wrapper object with a pointer to the object
      - We'll learn about these "smart pointers" soon

STL `vector`

- A generic, dynamically resizable array
  - http://www.cplusplus.com/reference/stl/vector/vector/
  - Elements are store in *contiguous* memory locations
    - Elements can be accessed using pointer arithmetic if you'd like
    - Random access is O(1) time
  - Adding/removing from the end is cheap (amortized constant time)
  - Inserting/deleting from the middle or start is expensive (linear time)

Tracer Class

- Wrapper class for an `int` `value_`
  - Class and member definitions can be found in Tracer.h and Tracer.cc
- Useful for tracing behaviors of containers
  - All methods print identifying messages
  - Unique `id_` allows you to follow individual instances

Tracer Example Walkthrough

See:

`Tracer.h`

`Tracer.cc`

`vectorfun.cc`

Why All the Copying?

- What's going on here?
- Answer: a C++ vector (like Java's ArrayList) is initially small, but grows if needed as elements are added
  - Implemented by allocating a new, larger underlying array, copy existing elements to new array, and then replace previous array with new one
- And vector starts out *really* small by default, so it needs to grow almost immediately!
  - But you can specify an initial capacity if "really small" is an inefficient initial size (use "reserve" member function)
  - Example: see vectorcap.cc

Lecture Outline

- Templates
- **The C++ Standard Template Library**
  - Containers: vector
  - **Iterators**

STL `iterator`

- Each container class has an associated iterator class (*e.g.* `vector<int>::iterator`) used to iterate through elements of the container
  - http://www.cplusplus.com/reference/std/iterator/
  - Iterator range is from `.begin()` up to `.end()`
    - `end` is one past the last container element!
  - Some container iterators support more operations than others
    - All can be incremented (`++`), copied, copy-constructed
    - Some can be dereferenced on RHS (*e.g.* `x = *it;`)
    - Some can be dereferenced on LHS (*e.g.* `*it = x;`)
    - Some can be decremented (`--`)
    - Some support more (`[]`, `+`, `-`, `+=`, `-=`, `<`, `>` operators)

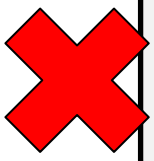
iterator Example

vectoriterator.cc

```
#include <vector>

#include "Tracer.h"

using namespace std;

int main(int argc, char** argv) {
  Tracer a, b, c;
  vector<Tracer> vec;

  vec.push_back(a);
  vec.push_back(b);
  vec.push_back(c);

  cout << "Iterating:" << endl;
  vector<Tracer>::iterator it;
  for (it = vec.begin(); it < vec.end(); it++) {
    cout << *it << endl;
  }
  cout << "Done iterating!" << endl;
  return EXIT_SUCCESS;
}
```

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;
}
```

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` Statement (C++11)

- Syntactic sugar similar to Java's `foreach`

```
for ( declaration : expression ) {
  statements
}
```

  - *`declaration`* defines loop variable
  - *`expression`* is an object representing a sequen
    - Strings, initializer lists, arrays with an explicit length
      containers that support iterators

```
// Prints out a string, o
// character per line
std::string str("h   llo");

for ( auto c : str ) {
  std::cout << c << std::endl;
}
```

Copy of the character

Updated `iterator` Example

vectoriterator_2011.cc

```
#include <vector>

#include "Tracer.h"

using namespace std;

int main(int argc, char** argv) {
  Tracer a, b, c;
  vector<Tracer> vec;

  vec.push_back(a);
  vec.push_back(b);
  vec.push_back(c);

  cout << "Iterating:" << endl;
  for (auto & p : vec) {   // p is a reference (alias) of vec
    cout << p << endl;     // element here; not a new copy
  }
  cout << "Done iterating!" << endl;
  return EXIT_SUCCESS;
}
```

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
  - General form: `algorithm(begin, end, ...);`
- Algorithms operate directly on range *elements* rather than the containers they live in
  - Make use of elements' copy ctor, =, ==, !=, <
  - Some do not modify elements
    - *e.g.* find, count, for_each, min_element, binary_search
  - Some do modify elements
    - *e.g.* sort, transform, copy, swap

Algorithms Example

vectoralgos.cc

```
#include <vector>
#include <algorithm>
#include "Tracer.h"
using namespace std;

void PrintOut(const Tracer& p) {
  cout << " printout: " << p << endl;
}

int main(int argc, char** argv) {
  Tracer a, b, c;
  vector<Tracer> vec;

  vec.push_back(c);
  vec.push_back(a);
  vec.push_back(b);
  cout << "sort:" << endl;
  sort(vec.begin(), vec.end());
  cout << "done sort!" << endl;
  for_each(vec.begin(), vec.end(), &PrintOut);
  return EXIT_SUCCESS;
}
```

Administrivia

- Homework 2 due **tomorrow night** (7/18)
  - Don't forget to clone your repo to double-/triple-/quadruple-check compilation, execution, and tests!

Review Questions (both template and class issues)

- Why are only `get_first()` and `get_second()` const?
- Why do the accessor methods return `Thing` and not references?
- Why is `operator<<` not a `friend` function?
- What happens in the default constructor when `Thing` is a class?
- In the execution of `Swap()`, how many times are each of the following invoked (assuming `Thing` is a class)?

  ctor _____ cctor _____ op= _____ dtor _____

Extra Exercise #1

- Using the `Tracer.h/.cc` files from lecture:
  - Construct a vector of lists of Tracers
    - *i.e.* a `vector` container with each element being a `list` of `Tracer`s
  - Observe how many copies happen ☺️
    - Use the sort algorithm to sort the vector
    - Use the `list.sort()` function to sort each list