Poll Everywhere

pollev.com/cse333

About how long did Exercise 6 take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn't submit / I prefer not to say

C++ Templates

CSE 333 Summer 2023

Instructor: Timmy Yang

Teaching Assistants:

Jennifer Xu Leanna Nguyen Pedro Amarante

Sara Deutscher Tanmay Shah

Relevant Course Information

- Exercise 7 due Wednesday (7/19) @ 1pm!
  - Builds off Exercise 6
  - Uses content from last Friday's lecture
- Homework 2 due Thursday (7/20) @ 11:59pm
  - Don't forget to clone your repo to double-/triple-/quadruple-check compilation!
  - Don't be afraid to use late days if you can't finish & polish your submission – they exist for a reason
- Quiz 2: Open Mon. (7/24) @ 2pm to Wed. (7/26) @ 11:59pm
  - Same format as Quiz 1
  - Individual, but high-level discussion allowed ("Gilligan's Island Rule")

Lecture Outline

- **Templates**

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

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;//-1
  std::cout << compare<std::string>(h, w) << std::endl; //-1
  std::cout << compare<double>(50.5, 50.6) << std::endl; //-1
  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;
}
```

compiler infers char*

-1

-1

1

comparing char*

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* valarray(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 = valarray<int, 10>(17);
  string *sp = valarray<string, 17>("hello");
  ...
}
```

valtemplate.cc

What's Going On?

- The compiler doesn't generate any code when it sees the template function definition
  - It doesn't know what code to generate yet, since it doesn't know what types are involved Different behavior for different types

- 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

g++ -c main.cc
↳ no definition of comp<>

```
#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

g++ -c compare.cc
↳ produces empty .o file

```
#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

g++ main.o compare.o
↳ Linker error! no def of comp<int>

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

less hiding of implementation

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

Poll Everywhere

pollev.com/cse333

Which is the *simplest* way to compile our program (`a.out`)?

- Assume we are using Solution #2 (`.h` includes `.cc`)

A. `g++ main.cc`

B. `g++ main.cc compare.cc`

C. `g++ main.cc compare.h`

D. `g++ -c main.cc`
`g++ -c compare.cc`
`g++ main.o compare.o`

E. We're lost…

main.cc
#include compare.h
↓
#include compare.cc

Makefile
a.out: main.cc compare.h
compare.cc
g++ main.cc

Class Templates

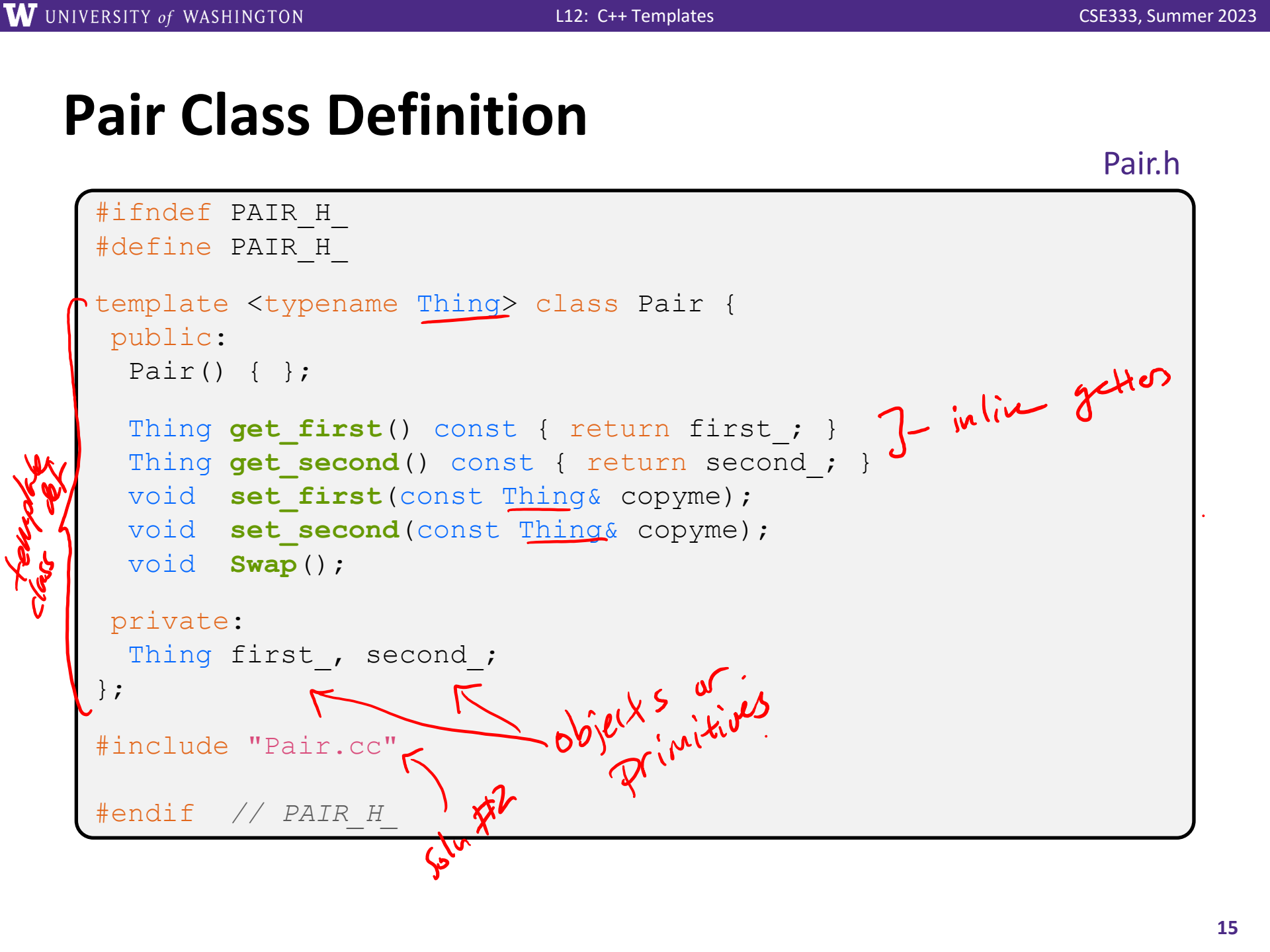
- Templates are useful for classes as well
  - (In fact, that was one of the main motivations for templates!)

- 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"

#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; // Invokes default ctor
  std::string x("foo"), y("bar");

  ps.set_first(x); // ("foo", )
  ps.set_second(y); // ("foo", "bar")
  ps.Swap();        // ("bar", "foo")
  std::cout << ps << std::endl; // Invokes non-member op<< func

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

Review Questions (Classes and Templates)

- Why are only `get_first()` and `get_second()` const?
  Accessors don't modify the class instance. Can (and should) declare const.
  Setters/Mutators like Swap() do modify the class can't be const.
- Why do the accessor methods return `Thing` and not references?
  References allow modification of private data members.
  This violates the "private" access modifier, return a copy instead.
- Why is `operator<<` not a `friend` function?
  Doesn't need access to private data members, can just use accessors like get_first() and get_second()
- What happens in the default constructor when `Thing` is a class?
  Calls default constructor on both first_ and second_,
  compiler error if no default ctor defined
- In the execution of `Swap()`, how many times are each of the following invoked (assuming `Thing` is a class)?

ctor 0 cctor 1 (tmp) op= 2 (first_, second_) dtor 1 (tmp)

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 standard template library (**STL**) ☜
     - Containers, iterators, algorithms (sort, find, etc.), numerics
  4) 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
  - More info in *C++ Primer* §9.2, 11.2

section

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

index numerically

index by value