https://github.com/zwimer/TemplateMetaTutorial

This presentation is **under construction**. External files above

C++ Template Meta

A basic introduction to basic C++ techniques used in template metaprogramming.

Important reminder

Otherwise identical classes with different template classes are **NOT** the same class!

For example:

- list<bool> != list<char>
- vector<int> != vector<double>
- list< list<int> > != list< list<char> >

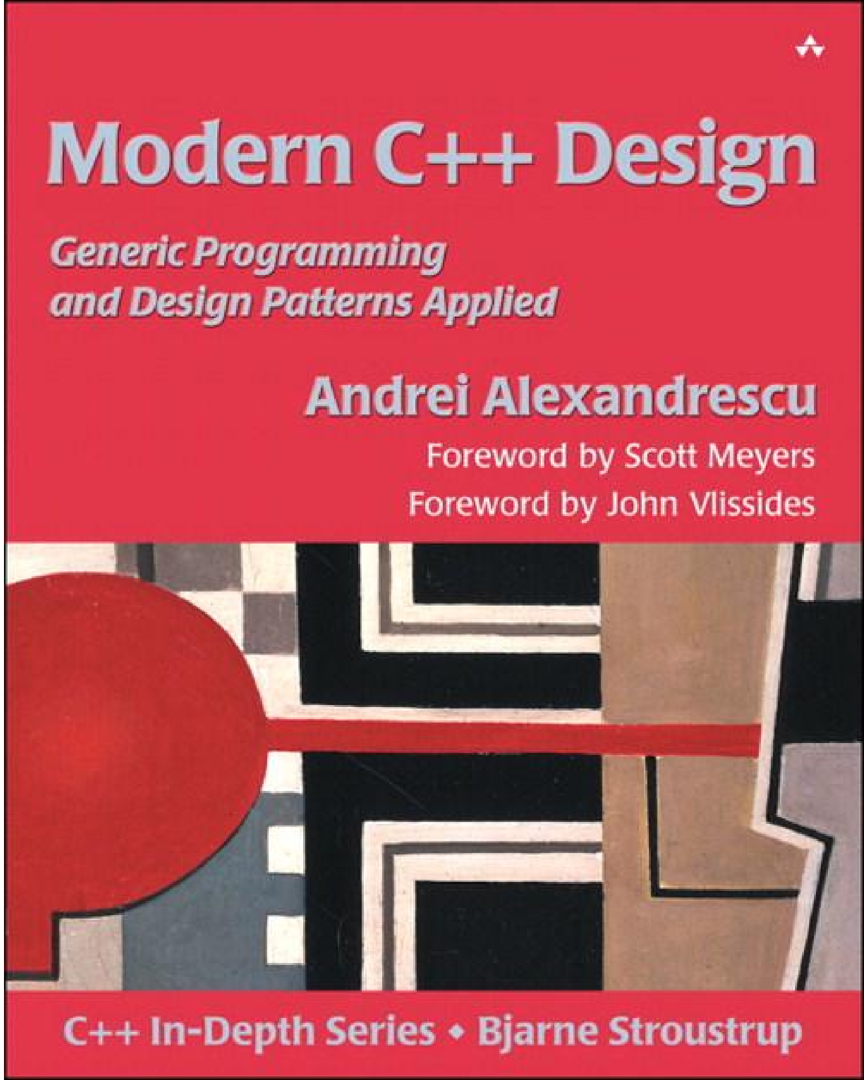
What you will learn

I will be teaching you using this book ->

We will be going over chapter's 2 and 3, techniques and typelists respectively.

If you would rather read it directly than listen to me, the links is here:

https://www.mimuw.edu.pl/~mrp/cpp/SecretCPP/Addison-Wesley%20-%20Modern%20C++%20Design.%20Generic%20Programming%20and%20Design%20Patterns%20Applied.pdf



What is TMP?

What is it?

- Code that is ‘run’ and evaluated at compile time
- ‘Compile time programming’
  - Immutable objects
  - Functional programming
- Can create
  - Data Structures
  - Compile time constants
  - Functions
- Takes advantage of templates to do this

Factorial: Run-Time vs. Compile-Time

```cpp
// Run time programming
unsigned int factorial(unsigned int n) {
        return n == 0 ? 1 : n * factorial(n - 1);
}


// Usage examples:
// factorial(0) would yield 1;
// factorial(4) would yield 24.
```

// Everything is evaluated at run-time

//Slower to run, faster to compile

```cpp
// Template Meta
//Recursive case
template <unsigned int n> struct factorial {
        enum { value = n * factorial<n - 1>::value };
};

// Base case
template <> struct factorial<0> {
        enum { value = 1 };
};

// Usage examples:
// factorial<0>::value would yield 1;
// factorial<4>::value would yield 24.
```

// Everything is evaluated at compile-time

//Faster to run, slower to compile

Factorial: Why does it work?

- <u>Remember</u>: factorial<N> is a class!
- factorial<4> != factorial<3>
    - They are <u>***different classes!***</u>
- Enum's are like static const ints
    - Though they are not the same, but that isn't relevant at the moment
- *Enums **<u>must</u>** be evaluated at compile time!*

```cpp
// Template Meta
template <unsigned int N> struct factorial {
        enum { value = N * factorial<N - 1>::value };
};

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

// Usage examples:
// factorial<0>::value would yield 1;
// factorial<4>::value would yield 24.

// Everything is evaluated at compile-time
```

Factorial: Why does it work?

- <u>Remember</u>: factorial<N> is a class!
- factorial<4> != factorial<3>
  - They are ***<u>different classes!</u>***
- Enum's are like static const ints
  - Though they are not the same, but that isn't relevant at the moment
- *Enums **<u>must</u>** be evaluated at compile time!*

Thus, the **<u>class</u>** factorial<4> has a will always have an enum 'value' with a value of N*factorial<N-1>::value that is *defined* at compile time.

```
// Template Meta
template <unsigned int N> struct factorial {
    enum { value = N * factorial<N - 1>::value };
};

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

// Usage examples:
// factorial<0>::value would yield 1;
// factorial<4>::value would yield 24.

// Everything is evaluated at compile-time
```

Weird Notation?

- Why do we have to say factorial<4>::value?
- <u>factorial<4> is a class</u>

- We want the value of the enum ‘value’ within the class factorial<4>

factorial<4>::value

```
// Template Meta
template <unsigned int N> struct factorial {
        enum { value = N * factorial<N - 1>::value };
};

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

// Usage examples:
// factorial<0>::value would yield 1;
// factorial<4>::value would yield 24.

// Everything is evaluated at compile-time
```

Did I peak your interest?

1. If you just came to see what this was on, hopefully I intrigued you enough to stay.

2. Next I am going to show you a few basic techniques

3. Before I do, <u>questions</u> on what TMP is?

Basic Techniques

Things to note

- I am going to teach you in **C++99**
- Most of what you are about to learn is *now* built into c++11, c++14, c++17, or their stl libraries.
- The rest exists in other libraries such as stl Loki, Blitz++, boost mpl, ipl, and boost::hana

Why Learn LEgacy Techniques?

1. These are fundamental techniques used in TMP
2. Many of these you will use anyway, just with a pretty wrapper around them
3. **To help you learn the TMP way of thinking, and better understand how to program in TMP**

Common Practice in TMP

1. Macros used as wrappers
   - Normally macros should be avoided, but in TMP it is common to have them wrappers
   - Functions can also be used as wrappers, *but they add overhead*
   - Not always all caps when wrappers
2. Structs with a typedef or enum that stores the result of a computation
   - Structs like this will often replace variables

```
// Template Meta
template <unsigned int N> struct _Factorial {
        enum { value = N * _Factorial<N - 1>::value };
};

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

// Factorial Wrapper
#define factorial(x) _Factorial<x>::value

// Usage examples:
// factorial(0) would yield 1;
// factorial(4) would yield 24.
```

Template Specialization

- One of the key elements in TMP
- When a template function / class is called, C++ algorithm matches it's call to the 'closest' matching 'most specialized' template it can

```
// Template Meta
template <unsigned int N> struct _Factorial {
	enum { value = N * _Factorial<N - 1>::value };
};

//Note that here we have template <>
//This is FULL template specialization
//We then specify what arguments in the class name
template <> struct _Factorial<0> {
	enum { value = 1 };
};

// Factorial Wrapper
#define factorial(x) _Factorial<x>::value

 // Usage examples:
// factorial(0) would yield 1;
// factorial(4) would yield 24.
```

Partial Template Specialization

- One of the key elements in TMP
- Note: This is **ONLY** allowed for classes and structs. It is not allowed for functions.

```
// Template Meta
template <int N, int N2> struct Division {
        enum { value = N / N2 };
};

//Note that here we have only one int in our template
//This is partial template specialization.
//We then specify what the arguments are below
template <int N> struct Division<N, 0> {
        enum { value = INT_MAX };
};

 // Usage examples:
// Division<4,2>::value would yield 1;
// Division<4,0>::value would yield INT_MAX.
```

Static assertions (Compile Time Assertions)

- Now standard in c++11 via static_assert

- TMP debugging is oft trying to make the program simply compile
- A simple compile time assertion
    - Makes debugging easier
    - Clearer error messages

- Trivial method without TMP.
    - Do you foresee any shortcomings?

```
//If A is false, char[0] is called, which is illegal
//If A is true, char[1] is called, then goes out of scope
#define STATIC_CHECK(A) {                                   \
        char test[ (A) ? 1 : 0 ];                           \
}

// Usage examples:
// STATIC_CHECK( 1 + 1 == 2 ) would compile
// STATIC_CHECK( 1 + 1 == 3 ) would not compile
```

Static assertions (Compile Time Assertions)

- Now standard in c++11 via static_assert

- Compiler may throw a warning instead of error
- What if you want a custom error message?

- What about a trivial TMP Method that utilizes incomplete instantiation?

```
//Declare the struct
template <bool> struct CompileTimeError;

//Define the struct for true
template <> struct CompileTimeError<true> {};

// Wrapper
#define STATIC_CHECK(A) CompileTimeError<A>()

// Usage examples:
// STATIC_CHECK( 1 + 1 == 2 ) would compile
// STATIC_CHECK( 1 + 1 == 3 ) may yield, depending
// on your compiler:
```

```
a.cpp: In function 'int main()':
a.cpp:8:29: error: invalid use of incomplete type 'struct CompileTi
meError<false>'
  CompileTimeError<2+1 == 2>();
                             ^
a.cpp:3:23: error: declaration of 'struct CompileTimeError<false>'
 template<bool> struct CompileTimeError;
                       ^
```

Static assertions (Compile Time Assertions)

- Now standard in c++11 via static_assert

- This is better, but what if we want a custom error message for <u>each</u> static assert?
  - Sidenote: Copy pasting and changing the name of the struct is bad...

```
//Declare the struct
template <bool> struct CompileTimeError;

//Define the struct for true
template <> struct CompileTimeError<true> {};

// Wrapper
#define STATIC_CHECK(A) CompileTimeError<A>()

// Usage examples:
// STATIC_CHECK( 1 + 1 == 2 ) would compile
// STATIC_CHECK( 1 + 1 == 3 ) may yield, depending
// on your compiler:
```

```
a.cpp: In function 'int main()':
a.cpp:8:29: error: invalid use of incomplete type 'struct CompileTi
meError<false>'
  CompileTimeError<2+1 == 2>();
                            ^
a.cpp:3:23: error: declaration of 'struct CompileTimeError<false>'
 template<bool> struct CompileTimeError;
                       ^
```

Static assertions (Compile Time Assertions)

- Now standard in c++11 via static_assert

UNDER CONSTRUCTION

- Macros to the rescue!
- Macros are not uncommon in TMP.
  - And smart usage can lead to better code

Mapping to Types

- Standard in many TMP libraries. Ex. Boost::Hana::Type

- One of the key elements in TMP
- Allow values and types to be declared **without** being instantiated
  - Save space
  - Save time
  - Prevent side effects
  - Allow compile time manipulation
- We **will** use these later.

```
//Map an integer to a type
template <int N> struct IntToType {
	enum { value = N };
};

//Map a type to a type
template <class T> struct TypeToType {
	typedef T value;
};
```

Second point

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Final point

A one-line description of it

“This is a super-important quote”

– From an expert

This is the most important takeaway that everyone has to remember.

THANKS!

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