Modern C++ Programming

9. C++ Templates and Meta-programming II

Federico Busato

University of Verona, Dept. of Computer Science
2021, v3.04

Table of Context

Class Template

Class Template

In a similar way to function templates, **class templates** are used to build a family of classes

```
template<typename T>
struct A { // templated class (typename template)
    T x = 0;
};

template<int N1>
struct B { // templated class (numeric template)
    const int N = N1;
};

A<int>    a1; // a1.x is int    = 0
A<float>  a2; // a2.x is float  = 0.0f
A<double> a4; // a3.x is double = 0.0
B<1>      b1; // b1.N is 1
B<2>      b2; // b2.N is 2
```

Template Class Constructor

C++17 introduces *automatic* deduction of class template arguments for object constructor

```
template<typename T, typename R>
struct A {
    A(T x, R y) {}
};

A<int, float> a1(3, 4.0f); // < C++17
A             a2(3, 4.0f); // C++17
```

The *main difference* with template functions is that classes can be **partially** specialized

Note: Every class specialization (both partial and full) is a completely **new class** and it does not share anything with the generic class

```
template<typename T, typename R>
struct A {              // generic template class
    T x;
};

template<typename T>
struct A<T, int> {     // partial specialization
    T y;
};

template<>
struct A<float, int> { // full specialization
    float z;
};
```

Template Class Specialization


```
template<typename T, typename R>
struct A {              // generic template class
    T x;
};

template<typename T>
struct A<T, int> {      // partial specialization
    T y;
};

A<float, float> a1;
a1.x;    // ok
// a1.y; // compile error

A<float, int> a2;
a2.y;    // ok
// a2.x; // compile error
```

```cpp
#include <iostream>
template<typename T, typename R>
struct A {                // generic template class
    void f() { std::cout << "A<T, R>"; }
};

template<typename T>
struct A<T, int> {        // partial specialization
    void f() { std::cout << "A<T, int>"; }
};

A<float, float> a1;
a1.f();  // print "A<T, R>"

A<float, int> a2;
a2.f();  // print "A<T, int>"
```

Example 1: Implement a Simple Type Trait

```
template<typename T, typename R> // GENERIC template declaration
struct is_same {
    static const bool value = false;
};

template<typename T>
struct is_same<T, T> {          // PARTIAL template specialization
    static const bool value = true;
};

template<>
struct is_same<int, double> { // FULL template specialization
    static const bool value = true;
};

cout << is_same<int,    char>::value; // print false
cout << is_same<float, float>::value; // print true
cout << is_same<int,  double>::value; // print true
```

Example 2: Check if a Pointer is `const`

```cpp
#include <type_traits>

// std::true_type, std::false_type contain a field "value"
//    set to true or false respectively

template<typename T>
struct is_const_pointer : std::false_type {};

template<typename R>    // const R*  specialization
struct is_const_pointer<const R*> : std::true_type {};

cout << is_const_pointer<int*>::value;       // print false
cout << is_const_pointer<const int*>::value; // print true
cout << is_const_pointer<int* const>::value; // print false
```

Example 3: Compare Class Templates

```cpp
#include <type_traits>

template<typename T> struct A {};
template<typename T> struct B {};

template<typename T, typename R>
struct Compare : std::false_type {};

template<typename T, typename R>
struct Compare<A<T>, A<R>> : std::true_type {};

cout << Compare<int, float>::value;        // false
cout << Compare<int, int>::value;          // false
cout << Compare<B<int>, B<int>>::value;    // false
cout << Compare<A<int>, B<int>>::value;    // false
cout << Compare<A<int>, A<float>>::value; // true
```

Given a template class and a template member function

```
template<typename T, typename R>
struct A {
    template<typename X, typename Y>
    void f();
};
```

There are two ways to specialize the class/function:

- **Generic class, generic function**
- **Full class specialization, generic/full specialization function**

```cpp
template<typename T, typename R>
template<typename X, typename Y>
void A<T, R>::f() {}
// ok, A<T, R> and f<X, Y> are not specialized

template<>
template<typename X, typename Y>
void A<int, int>::f() {}
//  ok, A<int, int> is full specialized
//  ok, f<X, Y> is not specialized

template<>
template<>
void A<int, int>::f<int, int>() {}
//  ok, A<int, int> and f<int, int> are full specialize
```

Errors

```cpp
template<typename T>
template<typename X, typename Y>
void A<T, int>::f() {}
// error A<T, int> is partially specialized
//      (A<T, int> class is not declared)

template<typename T, typename R>
template<typename X>
void A<T, R>::f<int, X>() {}
// error function members cannot be partially specialized

template<typename T, typename R>
template<>
void A<T, R>::f<int, int>() {}
// error function members of a unspecialized class cannot
//       be specialized
```

`virtual` Function and Template

Virtual functions cannot have template arguments

- **Templates** are a compile-time feature
- **Virtual functions** are a run-time feature

Full story:
The reason for the language disallowing the particular construct is that there are potentially infinite different types that could be instantiating your template member function, and that in turn means that the compiler would have to generate code to dynamically dispatch those many types, which is infeasible

`stackoverflow.com/a/79682130`

Class Template Hierarchy

Member of class templates can be used *internally* in derived class templates by specifying the particular type of the base class with the keyword `using`

```
template<typename T>
struct A {
    T x;
    void f() {}
};

template<typename T>
struct B : A<T> {
    using A<T>::x;  // needed (may be also a specialization)
    using A<T>::f;  // needed

    void g() {
        x;   // without 'using': this->x
        f();
    }
};
```

friend Keyword

```cpp
template<typename T>             struct A {};
template<typename T, typename R> struct B {};
template<typename T>             void f() {}
//----------------------------------------------------------------

class C {
    friend class A<int>;                  // match only A<int>

    template<typename> friend class A; // match all A templates

//  template<typename T> friend class B<int, T>;
//      partial specialization cannot be declared as a friend

    friend void f<int>();                    // match only f<int>

    template<typename T> friend void f(); // match all templates
};
```

Template Dependent Names (`template` Keyword)

The `template` keyword tells the compiler that what follows is a *function template*, and not a member data

This is important when there are two (or more) *dependent names*

```cpp
template<typename T>
struct A {
    template<typename R>
    void g() {}
};

template<typename T>   // (A<T> is a dependent name (from T)
void f(A<T> a) {
//  a.g<int>();   compile error
//                g<int> is a dependent name (from int)
//                interpreted as: "(a.g < int) > ()"
    a.template g<int>(); // ok
}
```

Template Template Arguments

Template template parameters match *templates* instead of concrete types

```
template<typename T> struct A {};
template<typename T> struct B {};

template<template <typename> class R>
struct B {
    R<int>   x;
    R<float> y;
};
template<template <typename> class R, typename S>
void f(R<S> x) {}  // works with every class and type

f( A<int>() );
f( B<float>() );
B<A> y;
```

Template Variable

C++14 allows the creation of variables that are templated

Template variable can be considered a special case of template class

```
template<typename T>
constexpr T pi{ 3.1415926535897932385 }; // variable template

template<typename T>
T circular_area(T r) {
    return pi<T> * r * r; // pi<T> is a variable template
}                         // instantiation

circular_area(3.3f); // float
circular_area(3.3);  // double
// circular_area(3); // compile error
                     // narrowing conversion on "pi"
```

Template Meta-Programming

Template Meta-Programming

"Metaprogramming is the writing of computer programs with the ability to ***treat programs as their data****. It means that a program could be designed to read, generate, analyse or transform other programs, and even modify itself while running"*

"Template meta-programming refers to uses of the C++ template system to ***perform computation at compile-time*** *within the code. Templates meta-programming include compile-time constants, data structures, and complete functions"*

Template Meta-Programming

- **Template Meta-Programming is fast** (runtime)
  Template Metaprogramming is computed at compile-time
  (nothing is computed at run-time)
- **Template Meta-Programming is Turing Complete***
  Template Metaprogramming is capable of expressing all tasks that standard programming language can accomplish
- **Template Meta-Programming requires longer compile time**
  Template recursion heavily slows down the compile time, and requires much more memory than compiling standard code
- **Template Meta-Programming is complex**
  Everything is expressed recursively. Hard to read, hard to write, and also very hard to debug

* `Full Proof that C++ Grammar is Undecidable`

Example 1: `Factorial`

```cpp
template <int N>
struct Factorial {       // specialization: recursive step
    static const int value = N * Factorial<N - 1>::value;
};

template <>
struct Factorial<0> {   // specialization: base case
    static const int value = 1;
};


int x = Factorial<5>::value;      // 120
// int y = Factorial<-1>::value; // Infinite recursion :)
```

Example 1: `Factorial` (Notes)

The previous example can be easily written as a `constexpr` in C++14

```
template <typename T>
constexpr int factorial(T value) {
    T tmp = 1;
    for (int i = 2; i <= value; i++)
        tmp *= i;
    return tmp;
};
```

Advantages:

- Easy to read and write (easy to debug)
- Faster compile time (no recursion)
- Works with different types (`typename T`)
- Works at run-time *and* compile-time

Example 2: Log2

```
template <int N>
struct Log2 {
    static_assert(N > 0, "N must be greater than zero");

    static const int value = 1 + Log2<N / 2>::value;
};

template <>
struct Log2<1> {   // partial specialization: base case
    static const int value = 0;
};

int x = Log2<20>::value; // 4
```

Example 3: Log

```cpp
template <int A, int B>
struct Max {
    static const int value = A > B ? A : B;
};

template <int N, int BASE>
struct Log {      // specialization: recursive step
    static_assert(N > 0,    "N must be greater than zero");
    static_assert(BASE > 0, "BASE must be greater than zero");

    static const int TMP   = Max<1, N / BASE>::value;
    static const int value = 1 + Log<TMP, BASE>::value;
};

template <int BASE>
struct Log<1, BASE> {   // partial specialization: base case
    static const int value = 0;
};

int x = Log<20, 2>::value; // 4
```

Example 4: Unroll (Compile-time/Run-time Mix) ★

```
template<int MAX_VALUE, int STEP = 0>
struct Unroll {                              // recursive step
    template<typename Op>
    static void run(Op op) {
        op(STEP);
        Unroll<MAX_VALUE, STEP + 1>::run(op);
    }
};

template<int MAX_VALUE>
struct Unroll<MAX_VALUE, MAX_VALUE> { // base case
    template<typename Op>             // (specialization)
    static void run(Op) {}
};

auto lambda = [](int step) { cout << step << ", "; };
Unroll<5>::run(lambda);  // print 0, 1, 2, 3, 4
```

SFINAE:
Substitution Failure
Is Not An Error

SFINAE

SFINAE

Substitution Failure Is Not An Error (SFINAE) applies during overload resolution of function templates. When substituting the deduced type for the template parameter fails, the specialization is discarded from the overload set *instead* of causing a compile error

The Problem

```
template<typename T>
T ceil_div(T value, T div);

unsigned ceil_div<unsigned>(unsigned value, unsigned div) {
    return (value + div - 1) / div;
}

int ceil_div<int>(int value, int div) { // handle negative values
    return (value > 0) ^ (div > 0) ?
           (value / div) : (value + div - 1) / div;
}
```

What about `long long int`, `long long unsigned`, `short`, `unsigned short`, etc.?

`std::enable_if` Type Trait

The most common way to adopt `SFINAE` is using the `std::enable_if/std::enable_if_t` type traits

`std::enable_if` allows a function template or a class template specialization to include or exclude itself from a set of matching functions/classes

```
template<bool B, class T = void>
struct enable_if {
//  "type" is not defined of "B = false"
};
template<class T>
struct enable_if<true, T> {
    using type = T;
};
```

helper alias: `std::enable_if_t<T>` instead of `typename std::enable_if<T>::type`

Function SFINAE (return type)


```
#include <type_traits>

template<typename T>
std::enable_if_t<std::is_signed_v<T>>
f(T) {
    cout << "signed";
}

template<typename T>
std::enable_if_t<!std::is_signed_v<T>>
f(T) {
    cout << "unsigned";
}

f(1);  // print "signed"
f(1u); // print "unsigned"
```

```cpp
#include <type_traits>

template<typename T>
void g(std::enable_if_t<std::is_signed_v<T>, T>) {
    cout << "signed";
}

template<typename T>
void g(std::enable_if_t<!std::is_signed_v<T>, T>) {
    cout << "unsigned";
}

h(1);  // print "signed"
h(1u); // print "unsigned"
```

Function SFINAE (hidden parameter)

```cpp
#include <type_traits>

template<typename T>
void h(T,
       std::enable_if_t<std::is_signed_v<T>, int> = 0) {
    cout << "signed";
}

template<typename T>
void h(T,
       std::enable_if_t<!std::is_signed_v<T>, int> = 0) {
    cout << "unsigned";
}

h(1);  // print "signed"
h(1u); // print "unsigned"
```

```cpp
#include <type_traits>
template<typename T, typename R>
decltype(T{} + R{}) add(T a, R b) { // T{} + R{} is not possible
    return a + b;                   // with A
}

template<typename T>
std::enable_if_t<std::is_class_v<T>, T> // int is not a class
add(T a, T b) {
    return a;
}

struct A {};

add(1, 2);     // return 3
add(A{}, A{}); // add() not supported
```

```cpp
#include <type_traits>

template<typename T,
         std::enable_if_t<std::is_signed_v<T>, int> = 0>
void f(T) {}

template<typename T,
         std::enable_if_t<!std::is_signed_v<T>, int> = 0>
void f(T) {}

f(4);
f(4u);
```

Function SFINAE Example

Array vs. Pointer:

```cpp
#include <type_traits>

template<typename T, int Size>
void f(T (&array)[Size]) {} // (1)

template<typename T>
std::enable_if_t<std::is_pointer_v<T>>
f(T array) {} // (2)


int* ptr;
int  array[3];
f(ptr);   // call (2)
f(array); // call (1), without std::is_pointer_v calls (2)
```

Class SFINAE

```cpp
#include <type_traits>

template <typename T, typename Enable = void>
struct A;

template <typename T>
struct A<T, std::enable_if_t<std::is_signed_v<T>>>
{};

template <typename T>
struct A<T, std::enable_if_t<!std::is_signed_v<T>>>
{};

A<int>;
A<unsigned>;
```

Class + Function SFINAE ★

```cpp
#include <type_traits>

template <typename T>
class A {
//  this does not work because T depends on A, not on h
//  void h(T,
//          std::enable_if_t<std::is_signed_v<T>, int> = 0) {
//      cout << "signed";
//  }
    template<typename R = T> // now R dependes on h
    void h(R,
            std::enable_if_t<std::is_signed_v<R>, int> = 0) {
        cout << "signed";
    }
};

A<int>;
```

Check Struct Member ★ 1/3

`SFINAE` can be also used to check if a structure has a specific data member or type

Let consider the following structures:

```
struct A {
    static int x;
    int        y;
    using type = int;
};

struct B {};
```

```cpp
#include <type_traits>
template<typename T, typename = void>
struct has_x : std::false_type {};

template<typename T>
struct has_x<T, decltype((void) T::x)> : std::true_type {};

template<typename T, typename = void>
struct has_y : std::false_type {};

template<typename T>
struct has_y<T, decltype((void) std::declval<T>().y)>
                                   : std::true_type {};

has_x< A >::value; // returns true
has_x< B >::value; // returns false
has_y< A >::value; // returns true
has_y< B >::value; // returns false
```

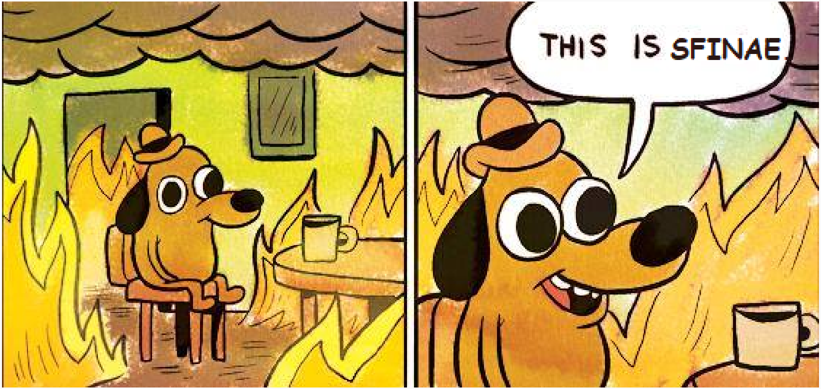
Check Struct Member - Type ★ 3/3

```cpp
template<typename...>
using void_t = void;  // included in C++17 <utility>

template<typename T, typename = void>
struct has_type : std::false_type {};

template<typename T>
struct has_type<T,
                std::void_t<typename T::R> > : std::true_type {};

has_type< A >::value; // returns true
has_type< B >::value; // returns false
```

Support Trait for Stream Operator ★

```cpp
template<typename T>
using EnableP = decltype( std::declval<std::ostream&>() <<
                          std::declval<T>() );

template<typename T, typename = void>
struct is_stream_supported : std::false_type {};

template<typename T>
struct is_stream_supported<T, EnableP<T>> : std::true_type {};

struct A {};

is_stream_supported<int>::value; // returns true
is_stream_supported<A>::value;   // returns false
```

SFINAE



https://twitter.com/IAmErikN/status/1252316405724336128

Variadic Templates

Variadic Template

Variadic template

Variadic templates (C++11), also called *template parameter pack*, are templates that take a variable number of arguments of any type

```
template<typename... TArgs> // variadic typename
void f(TArgs... args) {     // typename expansion
    args...;                // arguments expansion
}
```

Note: Variadic parameter must be the last one in the declaration

The number of variadic arguments can be retrieved with the `sizeof...` operator

```
sizeof...(args);
```

Variadic Template - Example

```
template<typename T, typename R>
auto add(T a, R b) {                        // base case
    return a + b;
}

// recursive case
template<typename T, typename... TArgs>  // variadic typename
auto add(T a, TArgs... args) {             // typename expansion
    return a + add(args...);               // parameters expansion
}

add(2, 3.0);       // 5
add(2, 3.0, 4);    // 9
add(2, 3.0, 4, 5); // 14
// add(2);         // compile error the base case
                   // accepts two parameters
```

Variadic Template - Parameter Types

```
template<typename... TArgs>
void f(TArgs... args) {}         // generic

template<typename... TArgs>
void g(const TArgs&... args) {}  // force "const references"

template<typename... TArgs>
void h(TArgs*... args) {}        // force "pointers"

// list of "pointers" followed by a list of "const references"
template<typename... TArgs1, typename... TArgs2>
void f2(const TArgs1*... args, const TArgs2& ...va) {}

f(1, 2.0);
g(1, 2.0);
int* a, *b;
h(a, b);
f2(a, b, 3);
```

Variadic Template - Function Application

```cpp
template<typename T>
T square(T value) { return value * value; }

template<typename T, typename R>
auto add(T a, R b) { return a + b; }    // base case

template<typename T, typename... TArgs> // recursive case
auto add(T a, TArgs... args) {
    return a + add(args...);
}
//-------------------------------------------------------------
template<typename... TArgs>
auto add_square(TArgs... args) {
    return add(square(args)...); // square is applied to
}                                // variadic arguments

add_square(2, 2, 3.0f); // returns 17.0f
```

Variadic Template - Arguments to Array

```cpp
#include <array>

// all arguments must have the same type
template<typename... TArgs>
auto f(TArgs... args) {
    std::array array{args...};                          // >= C++17
//  std::array<sizeof...(args), int> array{args...}; // <= C++14
    for (auto x : array)
        cout << x << " ";
}

f(1, 2, 3); // print "1 2 3"
```

C++17 **Folding expressions** perform a *fold* of a template parameter pack over a *binary* operator

Unary/Binary folding

```
template<typename... Args>
auto add_unary(Args... args) {  // Unary folding
    return (... + args);  // unfold: 1 + 2.0f + 3ull
}

template<typename... Args>
auto add_binary(Args... args) { // Binary folding
    return (1 + ... + args);    // unfold: 1 + 1 + 2.0f + 3ull
}

add_unary(1, 2.0f, 3ll);  // returns 6.0f (float)
add_binary(1, 2.0f, 3ll); // returns 7.0f (float)
```

Same example of “Variadic Template - Function Application” ...
but shorter

```
template<typename T>
T square(T value) { return value * value; }

template<typename... TArgs>
auto add_square(TArgs... args) {
    return (square(args) + ...); // square is applied to
}                                // variadic arguments

add_square(2, 2, 3.0f); // returns 17.0f
```

Variadic Template and Meta-Programming

```cpp
template<int... NArgs>
struct Add;               // data structure declaration

template<int N1, int N2>
struct Add<N1, N2> {    // base case
    static const int value = N1 + N2;
};

template<int N1, int... NArgs>
struct Add<N1, NArgs...> {  // recursive case
    static const int value = N1 + Add<NArgs...>::value;
};

Add<2, 3, 4>::value; // returns 9
// Add<>;            // compile error (no match)
// Add<2>::value;    // compile error (fall in Add<>)
```

Variadic Class Template ⋆

Variadic Template can be used to build recursive data structures

```cpp
template<typename... TArgs>
struct Tuple;       // data structure declaration

template<typename T>
struct Tuple<T> {   // base case
    T value;        // specialization with one parameter
};

template<typename T, typename... TArgs>
struct Tuple<T, TArgs...> {  // recursive case
    T              value;    // specialization with more
    Tuple<TArgs...> tail;    // than one parameter
};

Tuple<int, float, char> t1 { 2, 2.0, 'a' };
t1.value;            // 2
t1.tail.value;       // 2.0
t1.tail.tail.value;  // 'a'
```

Get function arity at compile-time:

```cpp
template <typename T>
struct GetArity;

// generic function pointer
template<typename R, typename... Args>
struct GetArity<R(*)(Args...)> {
    static const int value = sizeof...(Args);
};

// generic function reference
template<typename R, typename... Args>
struct GetArity<R(&)(Args...)> {
    static const int value = sizeof...(Args);
};

// generic function object
template<typename R, typename... Args>
struct GetArity<R(Args...)> {
    static const int value = sizeof...(Args);
};
```

```cpp
void f(int, char, double) {}

int main() {
    // function object
    GetArity<decltype(f)>::value;

    auto& g = f;
    // function reference
    GetArity<decltype(g)>::value;

    // function reference
    GetArity<decltype((f))>::value;

    auto* h = f;
    // function pointer
    GetArity<decltype(h)>::value;
}
```

Full Story:
stackoverflow.com/a/27867127

Variadic Template and Class Specialization ★ 2/2

Get `operator()` (and `lambda`) arity at compile-time:

```
template <typename T>
struct GetArity;

template<typename R, typename C, typename... Args>
struct GetArity<R(C::*)(Args...)> {         // class member
    static const int value = sizeof...(Args);
};

template<typename R, typename C, typename... Args>
struct GetArity<R(C::*)(Args...) const> {  // "const" class member
    static const int value = sizeof...(Args);
};

struct A {
    void operator()(char, char) {}
    void operator()(char, char) const {}
};

GetArity<A>::value;       // call GetArity<R(C::*)(Args...)>
GetArity<const A>::value; // call GetArity<R(C::*)(Args...) const>
```