Template Meta Programming

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Literature

[1] Boost c++ library.
`http://www.boost.org`.

[2] C++ reference.
`http://cppreference.com`.

[3] D. Abrahams and A. Gurtovoy.
C++ Template Metaprogramming: Concepts, Tools, and Techniques from Boost and Beyond.
Pearson Education, 2004.

[4] A. Alexandrescu.
Modern C++ design.
Addison-Wesley, 2001.

What is Template Meta Programming?

Programming using the template interface of C++ so that certain common computations can be carried out at compile time.

The "language" is functional in nature, no mutable data.

Advantages:

- Reduce code duplication
- Increase readability
- Move error checks to compile time
- More sophisticated type checking and lookup

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- Reduce code duplication
- Increase readability
- Move error checks to compile time
- More sophisticated type checking and lookup

- It is the next step in reducing code duplication over templates. While templates by themselves do a good job, using meta programming we can add additional checks and requirements on our types before choosing specialisations.
- Increase readability is a bit of an odd one as TMP is quite hard to read in my opinion. However, meta programming can be used to for example inline horrible low level algorithms into your code for specialised cases, and do for example loop unravelling and such. Leaving the code nice and readable while still being efficient at runtime.
- Always great to move error checks to happen as early as absolutely possible. Specially if a try-block is in a rarely executed part of your program. Also see our discussions on physics units in C++ to prevent other types of mistakes.

Looks familiar?

Type traits

```
template <class Itt>
void iterator_swap (Itt first, Itt second)
{
  typedef typename std::iterator_traits<Itt>::value_type
      iterator_deref_type;

  iterator_deref_type temp_value = *first;

  *first = *second;
  *second = temp_value;
}
```

Looks familiar?

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  iterator_deref_type temp_value = *first;

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  *second = temp_value;
}
```

First, ignore the fact that this is horribly optimized, and the fact that the problem here is easily solved by `auto`, also that it could be circumvented by using `std::swap`.

Also, `auto` doesn't necessarily give what you want when you have a proxy object with a conversion as `auto` will create an object of the same time, circumventing the conversion.

We ask the compiler to find out what type dereferencing the iterator gets us using the handy `iterator_traits` function. The iterator itself do not necessarily contain this information so `iterator_traits` must be specialised for say raw pointers. More on that in a bit.

Looks familiar?

enable_if (C++14)

```
template <
  class Itt,
  typename = std::enable_if_t<
    !std::is_same<
      typename std::iterator_traits<Itt>::value_type,
      void
     >::value
  >
>
void iterator_function (Itt first, Itt second)
{
  // ...
}
```

Looks familiar?

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  class Itt,
  typename = std::enable_if_t<
    !std::is_same<
      typename std::iterator_traits<Itt>::value_type,
      void
     >::value
  >
>
void iterator_function (Itt first, Itt second)
{
  // ...
}
```

Ignoring the SFINAE thingy going on, we basically ask the compiler to calculate the expression `!(Itt::value_type == void)` at compile time.

Recap: Template Specialisation

Heavily used in TMP to signal return paths and branch points for control structures.

iterator_traits

```
template <class Itt>
struct iterator_traits
{
  typedef typename Itt::value_type value_type;
};

template <class Type*>
struct iterator_traits
{
  typedef Type value_type;
};
```

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```

`iterator_traits`' existance is motivated by the fact that you can't call `::value_type` on a pointer. On top of that it is also useful in its own right, if only to create a unified interface for meta functions.

The Fundamental Theorem of Software Engineering (FTSE). We can solve any problem by introducing an extra level of indirection. (Butler Lampson)

When do you need typename?

typename is used to tell the compiler that what is coming up is a type. Used when you have a **dependent** name.

typename keyword

```
template <class Type>
typename traits_func<Type>::value_type //...
```

Exactly what traits_func<Type>::value_type is cannot be known at point of definition because of possible template specialisation. typename fixes that issue.

::value_type is said to be a dependent type.

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`::value_type` is said to be a dependent type.

Because of this it is generally a good idea to use the `class` keyword when giving a template a name so that it doesn't get mixed with typename's needed for dependent names.

When do you need template?

If the template class itself is a template, or has a template function, we need to tell the compiler.

template keyword

```
template <class Type, unsigned N>
void foo(int x)
{
  Type::function<N>(x);
};
```

which is interpreted as

```
(Type::function < N) > x;
```

When do you need `template`?

If the template class itself is a template, or has a template function, we need to tell the compiler.

`template` keyword

```
template <class Type, unsigned N>
void foo(int x)
{
  Type::template function<N>(x);
};
```

`template` is required when a **dependent** name access a template via `.`, `->` or `::`.

The Canonical Example

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

template<>
struct Factorial<0>
{
  enum { value = 1 };
};

int main(int, char**)
{
  std::cout << Factorial<10>::value << std::endl;
}
```

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Runtime constant

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int main(int, char**)
{
  std::cout << Factorial<10>::value << std::endl;
}
```

Runtime constant

Make use of the trick that for the compiler to be able to give you an object of type `Factorial`<10> it first need to initialise an object of type `Factorial`<9>, and so on. It continues until it hits the template specialisation `Factorial`<0> which we have predefined and requires no more initialisations.

Vocabulary

Metadata

A constant "value" accessible by calling `::value`

Metafunction

A function which takes its arguments as template arguments, and the result is stored in `::type`

```
some_metafunction<Arg1, Arg2>::type
```

Metafunction class

A function object that itself can be treated as a type. Function call accessed by a nested metafunction named `apply`

```
struct some_metafunction
{
  template <class Arg1, class Arg2>
  struct apply
  {
    // ...
  };
};
```

Vocabulary

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    // ...
  };
};
```

Metadata: Also known as an integral constant wrapper.

The metafunction class is the metaprogramming version of a functor, what you would pass to say STL library iterators such as `std::for_each` and `std::copy_if`. In metaprogramming this is even more important than normal as we rely much more heavily on passing function objects around when we have no mutable data.

Example: Multiplication

```
template <int N>
struct integer
{
  constexpr static int value = N;
  typedef integer type;
};

template <class Arg1, class Arg2>
struct multiply
{
  typedef integer< Arg1::value * Arg2::value > type;
};

int main(int, argc**)
{
  typedef integer<5> five;
  typedef integer<-9> m_nine;

  std::cout << multiply<five,m_nine>::type::value
    << std::endl;
}
```

Example: Multiplication

```
template <int N>
struct integer
{
  constexpr static int value = N;
  typedef integer type;
};

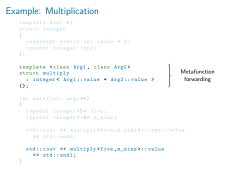
template <class Arg1, class Arg2>
struct multiply
  : integer< Arg1::value * Arg2::value >
{};

int main(int, argc**)
{
  typedef integer<5> five;
  typedef integer<-9> m_nine;

  std::cout << multiply<five,m_nine>::type::value
    << std::endl;

  std::cout << multiply<five,m_nine>::value
    << std::endl;
}
```

Metafunction forwarding



Function definition through inheritance is called metafunction forwarding, and it is one of the resons why we defined the type of the integer wrapper, so that we can more easily keep the language consistent.

See what we can access its value both through `multiply<x,y>::type::value` and `multiply<x,y>::value`. The first interface is expected to be there, while the second is a shortcut sometimes implemented into numerical metafunctions.

Higher Order Metafunctions

As TMP inherently is a functional programming language, it is best at doing those kind of computations, computations with functions.

Let us implement the `nest` function so that:

```
nest(f,x,5) = f(f(f(f(f(x)))))
```

Assume that the `integer` and `multiply` still are defined as previous.

Higher Order Metafunctions

```
template <class F, class X, unsigned N>
struct nest
  : nest<F, typename F::template apply<X>::type, N-1>
{};

template <class F, class X>
struct nest <F,X,0>
  : X
{};

struct squared_f
{
  template <class Arg>
  struct apply
    : multiply<Arg,Arg>
  {};
};

int main(int, char**)
{
  typedef integer<5> five;
  nest<squared_f,five,3>::type::value; // ((5^2)^2)^2
}
```

Higher Order Metafunctions

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struct nest
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Template specialisation

Metafunction class

Higher Order Metafunctions

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Higher Order Metafunctions

```cpp
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struct nest
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int main(int, char**)
{
  typedef integer<5> five;
  nest<squared_f,five,3>::type::value; // ((5^2)^2)^2
}
```

First notice that we need to pass a metafunction class to `nest` as a metafunction without arguments isn't a type in itself. We cannot write `nest<multiply,Var,N>` because `multiply` isn't defined without it's template arguments. We will see in a bit that we can do exactly that (or something similar) using MPL placeholders, but more on that later.

The MPL boost library

Collection of useful types and definitions to simplify TMP

- Metadata wrappers:
  - bool_<b>, int_<N>, long_<N>, ...
- Arithmetic functions and logic operators:
  - plus<Arg1,Arg2>, times<Arg1,Arg2>, ...
  - less<Arg1,Arg2>, equal_to<Arg1,Arg2>, ...
  - and_<Arg>, or_<Arg>, nor_<Arg>

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  - `if_<Pred,Func1,Func2>`, `eval_if<Pred,Func1,Func2>`

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- Lambda functions and placeholders
- Type selection
  - `if_<Pred,Func1,Func2>`, `eval_if<Pred,Func1,Func2>`
- Containers and iterators
  - `vector<Arg1,Arg2,...,ArgN>`, `set<Arg1,Arg2,...,ArgN>`, ...
  - `next<It>`, `prior<It>`, `advance<It,N>`, ...
- STL like algorithm library
  - `transform<Seq,Fun>`, `copy_if<Seq,Pred>`, ...

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  - `next<It>`, `prior<It>`, `advance<It,N>`, ...
- STL like algorithm library
  - `transform<Seq,Fun>`, `copy_if<Seq,Pred>`, ...

Functions such as `if_<Pred,Func1,Func2>` takes as an argument a metadata object and returns the first type `Func1` if `Pred::type::value` is `true` and the type `Func2` if it is `false`. There are also integer version of most such functions, denoted by an `_c`, so that e.g. `if_c<bool,Func1,Func2>` can be passed a bool instead of a metadata for convenience.

Remember that TMP has no mutable objects, so e.g. `transform` will return the transformed sequence rather than copying it to another sequece object (or itself).

Lambda functions and placeholders

First!

We will assume that we have the following header on all our code to reduce the examples:

```
namespace mpl = boost::mpl;
using namespace mpl::placeholders;
```

If not, we would have to write the following everywhere we wanted an MPL placeholder:

```
boost::mpl::placeholders::_1,
boost::mpl::placeholders::_2,
boost::mpl::placeholders::_3, ...
```

which gets tedious...

Lambda functions and placeholders

Lambda functions are a signature part of any functional programming language and also go very well with STL like algorithms.

From our example earlier with `square_f<Arg>`, that function in itself seems a bit redundant as it can easily be written as `multiply<Arg,Arg>` with the same argument. But we run into two problems:

- The `multiply` function is a metafunction, while the `nest` function takes a metafunction class (a functor).
- We have no way of reducing `multiply`'s argument list to only take one argument

MPL's placeholders solve this!

Lambda functions and placeholders

With MPL lambda functions

```
template <class F, class X, unsigned N>
struct nest
  : nest<F, typename F::template apply<X>::type, N-1>
{};

template <class F, class X>
struct nest <F,X,0>
  : X
{};

int main(int, char**)
{
  typedef integer<5> five;
  nest<
    mpl::lambda< multiply<_1,_1> >::type,five,3
  >::type::value;
}
```

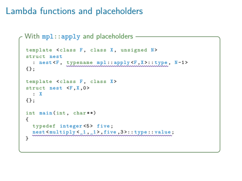
Lambda functions and placeholders

With mpl::apply and placeholders

```
template <class F, class X, unsigned N>
struct nest
  : nest<F, typename mpl::apply<F,X>::type, N-1>
{};

template <class F, class X>
struct nest <F,X,0>
  : X
{};

int main(int, char**)
{
  typedef integer<5> five;
  nest<multiply<_1,_1>,five,3>::type::value;
}
```



First option is to use `mpl::lambda` to change the call to `nest` without changing nest itself. As one can see, using the MPL lambda functions is very flexible and can easily be incorporated to work with existing metaprograms.

The special `mpl::apply` function scans the `Func` type and turns it into a metafunction class if it contains any placeholders.

Could of course use `mpl::int_<N>` and `mpl::times<Arg1,Arg2>` throughout, but we will stick with our previously defined metadata and metafunctions to see that they are compatible with the rest of boost.

Control structures

Previously: Used template specialisation to switch between implementations

Simple template specialisation

```
template <class Type, bool FastImpl>
struct algorithm
{
  void operator() (const Type &)
  {
    // faster algorithm
  }
};

template <class Type>
struct algorithm<Type,false>
{
  void operator() (const Type &)
  {
    // safer algorithm
  }
};
```

Specialised for `FastImpl = false`

Control structures

With TMP we can do more sophisticated checks and switches

One more level of indirection

```
struct fast_algorithm
{
  template <class Itt1, class Itt2>
  static void execute(Itt1, Itt2);
};

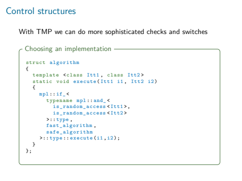
struct safe_algorithm
{
  template <class Itt1, class Itt2>
  static void execute(Itt1, Itt2);
};
```

Control structures

With TMP we can do more sophisticated checks and switches

Choosing an implementation

```
struct algorithm
{
  template <class Itt1, class Itt2>
  static void execute(Itt1 i1, Itt2 i2)
  {
    mpl::if_<
      typename mpl::and_<
        is_random_access<Itt1>,
        is_random_access<Itt2>
      >::type,
      fast_algorithm,
      safe_algorithm
    >::type::execute(i1,i2);
  }
};
```



See that we have a unified interface that itself makes sure that it isn't misused and chooses the correct implementation depending on the type it is given.

Example usage: could unify the STL sort algorithm. `std::sort` only takes random access operators, while things such as `std::set` and `std::map` come pre sorted and `std::list` have a sorting member function. Could write a function that takes arbitrary containers or iterators and use the correct implementation behind the scene. Drawback: hides the complexity of the operation.

Containers and iterators

boost provides a complete STL like container and algorithm library.

Different containers have different access concepts

Forward sequence
`begin<S>`, `end<S>`, `size<S>`, `front<S>`
`push_front<S,x>`, `pop_front<S>`
`insert<S,it,x>`, `erase<S,it>`, `clear<s>`
Bidirectional sequence
..., `back<S>`, `push_back<S,x>`, `pop_back<S>`
Random access sequence
..., `at<S,n>`

All functions return new sequences because we have no mutable objects.

Containers and iterators: Short example

mpl::transform and mpl::vector

```
typedef mpl::vector<
  integer<3>, integer<7>, integer<-1> > my_vector;   ←── ●

typedef mpl::transform<
  my_vector,
  multiply<_1,_1>
>::type square_vector;

typedef mpl::begin<square_vector>::type begin;
typedef mpl::next<begin>::type next;

mpl::is_same<
  mpl::deref<next>::type,
  integer<49>
>::value;
```

$$\{\ 3,\ 7,\ -1\ \}$$

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```

true

Where to go from here?

Try it for yourself!

Where to go from here?

Try it for yourself!

- Try to write simple programs
  - Calculate an arithmetic sum
  - Sum up the elements of a vector
  - Implement your own for-loop
  - ...
- Study the literature
- Familiarise yourself with the boost MPL library
- See if you can make use of type switching in your own programs
- See if you can catch potential errors in your own programs

Summary

- We have seen how we can use the C++ template system to write metaprograms that look like normal programs.
- Metadata are types that contain their value in a public `::value` type.
- Metafunctions are called by their public `::type` type

```
some_metafunction<Arg1,Arg2,...,ArgN>::type
```

- Language facilitates a functional programming style with functions that manipulate other functions
- boost's MPL library implement a lot of useful metafuntions and types