C++ Templates

CSE 333 Winter 2025

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Administrivia

- Homework 2 due tomorrow (2/6)
  - 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…
- No new exercises until after hw2 due
  - Next exercise out Friday, due Monday
- Midterm exam a week from tomorrow (Thur. 2/13, 5-6pm)
  - Topic list and old exams on website now (exams link on resources page)
  - Closed book, slides, etc., but you may have one 5x8 notecard with whatever handwritten notes you want on both sides
    - Free blank cards available in class later this week and next ☺
  - Review in sections next week

Administrivia (2)

- HW1 feedback available now on gradescope. Notes:
  - If you have questions or spot problems use a gradescope regrade request to ask (not ed, not email). That will route it to the right person to answer
  - Remember that does-it-work and code quality are two different scores with two max point values. The scales are not the same, and it makes no sense to add the numbers together (even though gradescope insists on doing exactly that)
  - HW1 bonus work not graded yet – will try to get to it before too long, but wanted to return feedback on basic part to everyone and not hold that up for the bonus parts
    - (And bonus scores will be on a separate 0-5 or 0-10 scale. They do not contribute to initial class grades; they are added in afterwards.)

Lecture Outline

- **Templates**

Suppose that…

- You want to write a function to compare two ints
- You want to write a function to compare two strings
  - 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;
}
```

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
  - Code that is compile-type polymorphic across types

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
  - 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)

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<std::string>(h, w) << std::endl;
  std::cout << compare<double>(50.5, 50.6) << 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

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");
  ...
}
```

valtemplate.cc

What's Going On?

- 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

This 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;
}
```

main.cc

```
#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

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(Thing &copyme);
  void set_second(Thing &copyme);
  void Swap();

 private:
  Thing first_, second_;
};

#include "Pair.cc" // or (better?) put entire template def here

#endif  // _PAIR_H_
```

Pair Function Definitions

Pair.cc

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

template <typename Thing>
void Pair<Thing>::set_second(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;
}
```

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 to minimize reader confusion
  - Only template methods that are actually called in your program are instantiated (but this is an implementation detail)