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Template Functions

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

CS106L - Spring 2024

Template Functions

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Attendance: midquarter evaluation!

https://bit.ly/4dkSYj7

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Template Functions

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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!

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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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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) {
  return a < b ? a : b;
}
```

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?

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int myMin(int a, int b) {
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int main() {
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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.

Template functions are completely generic functions!

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;
}
```

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

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

```
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) {
  return a < b ? a : b;
}
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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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These limits or requirements on are called **constraints.**

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)

Source: cppreference.com

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

This shorthand also works!

Source: cppreference.com

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) {
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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
```

Template Functions

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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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- Passed arguments to constant expressions should be const/constant expressions as well.

Aside: `constexpr`

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!

Applications of TMP

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- Optimizing matrices/trees/other mathematical structure operations
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- Game graphics

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Solving problems with generics

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Or a number in a vector?

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Solving problems with generics

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

Or a number in a vector?

Or a word in a stream?

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!