http://web.stanford.edu/class/cs106l/

Template Functions

What else in C++ can be generalized? What is the philosophy behind generalization?

CS106L - Winter 2024

Attendance: midquarter evaluation!

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Agenda

01. **Recap: Iterators & Template Classes**

02. **Template Functions**
Type deduction, lvalues and rvalues

03. **Template metaprogramming**
Gaming the system

04. **Introduction to Algorithms**
Prepping for Thursday!

Template Functions

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Review: Iterators

Containers all implement something called an iterator to do this!

- Iterators let you access **all** data in **all** containers programmatically!
- An iterator has a certain **order**; it “knows” what element will come next
  - Not necessarily the same each time you iterate!

Review: Iterators

All containers implement iterators, but they're not all the same!

- Each container has its own iterator, which can have different behavior.
- All iterators implement a few shared operations:
  - Initializing → `iter = s.begin();`
  - Incrementing → `++iter;`
  - Dereferencing → `*iter;`
  - Comparing → `iter != s.end();`
  - Copying → `new_iter = iter;`

Review: Iterators

```
for ( auto iter = set.begin() ; iter != set.end(); ; ++iter ) {
```

Now we can access each element individually!

If we want the element and not just a reference to it, we dereference (*iter).

```
const auto& elem = *iter;
```

Review: Template Classes

- Add `template<typename T1, typename T2..>` before class definition in .h
- Add `template<typename T1, typename T2..>` before all function signature in .cpp
- When returning nested types (like iterator types), put `typename ClassName<T1, T2..>::member_type` as return type, not just `member_type`
- Templates don't emit code until instantiated, so `#include` the .cpp file in the .h file, not the other way around!

Review: Const and Const Correctness

- Use const parameters and variables wherever you can in application code
- Every member function of a class that doesn't change its member variables should be marked `const`
- auto will drop all const and &, so be sure to specify
- Make iterators and const_iterators for all your classes!
  - **`const iterator`** = cannot increment the iterator, can dereference and change underlying value
  - **`const_iterator`** = can increment the iterator, cannot dereference and change underlying value
  - **`const const_iterator`** = cannot increment iterator, cannot change underlying value

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C++ is strongly typed, but generic C++ lets you parametrize data types!

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C++ is strongly typed, but generic C++ lets you parametrize data types!

- Ex. variable return type or input in a class (template classes)

Can we parametrize even more?

Can we write a function that works on **any data type?**

Why not!

Let’s say we want a function to return the min of two ints!

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```
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  return a < b ? a : b;
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We take in two ints…

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And return an int!

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We take in two ints...

And return an int!

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int myMin(int a, int b) {
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```

What about doubles? Floats? Longs?

What about function overloading?

Sure, we

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Sure, we could…

```
int myMin(int a, int b) {
  return a < b ? a : b;
}

// exactly the same except for types
std::string my_min(std::string a, std::string b) {
  return a < b ? a : b;
}

int main() {
  auto min_int = myMin(1, 2);                 // 1
  auto min_name = myMin( "Fabio" , "Haven" );   // Fabio
}
```

What about function overloading?

Sure, we could…

What about other types?

```
int myMin(int a, int b) {
  return a < b ? a : b;
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// exactly the same except for types
std::string my_min(std::string a, std::string b) {
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int main() {
  auto min_int = myMin(1, 2);                    // 1
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}
```

Template functions:

Functions whose functionality can be adapted to more than one type or class without repeating the entire code for each type.

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Just like classes, they work regardless of type!

Let's break it down:

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Let's break it down:

```
template <typename Type>
Type myMin(Type a, Type b) {
  return a < b ? a : b;
}
```

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Just like classes, they work regardless of type!

Let's break it down:

Indicating this function is a template

Specifies that Type is generic

List of your template variables

```
template <typename Type>
Type myMin(Type a, Type b) {
  return a < b ? a : b;
}
```

Template functions are completely generic functions!

Just like classes, they work regardless of type!

Let's break it down:

Indicating this function is a template

The class keyword is interchangeable!

List of your template variables

```cpp
template <class Type>
Type myMin(Type a, Type b) {
  return a < b ? a : b;
}
```

Default Types

We can define default parameter types!

```
template <typename Type=int>
Type myMin(Type a, Type b) {
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}
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If a type isn't specified, it will default to int if possible!

Aside: Constraints and Concepts

As of C++20, we can limit the acceptable types in:

- template classes
- template functions
- non-template member functions of a template class

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A named set of constraints is a **concept**.

Aside: Constraints and Concepts

Constraints can be simple:

```
template<typename T>
concept Addable = requires (T a, T b)
{
    a + b; // "the expression a+b is a valid expression that will compile"
};

template<typename T> requires Addable<T> // requires-clause
T add(T a, T b) { return a + b; }
```

Source: cppreference.com

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Can also appear at the end of a function declaration (ex. forward declarations)

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template<Addable T>
T add(T a, T b) { return a + b; }
```

Source: cppreference.com

This shorthand also works!

Aside: Constraints and Concepts

Or they can be complex!

Core language concepts	Notes
same_as	
derived_from	
convertible_to	
common_reference_with	
common_with	
integral	
signed_integral	
unsigned_integral	
floating_point	
assignable_from	
swappable/swappable_with	
destructible	
constructible_from	
default_initializable	
move_constructible	
copy_constructible	

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Default Types

We can define default parameter types!

```
template <typename Type=int>
Type myMin(Type a, Type b) {
  return a < b ? a : b;
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What does it look like to use a template function?

Calling template functions

We can explicitly define what type we will pass, like this:

```
template <typename Type>
Type myMin(Type a, Type b) {
  return a < b ? a : b;
}

// int main() {} will be omitted from future examples
// we'll instead show the code that'd go inside it
cout << myMin<int>(3, 4) << endl; // 3
```

Calling template functions

We can **explicitly** define what type we will pass, like this:

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template <typename Type>
Type myMin(Type a, Type b) {
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cout << myMin<int>(3, 4) << endl; // 3
```

Just like in template classes!

Calling template functions

We can also **implicitly** leave it for the compiler to deduce!

```
template <typename T, typename U>
auto smarterMyMin(T a, U b) {
  return a < b ? a : b;
}

// int main() {} will be omitted from future examples
// we'll instead show the code that'd go inside it
cout << myMin(3.2, 4) << endl; // 3.2
```

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We might like explicit calling of a template function to specify number types if passed in as literals!

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Remember: like in template classes, **template functions are not compiled until used!**

- For each instantiation with different parameters, the compiler generates a new specific version of your template
- After compilation, it will look like you wrote each version yourself

Wait a minute...

The code doesn't exist until you instantiate it, which runs quicker.

Can we take advantage of this behavior?

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```
template<unsigned n>
struct Factorial {
  enum { value = n * Factorial<n - 1>::value };
};

template<> // template class "specialization"
struct Factorial<0> {
  enum { value = 1 };
};

std::cout << Factorial<10>::value << endl; // prints 3628800, but run during compile time!
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There are other ways in C++ to make code run during compile time.

The **`constexpr`** keyword specifies a constant expression.

- Constant expressions must be immediately initialized and will run at compile time!
- Passed arguments to constant expressions should be const/constant expressions as well.

Variables can also be declared as **`constexpr`** !

Aside: constexpr

constexpr is an institutionalization of template metaprogramming and is often more readable!

```
constexpr double fib(int n) { // function declared as constexpr
  if (n == 1) return 1;
  return fib(n-1) * n;
}

int main() {
  const long long bigval = fib(20);
  std: : cout << bigval << std::endl;
}
```

Why?

Overall, can increase performance for these pieces!

- Compiled code ends up being smaller

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TMP was an accident; it was discovered, not invented!

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- Game graphics

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Solving problems with generics

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What if we wanted to count all the occurrences of a character in a string?

Or a number in a vector?

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These are all the same problem!

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Let's take a look!

Summary

- Template functions allow you to parametrize the type of a function to be anything without changing functionality
- Generic programming can solve a complicated conceptual problem for any specifics – powerful and flexible!
- Template code is instantiated at compile time; template metaprogramming takes advantage of this to run code at compile time

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Thanks!

Next up: Functions and Lambdas!