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Reply-to: Matúš Chochlík(chochlik@gmail.com)

Static reflection (rev. 2)

Matúš Chochlík

Abstract In N3996 [1] we presented some ideas on the design and possible implementation of a compile-time reflection facility for standard C++. N3996 also contained extensive discussion about usefulness of reflection, description of several use-cases and motivational examples from the Mirror reflection utilities [2]. The actual proposal was however found to be confusing in some points. This paper tries to make the proposal more concise and detailed.

Contents

1. Introduction

Reflection and reflective programming can be used for a wide range of tasks, such as the implementation of serialization-like operations, object-relational mapping, remote procedure calls, scripting, automated GUI-generation, implementation of several software design patterns, etc. C++ as one of the most prevalent programming languages lacks a standardized reflection facility.

In this paper we propose to add native support for compile-time reflection to C++ by the means of compiler generated types providing basic metadata describing various program constructs. These metaobjects, together with some additions to the standard library can later be used to implement other third-party libraries providing both compile-time and run-time high-level reflection utilities.

The basic static metadata provided by compile-time reflection should be as complete as possible to be applicable in a wide range of scenarios and allow to implement custom higher-level static and dynamic reflection libraries and reflection-based utilities.

1.1. Differences between n3996 and n4111

This proposal (n4111) is a conceptual successor of n3996 [1], but it has been rewritten nearly from scratch (some parts of the text were reused). The main differences are listed here:

- n3996 included a brief introduction to reflection, a discussion of its usefulness and presented several use-cases.
- n3996 included multiple examples from the Mirror reflection utilities [2], for example the factory generator.
- In n3996, the metaobject concepts were described just conceptually and a possible renderings of the concepts into valid C++ were discussed. In n4111 the definition of the concepts is more detailed, specific and includes concrete definitions of what should be added to the standard and hints how certain concepts could be implemented.
- The definition of several concepts was changed. For example
  - the requirements for the *MetaNamedScoped* concept were moved to the *MetaNamed* concept,
  - the string which is the result of the `base_name` template class has been changed,
  - the definition of the `named_typedef` and the `named_mem_var` template classed is more detailed,

    – some of the metaobject attributes (rendered as template classes) were renamed.

- This proposal includes additions to the standard library.
- The appendices in n4111 include concrete examples of usage of the proposed metaobjects and the added template classes.

2. Metaobject concepts

We propose that the basic metadata describing a program written in C++ should be made available through a set of *anonymous* types and related functions and templates defined by the compiler. These types should describe various program constructs like, namespaces, types, typedefs, classes, their member variables (member data), member functions, inheritance, templates, template parameters, enumerated values, etc.

The compiler should generate metadata for the program constructs defined in the currently processed translation unit. Indexed sets (ranges) of metaobjects, like scope members, parameters of a function, etc. should be listed in the order of appearance in the processed source code.

Since we want the metadata to be available at compile-time, different base-level constructs should be reflected by *"statically" different* metaobjects and thus by *different* types. For example a metaobject reflecting the global scope namespace should be a different *type* than a metaobject reflecting the `std` namespace, a metaobject reflecting the `int` type should have a different type then a metaobject reflecting the `double` type, a metaobject reflecting `::foo(int)` function should have a different type than a metaobject reflecting `::foo(double)`, function, etc.

In a manner of speaking these special types (metaobjects) should become "instances" of the meta-level concepts (static interfaces which should not exist as concrete types, but rather only at the "specification-level" similar for example to the iterator concepts). This section describes a set of metaobject concepts, their interfaces, tag types for metaobject classification and functions (or operators) providing access to the metaobjects.

This section conceptualy describes the requirements that various metaobjects need to satisfy in order to be considered models of the individual concepts.

Unless stated otherwise all additions proposed and described below should go into the `std` namespace. Alternatively, if any of the definitions proposed here clash with existing members (or new members proposed elsewhere) of the `std` namespace then they can be nested in a namespace like `std::meta` or `std::mirror`.

Also note, that in the sections below, the exaples use names for concrete metaobjects, like `__meta_std_string`, etc.. This convention is *NOT* part of this proposal. The actual naming of the metaobjects should be left to the compiler implementations and for all purposes from the users point of view the metaobjects should be anonymous types.

2.1. Categorization and Traits

In order to provide means for distinguishing between regular types and metaobjects generated by the compiler, the `is_metaobject` trait should be added to the `std` namespace (even if a nested namespace like `std::meta` is used for everything else) and should inherit from `true_type` for metaobjects (types generated by the compiler providing metadata) and from `false_type` for non-metaobjects (native or user defined types):

```
template <typename T>
struct is_metaobject
 : false_type
{ };
```

2.1.1. Metaobject category tags

To distiguish between various metaobject kinds (satisfying different concepts as described below) a set of tag `structs` (indicating the kind of the metaobject) should be added:

```
struct specifier_tag
{
        typedef specifier_tag type;
};

struct namespace_tag
{
        typedef namespace_tag type;
};

struct global_scope_tag
{
        typedef global_scope_tag type;
};

struct type_tag
{
        typedef type_tag type;
};

struct typedef_tag
{
```

```
        typedef typedef_tag type;
};

struct class_tag
{
        typedef class_tag type;
};

struct function_tag
{
        typedef function_tag type;
};

struct constructor_tag
{
        typedef constructor_tag type;
};

struct operator_tag
{
        typedef operator_tag type;
};

struct overloaded_function_tag
{
        typedef overloaded_function_tag type;
};

struct enum_tag
{
        typedef enum_tag type;
};

struct enum_class_tag
{
        typedef enum_class_tag type;
};

struct inheritance_tag
{
        typedef inheritance_tag type;
};

struct constant_tag
```

```
{
        typedef constant_tag type;
};

struct variable_tag
{
        typedef variable_tag type;
};

struct parameter_tag
{
        typedef parameter_tag type;
};
```

These tags are referred-to as `MetaobjectCategory` below:

2.1.2. Specifier category tags

Similar to the metaobject tag types, a set of tag types for individual C++ specifier keywords should be defined:

```
// indicates no specifier
struct none_tag
{
        typedef none_tag type;
};

struct extern_tag
{
        typedef extern_tag type;
};

struct static_tag
{
        typedef static_tag type;
};

struct mutable_tag
{
        typedef mutable_tag type;
};

struct register_tag
{
```

```
        typedef register_tag type;
};

struct thread_local_tag
{
        typedef thread_local_tag type;
};

struct const_tag
{
        typedef const_tag type;
};

struct virtual_tag
{
        typedef virtual_tag type;
};

struct private_tag
{
        typedef private_tag type;
};

struct protected_tag
{
        typedef protected_tag type;
};

struct public_tag
{
        typedef public_tag type;
};

struct class_tag
{
        typedef class_tag type;
};

struct struct_tag
{
        typedef struct_tag type;
};

struct union_tag
```

```
{
        typedef union_tag type;
};

struct enum_tag
{
        typedef enum_tag type;
};

struct enum_class_tag
{
        typedef enum_class_tag type;
};

struct constexpr_tag
{
        typedef constexpr_tag type;
};
```

These tags are collectively referred-to as `SpecifierCategory` below.

2.2. StringConstant

A *StringConstant* is a class conforming to the following:

```
struct StringConstant
{
        typedef StringConstant type;

        // null terminated char array with size (string length+1)
        // known to sizeof at compile-time
        static constexpr const char value[Length+1] = {..., '\0'};

        // implicit compile-time conversion to null terminated
        // c-string
        constexpr operator const char* (void) const
        {
                return value;
        }
};

constexpr const char StringConstant::value[Length+1];
```

Concrete models of *StringConstant* are used to return compile-time string values. For example the `_str_void` type defined below, conforms to the *StringConstant* concept:

```
template <char ... C>
struct string_constant
{
	typedef string_constant type;

	static constexpr const char value[sizeof...(C)+1] = {C...,'\0'};

	constexpr operator const char* (void) const
	{
		return value;
	}
};

template <char ... C>
constexpr const char string_constant::value[sizeof...(C)+1];

//...

typedef string_constant<'v','o','i','d'> _str_void;

cout << _str_void::value << std::endl;
cout << _str_void() << std::endl;
static_assert(sizeof(_str_void::value) == 4+1, "");
```

The strings stored in the `value` array should be UTF-8 encoded.

Also note, that the `string_constant` class as defined above is just one of the possible implementations of *StringConstant*, we do not however imply that it must be implemented this way.

2.3. Metaobject Sequence

As the name implies *MetaobjectSequence*s are used to store seqences or tuples of metaobjects. A model of *MetaobjectSequence* is a class conforming to the following:

It is a nullary metafunction returning itself:

```
template <typename Metaobject>
struct MetaobjectSequence
{
	typedef MetaobjectSequence type;
};
```

Note: The definition above is only a psedo-code and the template parameter `Metaobject` indicates here the minimal metaobject concept which all elements in the sequence must satisfy. For example a `MetaobjectSequence<MetaConstructor>` denotes a sequence of metaobjects that all satisfy the *MetaConstructor* concept, etc.

2.3.1. `size`

A template class `size` is defined as follows:

```
template <typename T>
struct size;

template <>
struct size<MetaobjectSequence<Metaobject>>
 : integral_type<size_t, N>
{ };
```

Where `N` is the number of elements in the sequence.

2.3.2. `at`

A template class `at`, providing random access to metaobjects in a sequence is defined (for values of `I` between `0` and `N-1` where `N` is the number of elements returned by `size`) as follows:

```
template <typename T, size_t I>
struct at;

template <size_t I>
struct at<MetaobjectSequence<Metaobject>, I>
 : Metaobject
{ };
```

For example if `__meta_seq_ABC` is a metaobject sequence containing three metaobjects; `__meta_A`, `__meta_B` and `__meta_C` (in that order), then:

```
template <>
struct size<__meta_seq_ABC>
 : integral_constant<size_t, 3>
{ };
```

and

```
template <>
struct at<__meta_seq_ABC, 0>
 : __meta_A
```

```
{ };

template <>
struct at<__meta_seq_ABC, 1>
 : __meta_B
{ };

template <>
struct at<__meta_seq_ABC, 2>
 : __meta_C
{ };
```

Note: The order of the metaobjects in a sequence is determined by the order of appearance in the processed translation unit.

2.4. Metaobject

Metaobject

A *Metaobject* is a stateless anonymous type generated by the compiler which provides metadata reflecting a specific program feature. Each metaobject should satisfy the following:

Every metaobject should be a nullary metafunction returning itself:

```
struct Metaobject
{
        typedef Metaobject type;
};
```

One possible way how to achieve this is to define *basic metaobjects* as plain types (without any internal structure) and define a class template like:

```
template <typename BasicMetaobject>
struct metaobject
{
        typedef metaobject type;
};
```

and then, implement the actual *Metaobject*s as instantiations of this template. For example if `__base_meta_int` is a basic metaobject reflecting the `int` type then the actual metaobject `__meta_int` conforming to this concept could be defined as:

```
typedef metaobject<__base_meta_int> __meta_int;
```

Although, this is just a suggestion not a requirement of this proposal.

2.4.1. is_metaobject

The `is_metaobject` template should return `true_type` for all *Metaobjects*.

```
template <>
struct is_metaobject<Metaobject>
 : true_type
{ };
```

2.4.2. metaobject_category

A template class `metaobject_category` should be defined in the `std` namespace (even if everything else is defined inside of a nested namespace like `std::meta`) and should inherit from one of the metaobject category tags, depending on the actual kind of the metaobject.

```
template <typename T>
struct metaobject_category;

template <>
struct metaobject_category<Metaobject>
 : MetaobjectCategory
{ };
```

For example if the `__meta_std` metaobject reflects the `std` namespace, then the specialization of `metaobject_category` should be:

```
template <>
struct metaobject_category<__meta_std>
 : namespace_tag
{ };
```

2.4.3. Traits

The following template classes indicating various properties of a *Metaobject* should be defined and should by default inherit from `false_type` unless stated otherwise below:

`has_name` – indicates that a *Metaobject* is a *MetaNamed*:

```
template <typename T>
struct has_name
 : false_type
{ };
```

`has_scope` – indicates that a *Metaobject* is a *MetaScoped*:

```
template <typename T>
struct has_scope
 : false_type
{ };
```

`is_scope` – indicates that a *Metaobject* is a *MetaScope*:

```
template <typename T>
struct is_scope
 : false_type
{ };
```

`is_class_member` – indicates that a *Metaobject* is a *MetaClassMember*:

```
template <typename T>
struct is_class_member
 : false_type
{ };
```

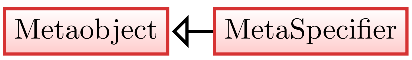
`has_template` – indicates that a *Metaobject* is a *MetaInstantiation*:

```
template <typename T>
struct has_template
 : false_type
{ };
```

`is_template` – indicates that a *Metaobject* is a *MetaTemplate* or *MetaTemplateParameter*:

```
template <typename T>
struct is_template
 : false_type
{ };
```

2.5. MetaSpecifier



MetaSpecifier is a *Metaobject* reflecting a C++ specifier. There also should be a "none" *MetaSpecifier* reflecting a missing specifier. For example the `const` specifier on member functions can be either specified or not. In the latter case this "none" *MetaSpecifier* should be "returned".

In addition to the requirements inherited from *Metaobject*, types conforming to this concept must satisfy the following:

The `metaobject_category` template should return `specifier_tag` for all *MetaSpecifiers*.

```
template <>
struct metaobject_category<MetaSpecifier>
 : specifier_tag
{ };
```

2.5.1. `specifier_category`

A template struct `specifier_category` should be defined and should inherit from one of the specifier category tags, depending on the actual reflected specifier.

```
template <typename T>
struct specifier_category;

template <>
struct specifier_category<MetaSpecifier>
 : SpecifierCategory
{ };
```

For example if the `__meta_static` metaobject reflects the `static` C++ specifier, then the specialization of `specifier_category` should be:

```
template <>
struct specifier_category<__meta_static>
 : static_tag
{ };
```

If `__meta_nospec` is the *MetaSpecifier* reflecting the "none" (missing) specifier, then the specialization of `specifier_category` should be:

```
template <>
struct specifier_category<__meta_nospec>
 : none_tag
{ };
```

2.5.2. `keyword`

A template struct `keyword` should be defined and should return the keyword matching the reflected specifier as a *StringConstant*.

```
template <typename T>
struct keyword;

template <>
struct keyword_category<MetaSpecifier>
```

```
 : StringConstant
{ };
```

For example if the `__meta_thread_local` metaobject reflects the `thread local` specifier, then the matching specialization of `keyword` could be following:

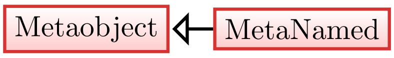
```
template <>
struct keyword<__meta_thread_local>
 : string_constant<'t','h','r','e','a','d',' ','l','o','c','a','l'>
{ };
```

If `__meta_nospec` is the *MetaSpecifier* reflecting the "none" (missing) specifier, then the specialization of `keyword` should return an empty string constant. For example:

```
template <>
struct keyword<__meta_nospec>
 : string_constant<>
{ };
```

The `string_constant<'t','h','r','e','a','d',' ','l','o','c','a','l'>` and the `string_constant<>` classes should be models of *StringConstant* as described above.

2.6. MetaNamed



MetaNamed is a *Metaobject* reflecting program constructs, which have a name (are identified by an identifier) like namespaces, types, functions, variables, parameters, etc.

In addition to the requirements inherited from *Metaobject*, the following requirements must be satisfied:

The `has_name` template class specialization for a *MetaNamed* should inherit from `true_type`:

```
template <>
struct has_name<MetaNamed>
 : true_type
{ };
```

2.6.1. base_name

A template class `base_name` should be defined an should return the base name of the reflected construct, without the nested name specifier nor any qualifications or other decorations, as a *StringConstant*:

```
template <typename T>
struct base_name;
```

```
template <>
struct base_name<MetaNamed>
 : StringConstant
{ };
```

For example, if `__meta_std_size_t` reflects the `std::size_t` type, then the matching specialization of `base_name` could be implmented in the following way:

```
template <>
struct base_name<__meta_std_size_t>
 : string_constant<'s','i','z','e','_','t'>
{ };
```

where the `string_constant<'s','i','z','e','_','t'>` class is a model of *StringConstant* as described above.

For namespace `std` the value should be `"std"`, for namespace `foo::bar::baz` it should be `"baz"`, for the global scope the value should be an empty string.

For `unsigned long int * const *` it should be `"unsigned long int"`.

For `std::vector<int>::iterator` it should be `"iterator"`. For derived, qualified types like `volatile std::vector<const foo::bar::fubar*> * const *` it should be `"vector"`, etc.

2.6.2. `full_name`

A template class `full_name` should be defined and should return the fully qualified name of the reflected construct, including the nested name specifier and all qualifiers.

For namespace `std` the value should be `"std"`, for namespace `foo::bar::baz` the value should be `"foo::bar::baz"`, for the global scope the value should be an empty *StringConstant*. For `std::vector<int>::iterator` it should be `"std::vector<int>::iterator"`. For derived qualified types like `volatile std::vector<const foo::bar::fubar*> * const *` it should be defined as `"volatile std::vector<const foo::bar::fubar*> * const *"`, etc.

```
template <typename T>
struct full_name;

template <>
struct full_name<MetaNamedScoped>
 : StringConstant
{ };
```

2.6.3. named_typedef

A template class `named_typedef` should be defined:

```
template <typename X, typename T>
struct named_typedef;

template <typename X>
struct named_typedef<X, MetaNamedScoped>
{
        typedef X <NAME>;
};
```

The `<NAME>` expression above should be replaced in the actual specialization generated by the compiler by the name of the reflected named object. If the generated identifier would clash with a C++ reserved keyword, then a single trailing underscore should be appended to the identifier. If the generated identifier consists of multiple whitespace separated words then the whitespaces should be replaced by a single underscore.

For example if a type `__meta_std_thread` reflects the `std::thread` class, then the specialization of `named_typedef` for this metaobject should be following:

```
template <typename X>
struct named_typedef<X, __meta_std_thread>
{
        typedef X thread;
};
```

if a type `__meta_std` reflects the `std` namespace, then the specialization of `named_typedef` should be:

```
template <typename X>
struct named_typedef<X, __meta_std>
{
        typedef X std;
};
```

if a type `__meta_` reflects the global scope (or another anonymous base-level object), then the specialization of `named_typedef` should be:

```
template <typename X>
struct named_typedef<X, __meta_>
{
        typedef X _;
};
```

If the types `__meta_int` and `__meta_unsigned_long_long_int` reflect the `int` and the `unsigned long long int` type respectively, then the matching instantiations of `named_typedef` should be:

```
template <typename X>
struct named_typedef<X, __meta_int>
{
        // note the trailing underscore
        typedef X int_;
};

template <typename X>
struct named_typedef<X, __meta_long_long_unsigned_int>
{
        // note underscores replacing the spaces
        typedef X long_long_unsigned_int;
};
```

If the types `__meta_char_const`, `__meta_long_const_ref`, `__meta_int_volatile_ptr` and `__meta_double_array_5` reflect `char const`, `long const&`, `int volatile*` and `double[5]` respectively, then the specializations of `named_typeded` should be:

```
template <typename X>
struct named_typedef<X, __meta_char_const>
{
        typedef X char_;
};
template <typename X>
struct named_typedef<X, __meta_long_const_ref>
{
        typedef X long_int;
};
template <typename X>
struct named_typedef<X, __meta_int_volatile_ptr>
{
        typedef X int_;
};
template <typename X>
struct named_typedef<X, __meta_double_array_5>
{
        typedef X double_;
};
```

2.6.4. `named_mem_var`

A template class `named_mem_var` should be defined as follows:

```
template <typename X, typename T>
struct named_mem_var;

template <typename X>
struct named_mem_var<X, MetaNamedScoped>
{
        X <NAME>;

        template <typename ... P>
        named_mem_var(P&& p)
         : <NAME>(std::forward<P>(p)...)
        { };
};
```

The `<NAME>` expression above should be replaced in the actual specialization generated by the compiler by the name of the reflected named object. If the generated identifier would clash with a C++ reserved keyword, then a single trailing underscore should be appended to the identifier. If the generated identifier consists of multiple whitespace separated words then the whitespaces should be replaced by a single underscore.

For example if a type `__meta_std_string` reflects the `std::string` typedef, then the specialization of `named_mem_var` for this metaobject should be following:

```
template <typename X>
struct named_mem_var<X, __meta_std_string>
{
        X string;

        template <typename ... P>
        named_mem_var(P&& ... p)
         : string(std::forward<P>(p)...)
        { }
};
```

If types `__meta_void` and `_meta_long_double` reflect the `void` and `long double` types respectively, then the matching instantiations of `named_mem_var` should be: should be:

```
template <typename X>
struct named_mem_var<X, __meta_void>
{
        // note the trailing underscore
        X void_;

        template <typename ... P>
        named_mem_var(P&& ... p)
         : void_(std::forward<P>(p)...)
```

```
        { }
};

template <typename X>
struct named_mem_var<X, __meta_long_double>
{
        // note underscores replacing the spaces
        typedef X long_double;

        template <typename ... P>
        named_mem_var(P&& ... p)
         : long_double_(std::forward<P>(p)...)
        { }
};
```

For decorated and qualified types the same rules apply as for `named_typedef`. If `__meta_std_string_const_ref` reflects `std::string const&`, then:

```
template <typename X>
struct named_typedef<X, __meta_std_string_const_ref>
{
        typedef X string;
};
```

2.7. MetaScoped

Metaobject ← MetaScoped

MetaScoped is a *Metaobject* reflecting program constructs defined inside of a named scope (like the global scope, a namespace, a class, etc.)

In addition to the requirements inherited from *Metaobject*, the following requirements must be satisfied:

The `has_scope` template class specialization for a *MetaScoped* should inherit from `true_type`:

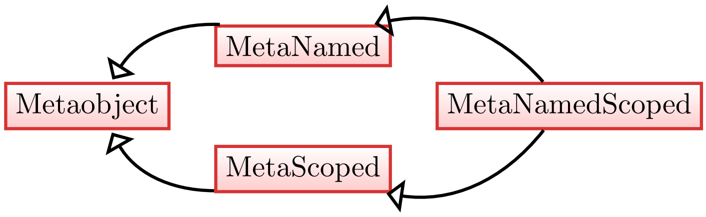
```
template <>
struct has_scope<MetaScoped>
 : true_type
{ };
```

2.7.1. `scope`

A template class `scope` should be defined and should inherit from the *MetaScope* which reflects the parent scope of the program construct reflected by this *MetaScoped*.

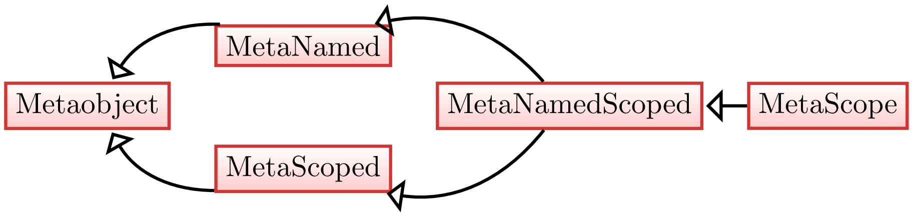
```
template <typename T>
struct scope;

template <>
struct scope<MetaScoped>
 : MetaScope
{ };
```

2.8. MetaNamedScoped



Models of *MetaNamedScoped* combine the requirements of *MetaNamed* and *MetaScoped*.

2.9. MetaScope



MetaScoped is a *MetaNamedScoped* reflecting program constructs defined inside of a named scope (like the global scope, a namespace, a class, etc.)

In addition to the requirements inherited from *MetaNamedScoped*, the following is required:

The `is_scope` template class specialization for a *MetaScope* should inherit from `true_type`:

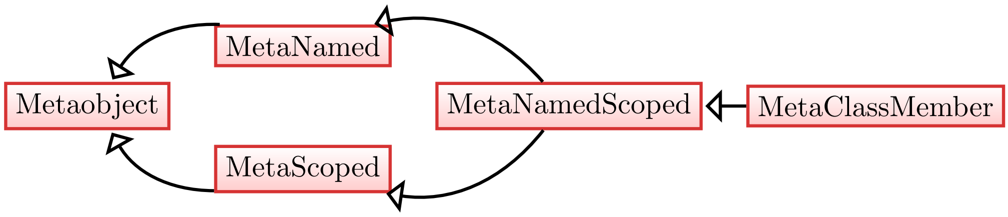
```
template <>
struct is_scope<MetaScope>
 : true_type
{ };
```

2.9.1. `members`

A template class `members` should be defined and should inherit from a *MetaobjectSequence* containing *MetaNamedScoped* metaobjects reflecting all members of the base-level scope reflected by this *MetaScope*.

```
template <typename T>
struct members;

template <>
struct members<MetaScope>
 : MetaobjectSequence<MetaNamedScoped>
{ };
```

2.10. MetaClassMember



MetaClass is a *MetaType* and a *MetaScope* if reflecting a regular class or possibly also a *MetaTemplate* if it reflects a class template.

In addition to the requirements inherited from *MetaNamedScoped*, the following is required for *MetaClassMember*s:

The `is_class_member` template class specialization for a *MetaClassMember* should inherit from `true_type`:

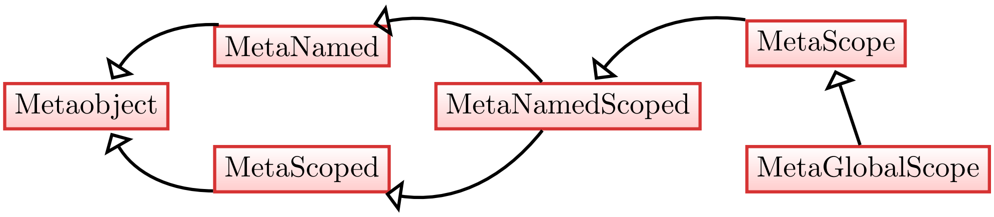
```
template <>
struct is_class_member<MetaClassMember>
 : true_type
{ };
```

2.10.1. access_specifier

A template class called `access_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting the `private`, `protected` or `public` access specifier:

```
template <typename T>
struct access_specifier;

template <>
struct access_specifier<MetaClassMember>
 : MetaSpecifier
{ };
```

2.11. MetaGlobalScope



MetaGlobalScope is a *MetaScope* reflecting the global scope.

In addition to the requirements inherited from *MetaScope*, the following must be satisfied:

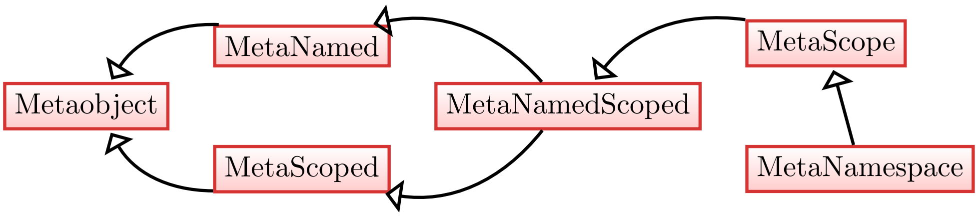
The `metaobject_category` template class specialization for a *MetaGlobalScope* should inherit from `global_scope_tag`:

```
template <>
struct metaobject_category<MetaNamespace>
 : global_scope_tag
{ };
```

The `scope` template class specialization (required by *MetaScoped*) for *MetaGlobalScope* should inherit from the *MetaGlobalScope* itself:

```
template <>
struct scope<MetaGlobalScope>
 : MetaGlobalScope
{ };
```

2.12. MetaNamespace



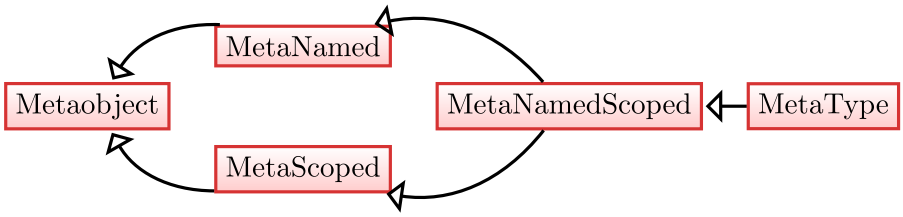
MetaNamespace is a *MetaScope* reflecting a namespace.

In addition to the requirements inherited from *MetaScope*, the following must be satisfied:

The `metaobject_category` template class specialization for a *MetaNamespace* should inherit from `namespace_tag`:

```
template <>
struct metaobject_category<MetaNamespace>
 : namespace_tag
{ };
```

2.13. MetaType



MetaType is a *MetaNamedScoped* reflecting types.

In addition to the requirements inherited from *MetaNamedScoped*, the following is required:

The `metaobject_category` template class specialization for a *MetaType* should inherit from `type_tag`:

```
template <>
struct metaobject_category<MetaType>
 : type_tag
{ };
```

2.13.1. `original_type`

A template class `original_type` should be defined and should "return" the original type reflected by this *MetaType*:

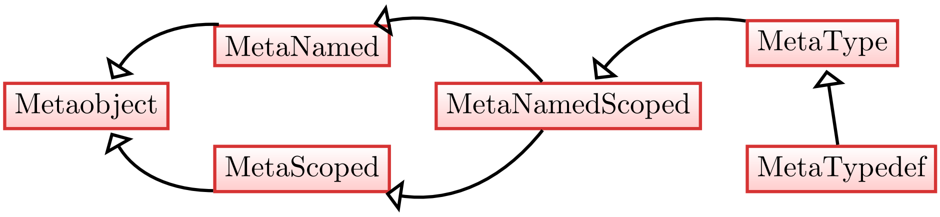
```
template <typename T>
struct original_type;

template <>
struct original_type<MetaType>
{
        static_assert(not(is_template<MetaType>::value), "");
        typedef original-type type;
};
```

For example, if `__meta_int` is a metaobject reflecting the `int` type, then the specialization of `original_type` should be following:

```
template <>
struct original_type<__meta_int>
{
        typedef int type;
};
```

Note: If a concept derived from *MetaType*, for example a *MetaClass*, is also a *MetaTemplate* (i.e. is reflecting a template not a concrete type), then the `original_type` template should be left undefined.

2.14. MetaTypedef



MetaTypedef is a *MetaType* reflecting `typedef`s.

In addition to the requirements inherited from *MetaType*, the following is required:

The `metaobject_category` template class specialization for a *MetaTypedef* should inherit from `typedef_tag`:

```
template <>
struct metaobject_category<MetaTypedef>
 : typedef_tag
{ };
```

2.14.1. `type`

A template class called `type` should be defined and should inherit from the *MetaType* reflecting the "source" type of the typedef:

```
template <typename T>
struct type;

template <>
struct type<MetaTypedef>
 : MetaType
{ };
```

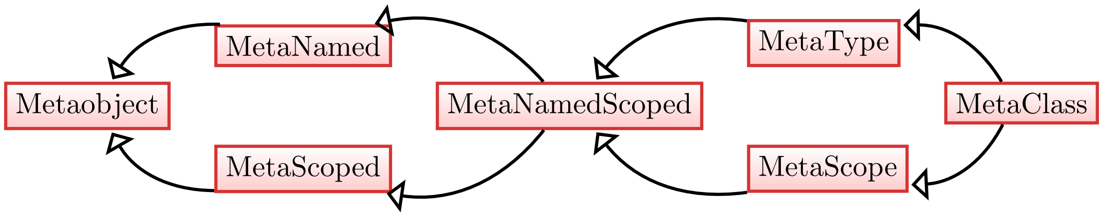
For example if `__meta_std_string` is a *MetaTypedef* reflecting the `std::string` typedef and `__meta_std_basic_string_char` is the *MetaType* that reflects the `std::basic_string<char>` type, and `std::string` is defined as:

```
namespace std {
typedef basic_string<char> string;
}
```

then the specialization of `type` for `__meta_std_string` should be following:

```
template <>
struct type<__meta_std_string>
 : __meta_std_basic_string_char
{ };
```

2.15. MetaClass



MetaClass is a *MetaType* and a *MetaScope* if reflecting a regular class or possibly also a *MetaTemplate* if it reflects a class template.

In addition to the requirements inherited from *MetaType*, *MetaScope* and optionally from *MetaTemplate*, models of *MetaClass* are subject to the following:

The `metaobject_category` template class specialization for a *MetaClass* should inherit from `class_tag`:

```
template <>
struct metaobject_category<MetaClass>
 : class_tag
{ };
```

If a *MetaClass* reflects a class template, then the `is_template` trait should inherit from `true_type`

2.15.1. `elaborated_type_specifier`

A template class called `elaborated_type_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting the `class`, `struct` or `union` specifiers:

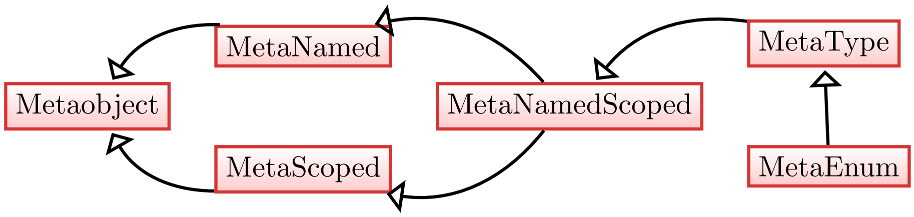
```
template <typename T>
struct elaborated_type_specifier;

template <>
struct elaborated_type_specifier<MetaClass>
 : MetaSpecifier
{ };
```

2.15.2. base_classes

A template class `base_classes` should be defined and should inherit from a *Metaobject-Sequence* of *MetaInheritance*s, each one of which reflects the inheritance of a single base class of the class reflected by the *MetaClass*:

```
template <typename T>
struct base_classes;

template <>
struct base_classes<MetaClass>
 : MetaobjectSequence<MetaInheritance>
{ };
```

2.16. MetaEnum



MetaEnum is a *MetaType* reflecting an enumeration type.

In addition to the requirements inherited from *MetaType*, *MetaEnum* requires also the following:

The `metaobject_category` template class specialization for a *MetaEnum* should inherit from `enum_tag`:

```
template <>
struct metaobject_category<MetaEnum>
 : enum_tag
{ };
```

The `members` of *MetaEnumClass* are only *MetaNamed MetaConstant*s.

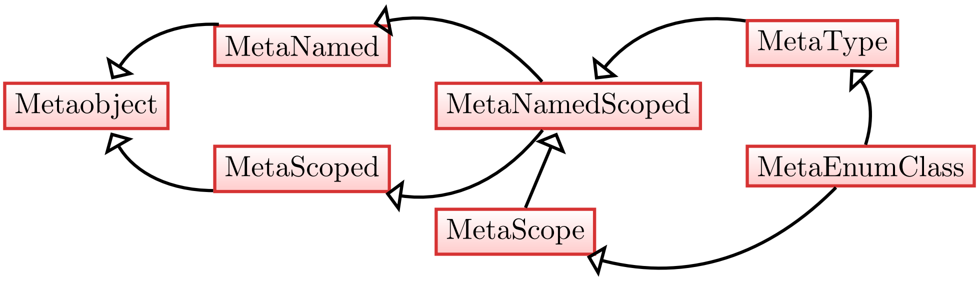
2.16.1. base_type

A template class `base_type` should be defined and should inherit from a *MetaType* reflecting the underlying type of the enumeration:

```
template <typename T>
struct base_type;
```

```
template <>
struct base_type<MetaEnum>
 : MetaType
{ };
```

2.17. MetaEnumClass



MetaEnumClass is a *MetaType* and a *MetaScope* reflecting a strongly type enumeration.

In addition to the requirements inherited from *MetaType* and *MetaScope*, the following must be satisfied:

The `metaobject_category` template class specialization for a *MetaEnumClass* should inherit from `enum_class_tag`:

```
template <>
struct metaobject_category<MetaEnumClass>
 : enum_class_tag
{ };
```

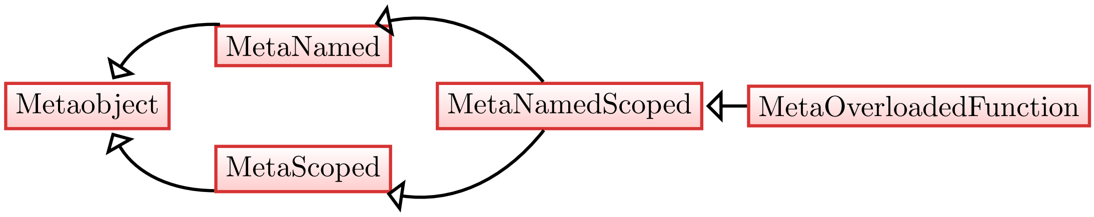
The `members` of *MetaEnumClass* are only *MetaNamedScoped MetaConstant*s.

2.17.1. base_type

A template class `base_type` should be defined and should inherit from a *MetaType* reflecting the base type of the enumeration:

```
template <typename T>
struct base_type;

template <>
struct base_type<MetaEnumClass>
 : MetaType
{ };
```

2.18. MetaOverloadedFunction



Models of *MetaOverloadedFunction* reflect overloaded functions. *MetaFunction*s (and *MetaOperator*s, *MetaInitializer*s, *MetaConstructor*s, etc.) are not direct members of scopes (they are not listed in the *MetaobjectSequence* "returned" by the `members<MetaScope>` template class). Instead, all functions, operators and constructors with the same name, (and even those that are not overloaded in a specific scope) are grouped into a *MetaOverloadedFunction*. Individual overloaded *MetaFunction*s in the group can be obtained through the interface of *MetaOverloadedFunction* (specifically through the `overloads` template described below). The same also applies to *MetaConstructor*s and *MetaOperator*s.

The rationale for this is that direct scope members, i.e. metaobjects accessible through the *MetaScope*'s `members` template class should have unique names, which would not be the case if *MetaFunction*s were direct scope members.

The `scope` of an *MetaOverloadedFunction* is the same as the `scope` of all *MetaFunction*s grouped by that *MetaOverloadedFunction*.

In addition to the requirements inherited from *MetaNamedScoped*, models of *MetaOverloadedFunction* are subject to the following:

The `metaobject_category` template class specialization for a *MetaOverloadedFunction* should inherit from `overloaded_function_tag`:

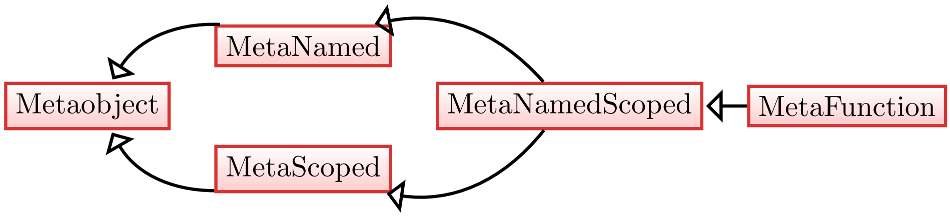
```
template <>
struct metaobject_category<MetaOverloadedFunction>
 : overloaded_function_tag
{ };
```

2.18.1. `overloads`

A template class called `overloads` should be defined and should return a *MetaobjectSequence* of *MetaFunction*s, reflecting the individual overloads:

```
template <>
struct overloads<MetaOverloadedFunction>
 : MetaobjectSequence<MetaFunction>
{ };
```

2.19. MetaFunction



MetaFunction is a *MetaNamedScoped* which reflects a function or a function template.

In addition to the requirements inherited from *MetaNamedScoped*, models of *MetaFunction* are subject to the following:

The `metaobject_category` template class specialization for a *MetaFunction* should inherit from `function_tag`:

```
template <>
struct metaobject_category<MetaFunction>
 : function_tag
{ };
```

If a *MetaFunction* reflects a function template, then the `is_template` trait should inherit from `true_type`

2.19.1. linkage_specifier

A template class `linkage_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting the linkage specifier of the function reflected by the *MetaFunction*:

```
template <typename T>
struct linkage_specifier;

template <>
struct linkage_specifier<MetaFunction>
 : MetaSpecifier
{ };
```

2.19.2. constexpr_specifier

A template class `constexpr_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting the constexpr specifier of the reflected function:

```
template <typename T>
struct constexpr_specifier;
```

```
template <>
struct constexpr_specifier<MetaFunction>
 : MetaSpecifier
{ };
```

In case the reflected function does not have the `constexpr` specifier, then the result should be a *MetaSpecifier* reflecting the "none" specifier.

2.19.3. result_type

A template class `result_type` should be defined and should inherit from a *MetaType* reflecting the return value type of the reflected function:

```
template <typename T>
struct result_type;

template <>
struct result_type<MetaFunction>
 : MetaType
{ };
```

2.19.4. parameters

A template class `parameters` should be defined and should inherit from a *MetaobjectSequence* or *MetaParameter*s reflecting the individual parameters of the function:

```
template <typename T>
struct parameters;

template <>
struct parameters<MetaFunction>
 : MetaobjectSequence<MetaParameter>
{ };
```

2.19.5. noexcept_specifier

A template class `noexcept_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting the noexcept specifier of the reflected function:

```
template <typename T>
struct noexcept_specifier;

template <>
```

```
struct noexcept_specifier<MetaFunction>
 : MetaSpecifier
{ };
```

In case the reflected function does not have the `noexcept` specifier, then the result should be a *MetaSpecifier* reflecting the "none" specifier.

2.19.6. `exceptions`

A template class `exceptions` should be defined and should inherit from a *MetaobjectSequence* of *MetaType*s reflecting the individual exception types that the reflected function is allowed to throw:

```
template <typename T>
struct exceptions;

template <>
struct exceptions<MetaFunction>
 : MetaobjectSequence<MetaType>
{ };
```

2.19.7. `const_specifier`

In case a *MetaFunction* is also a *MetaClassMember*, a template class `const_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting the const specifier of the reflected member function:

```
template <typename T>
struct const_specifier;

template <>
struct const_specifier<MetaFunction>
 : MetaSpecifier
{
        static_assert(is_class_member<MetaFunction>::value, "");
};
```

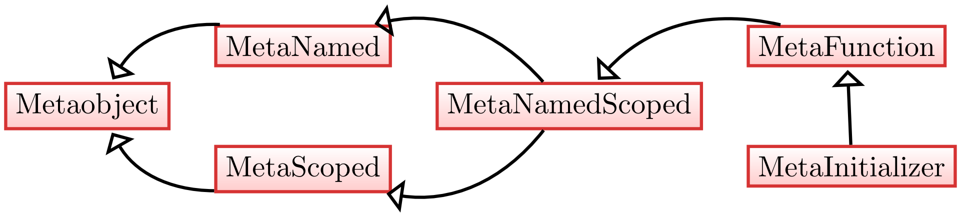
In case the reflected member function does not have the `const` specifier, then the result should be a *MetaSpecifier* reflecting the "none" specifier.

2.19.8. `is_pure`

In case a *MetaFunction* is also a *MetaClassMember*, a template class `is_pure` should be defined and should inherit from `true_type` if the reflected function is pure virtual or from `false_type` otherwise:

```
template <typename T>
struct is_pure;

struct is_pure<MetaFunction>
 : std::integral_constant<bool, B>
{
        static_assert(is_class_member<MetaFunction>::value, "");
};
```

2.20. MetaInitializer



MetaInitializer reflects an initializer (constructor) of a native type.

In addition to the requirements inherited from *MetaFunction*, models of *MetaInitializer* must conform to the following:

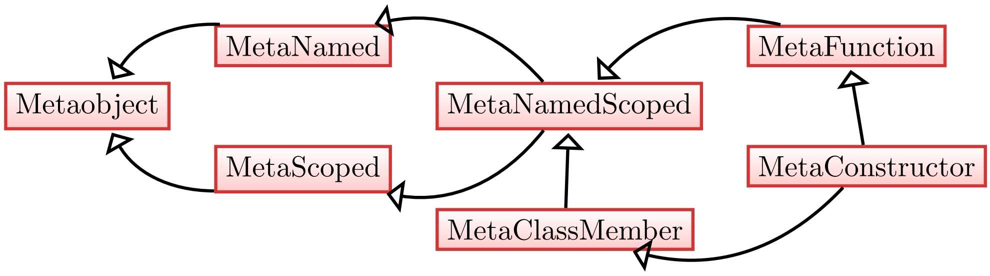
The `metaobject_category` template class specialization for a *MetaInitializer* should inherit from `constructor_tag`:

```
template <>
struct metaobject_category<MetaInitializer>
 : constructor_tag
{ };
```

The specialization of the `result_type` template class for a *MetaInitializer* should inherit from a *MetaType* reflecting the initialized type:

```
template <>
struct result_type<MetaInitializer>
 : MetaType
{ };
```

2.21. MetaConstructor



MetaConstructor reflects a constructor of an elaborated type.

In addition to the requirements inherited from *MetaFunction* and *MetaClassMember*, the following is required for *MetaConstructor*s:

The `metaobject_category` template class specialization for a *MetaConstructor* should inherit from `constructor_tag`:

```
template <>
struct metaobject_category<MetaConstructor>
 : constructor_tag
{ };
```

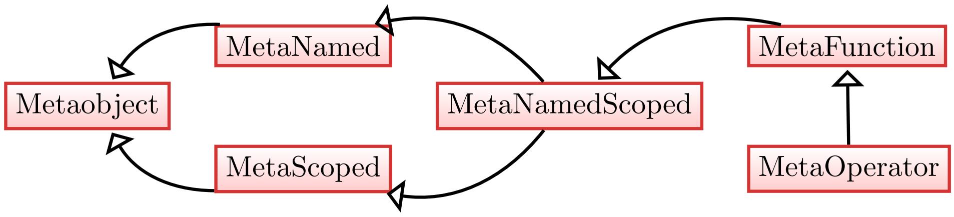
The specialization of the `result_type` template class for a *MetaConstructor* should inherit from a *MetaClass* reflecting the constructed type.

```
template <>
struct result_type<MetaConstructor>
 : MetaClass
{ };
```

The specialization of the `scope` template class for a *MetaConstructor* should inherit from a *MetaClass* reflecting the constructed type.

```
template <>
struct scope<MetaConstructor>
 : MetaClass
{ };
```

2.22. MetaOperator



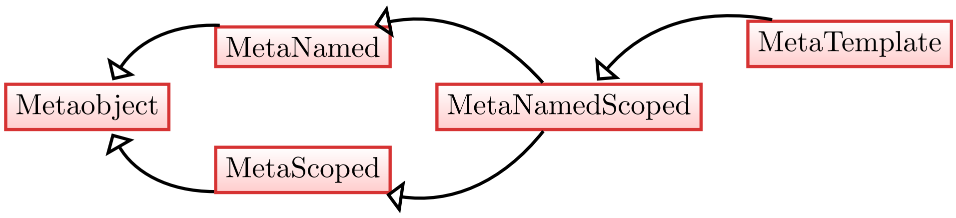
MetaOperator is a *MetaFunction* which reflects an operator.

In addition to the requirements inherited from *MetaFunction*, models of *MetaOperator* must conform to the following:

The `metaobject_category` template class specialization for a *MetaOperator* should inherit from `operator_tag`:

```
template <>
struct metaobject_category<MetaOperator>
 : operator_tag
{ };
```

2.23. MetaTemplate



MetaTemplate is a *MetaNamedScoped* and either a *MetaClass* or a *MetaFunction*.

Note: The *MetaTemplate* concept slightly modifies the requirements of the *MetaClass* and *MetaFunction* concepts.

In addition to the requirements inherited from *MetaNamedScoped*, models of *MetaTemplate* must conform to the following:

The `is_template` template class specialization for a *MetaTemplate* should inherit from `true_type`:

```
template <>
struct is_template<MetaTemplate>
 : true_type
{ };
```

2.23.1. `template_parameters`

A template class called `template_parameters` should be defined and should inherit from a *MetaobjectSequence* of *MetaTemplateParameter*s, reflecting the individual type or constant template parameters:

```
template <typename T>
struct template_parameters;
```

```
template <>
struct template_parameters<MetaTemplate>
 : MetaobjectSequence<MetaTemplateParameter>
{ };
```

2.23.2. `instantiation`

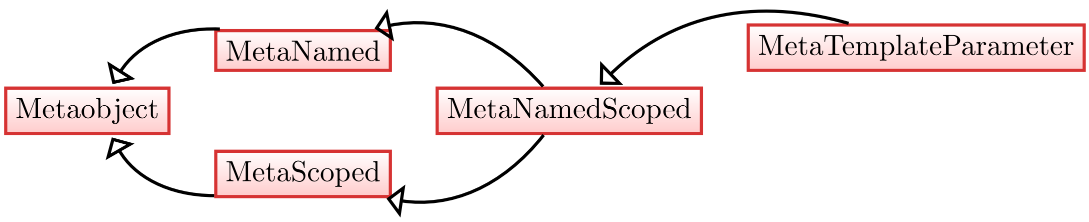
A template class `instantiation` should be defined and should inherit from a *MetaInstantiation* reflecting a concrete instantiation of the template reflected by this *MetaTemplate*:

```
template <typename T, typename ... P>
struct instantiation;

template <typename ... P>
struct instantiation<MetaTemplate, P...>
 : MetaInstantiation
{ };
```

For example if `__meta_std_pair` is a *MetaTemplate* and a *MetaClass* reflecting the `std::pair` template and `__meta_std_pair_int_double` is a *MetaInstantiation* and a *MetaClass* reflecting the `std::pair<int, double>` class then:

```
static_assert(
        is_base_of<
                __meta_std_pair_int_double,
                instantiation<__meta_std_pair, int, double>
        >() , ""
);
```

2.24. MetaTemplateParameter



MetaTemplateParameter is a *MetaNamedScoped* and either a *MetaTypedef* or a *MetaConstant*.

In addition to the requirements inherited from *MetaNamedScoped*, models of *MetaTemplateParameter* must conform to the following:

The `is_template` template class specialization for a *MetaTemplateParameter* should inherit from `true_type`:

```
template <>
struct is_template<MetaTemplateParameter>
 : true_type
{ };
```

The `full_name` inherited from *MetaNamed* should return the same *StringConstant* as `base_name` for models of *MetaTemplateParameter*, i.e. the plain template parameter name without any qualifications.

2.24.1. position

A template class `position` should be defined and should inherit from `integral_constant<size_t, I>` where `I` is a zero-based position (index) of the parameter.

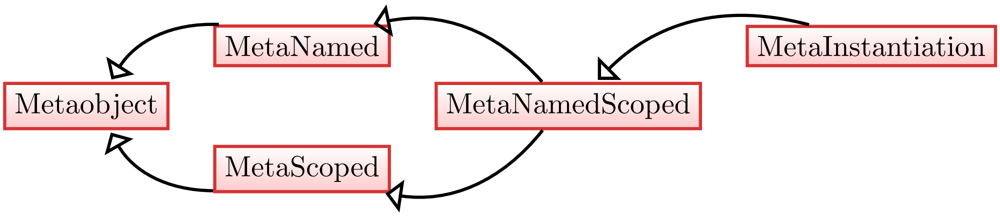
```
template <typename T>
struct position;

template <>
struct position<MetaTemplateParameter>
 : integral_constant<size_t, I>
{ };
```

2.24.2. is_pack

A template class called `is_pack` should be defined and should inherit from `true_type` if the template parameter is a pack parameter or from `false_type` otherwise.

```
template <typename T>
struct is_pack;

template <>
struct is_pack<MetaTemplateParameter>
 : integral_constant<bool, B>
{ };
```

2.25. MetaInstantiation



MetaInstantiation is a *MetaNamedScoped* and either a *MetaClass* or a *MetaFunction*.

In addition to the requirements inherited from *MetaNamedScoped*, models of *MetaInstantiation* must conform to the following:

The `has_template` template class specialization for a *MetaInstantiation* should inherit from `true_type`:

```
template <>
struct has_template<MetaInstantiation>
 : true_type
{ };
```

2.25.1. template_arguments

A template class called `template_arguments` should be defined and should inherit from a *MetaobjectSequence* of *MetaNamedScoped* metaobjects each of which is either a *MetaType* or a *MetaConstant* and reflects the i-th template argument:

```
template <typename T>
struct template_arguments;

template <>
struct template_arguments<MetaInstantiation>
 : MetaobjectSequence<MetaNamedScoped>
{ };
```

2.25.2. template_

A template class called `template_` should be defined and should inherit from a *MetaTemplate* reflecting the instantiation's template:

```
template <typename T>
struct template_;

template <>
struct template_<MetaInstantiation>
```

```
 : MetaTemplate
{ };
```

For example if `__meta_std_pair` is a *MetaTemplate* and a *MetaClass* reflecting the `std::pair` template and `__meta_std_pair_int_double` is a *MetaInstantiation* and a *MetaClass* reflecting the `std::pair<int, double>` class then:

```
static_assert(
        is_base_of<
                __meta_std_pair,
                template_<__meta_std_pair_int_double>
        >() , ""
);
```

2.26. MetaInheritance

Metaobject ← MetaScoped ← MetaInheritance

MetaInheritance is a *MetaScoped* reflecting class inheritance.

In addition to the requirements inherited from *MetaScoped*, types conforming to this concept must satisfy the following:

The `metaobject_category` template should return `inheritance_tag` for models of *MetaInheritance*:

```
template <>
struct metaobject_category<MetaInheritance>
 : inheritance_tag
{ };
```

The `scope` member function should inherit from a *MetaClass* reflecting the derived class in the inheritance:

```
template <>
struct scope<MetaInheritance>
 : MetaClass
{ };
```

2.26.1. access_specifier

A template struct `access_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting one of the `private`, `protected` and `public` access specifiers.

```
template <typename T>
struct access_specifier;
```

```
template <>
struct access_specifier<MetaInheritance>
 : MetaSpecifier
{ };
```

2.26.2. inheritance_specifier

A template struct `inheritance_specifier` should be defined and should inherit from a *MetaSpecifier* reflecting one of the `virtual` and "none" access specifiers.

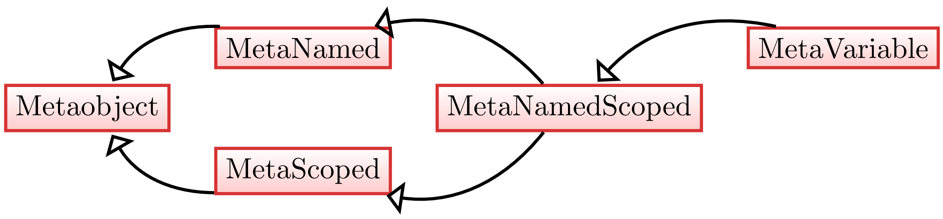
```
template <typename T>
struct inheritance_specifier;

template <>
struct inheritance_specifier<MetaInheritance>
 : MetaSpecifier
{ };
```

2.26.3. base_class

A template struct `base_class` should be defined and should inherit from a *MetaClass* reflecting the base class in the inheritance:

```
template <typename T>
struct base_class;

template <>
struct base_class<MetaInheritance>
 : MetaClass
{ };
```

2.27. MetaVariable



MetaVariable is a *MetaNamedScoped* reflecting a variable.

In addition to the requirements inherited from *MetaNamedScoped*, the following must be satisfied:

The `metaobject_category` template class specialization for a *MetaVariable* should inherit from `variable_tag`:

```
template <>
struct metaobject_category<MetaVariable>
 : variable_tag
{ };
```

2.27.1. `storage_specifier`

A template class `storage_specifier` should be added and should inherit from a *MetaSpecifier* reflecting a storage class specifier:

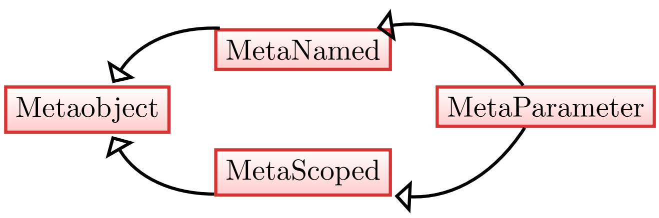
```
template <typename T>
struct storage_specifier;

template <>
struct storage_specifier<MetaVariable>
 : MetaSpecifier
{ };
```

2.27.2. `type`

A template class `type` should be added and should inherit from a *MetaType* reflecting the type of the variable:

```
template <typename T>
struct type;

template <>
struct type<MetaVariable>
 : MetaType
{ };
```

2.28. MetaParameter



MetaParameter is a *MetaNamed* and *MetaScoped*, reflecting a function parameter or a parameter pack.

In addition to the requirements inherited from *MetaNamed* and *MetaScoped*, the following must be satisfied:

The `metaobject_category` template class specialization for a *MetaParameter* should inherit from `parameter_tag`:

```
template <>
struct metaobject_category<MetaParameter>
 : parameter_tag
{ };
```

The `scope` of a *MetaParameter* should be a *MetaFunction* reflecting the function to which the parameter belongs:

```
template <>
struct scope<MetaParameter>
 : MetaFunction
{ };
```

The `full_name` inherited from *MetaNamed* should return the same *StringConstant* as `base_name` for models of *MetaParameter*, i.e. the plain parameter name without any qualifications.

2.28.1. `type`

A template class `type` should be added and should inherit from a *MetaType* reflecting the type of the parameter:

```
template <typename T>
struct type;

template <>
struct type<MetaParameter>
 : MetaType
{ };
```

2.28.2. `position`

A template class `position` should be defined and should inherit from `integral_constant<size_t, I>` type where `I` is a zero-based position (index) of the parameter.

```
template <typename T>
struct position;
```

```
template <>
struct position<MetaParameter>
 : integral_constant<size_t, I>
{ };
```

2.28.3. `is_pack`

A template class called `is_pack` should be defined and should inherit from `true_type` if the parameter is a pack parameter or from `false_type` otherwise.

```
template <typename T>
struct is_pack;

template <>
struct is_pack<MetaParameter>
 : integral_constant<bool, B>
{ };
```

2.29. MetaConstant

Metaobject ← MetaConstant

MetaConstant is a *Metaobject* reflecting a compile-time constant value.

In addition to the requirements inherited from *Metaobject*, the following must be satisfied:

The `metaobject_category` template class specialization for a *MetaConstant* should inherit from `constant_tag`:

```
template <>
struct metaobject_category<MetaConstant>
 : constant_tag
{ };
```

2.29.1. `type`

A template class `type` should be added and should inherit from a *MetaType* reflecting the type of the constant value

```
template <typename T>
struct type;
```

```
template <>
struct type<MetaVariable>
 : MetaType
{ };
```

2.29.2. value

A template class `value` should be added and should inherit from an `integral_constant<T, V>`:

```
template <typename T>
struct value;

template <>
struct value<MetaConstant>
 : integral_constant<T, V>
{ };
```

3. Reflection operator

The metaobjects reflecting some program feature `X` as described above should be made available to the user by the means of a new operator or expression. More precisely, the reflection operator returns a type conforming to a particular metaobject concept, depending on the reflected expression.

Since adding a new keyword has the potential to break existing code, we do not insist on any particular expression, here follows a list of suggestions in order of preference (from the most to the least preferrable):

- `mirrored(X)`
- `reflected(X)`
- `reflexpr(X)`
- `|X`
- `[[X]]`
- `<<X>>`

The reflected expression `X` in the items listed above can be any of the following:

- `::` – The global scope, the returned metaobject is a *MetaGlobalScope*.
- *Namespace name* – (`std`) the returned metaobject is a *MetaNamespace*.
- *Type name* – (`long double`) the returned metaobject is a *MetaType*.

- `typedef` *name* – (`std::size_t` or `std::string`) the returned metaobject is a *MetaTypedef*.
- *Template name* – (`std::tuple` or `std::map`) the returned metaobject is a *MetaTemplate*.
- *Class name* – (`std::thread` or `std::map<int, double>`) the returned metaobject is a *MetaClass*.
- *Function name* – (`std::sin` or `std::string::size`) the returned metaobject is a *MetaOverloadedFunction*.
- *Function signature* – (`std::sin(double)` or `std::string::front(void) const`) the returned metaobject is a *MetaFunction*. The signature may be specified without the return value type.
- *Constructor signature* – (`std::pair<char, double>::pair(char, double)` or `std::string::string(void)`) the returned metaobject is a *MetaConstructor*.
- *Variable name* – (`std::errno`) the returned metaobject is a *MetaVariable*.

The reflection operator or expression should have access to `private` and `protected` members of classes. The following should be valid:

```
struct A
{
        int a;
};

class B
{
protected:
        int b;
};

class C
 : protected A
 , public B
{
private:
        int c;
};

typedef mirrored(A::a) meta_A_a;
typedef mirrored(B::b) meta_B_b;
typedef mirrored(C::a) meta_C_a;
typedef mirrored(C::b) meta_C_b;
typedef mirrored(C::c) meta_C_c;
```

4. Additions to the library

In order to simplify composition of the metaobjects and metafunctions defined above, several further additions to the standard library should be made.

4.1. Metaobject expressions

A *metaobject expression* is a class which can be *evaluated* into a *Metaobject*. By default any class, that has a member typedef which is a model of *Metaobject* is a metaobject expression.

```
struct SomeMetaobjectExpression
{
        typedef Metaobject type;
};
```

And thus, any *Metaobject* is also a *metaobject expression*.

Generally, however, any type for which the `evaluate` metafunction (described below), "returns" a *Metaobject* is a *metaobject expression*.

4.1.1. `evaluate`

A class template called `evaluate` should be defined and should "return" a *Metaobject* resulting from a *metaobject expression*:

```
template <class MetaobjectExpression>
struct evaluate
 : Metaobject
{ };
```

that could be implemented for example as follows:

```
template <class X, bool IsMetaobject>
struct do_evaluate;

template <class X>
struct do_evaluate<X, true>
 : X
{ };

template <class X>
struct do_evaluate<X, false>
 : do_evaluate<
        typename X::type,
```

```
        is_metaobject<typename X::type>::value
> { };

template <class X>
struct evaluate
 : do_evaluate<X, is_metaobject<X>::value>
{ };
```

The users should be allowed to add specializations of `evaluate` for other types if necessary.

4.2. Default implementation of metafunctions

The default implementation of the metafunction template classes defined above, should follow this pattern:

```
template <typename T>
struct Template;

template <typename T>
struct Template
 : Template<typename evaluate<T>::type>
{ };
```

Where `Template` is each of the following:

- `metaobject_category`
- `specifier_category`
- `keyword`
- `base_name`
- `full_name`
- `named_typedef`
- `named_mem_var`
- `scope`
- `members`
- `overloads`
- `type`
- `base_classes`
- `base_class`
- `base_type`
- `result_type`
- `parameters`
- `template_parameters`
- `template_arguments`
- `template_`
- `exceptions`
- `instantiation`
- `position`
- `value`
- `elaborated_type_specifier`
- `access_specifier`
- `constexpr_specifier`
- `noexcept_specifier`
- `const_specifier`
- `inheritance_specifier`
- `linkage_specifier`
- `storage_specifier`
- `is_pure`
- `is_pack`
- `original_type`

For example:

```
template <typename T>
struct metaobject_category
 : metaobject_category<typename evaluate<T>::type>
{ };
```

This will allow to compose metaobject expressions into algorithms. For example:

```
// print the number of members of the scope where mycls is defined
cout << size<members<scope<mirrored(mycls)>>>() << endl;

// print the name of the first base class of mycls
cout <<
    base_name<base_class<at<base_classes<mirrored(mycls)>, 0>>>()
<< endl;

// print the access specifier keyword of the second base of mycls
cout <<
    keyword<access_specifier<at<base_classes<mirrored(mycls)>, 1>>>()
<< endl;

// print the fully qualified name of the scope of
// the source type of the third member of mycls
cout <<
    full_name<scope<type<at<members<mirrored(mycls)>, 2>>>>()
<< endl;
```

5. Rationale

This section explains some of the design decisions behind this proposal and answers several frequently asked questions.

5.1. Why metaobjects, why not reflect directly?

Q: *Why should we define a set of metaobject concepts, let the compiler generate models of these concepts and use those to obtain the metadata? Why not just extend the existing type traits?*

A: The most important reason is the completeness and the scope of reflection. Type traits (as they are defined now) work just with types. A reflection facility should however provide much more metadata. It should be able to reflect namespaces, functions, constructors, inheritance, variables, etc.

For example:

```
pair<long, string> my_var;

// OK, we can print the name of the type of a variable:
cout << type_name<decltype(my_var)>() << endl;
// But we really, really want to print the name of the variable
// (without the use of the preprocessor)
cout << type_name<my_var>() << endl; // Error
// similar with namespaces:
cout << type_name<std::chrono>() << endl; // Error
// etc.
```

Doing reflection with type traits limits the scope, because of the rules defining what can be a template parameter. This rules could be updated to allow for example an expression representing a particular class constructor to be passed as a template argument. Also currently there is no expression for specifying (not invoking) a constructor or a particular function overload, so additional rules would have to be added.

This would (in our opinion) be a much more drastic change to the standard, than the adoption of this proposal. If expressions denoting a namespace or a particular constructor or a function overload were added just for the purpose of reflecting them (with the `mirroed` keyword), then all the changes could be localized in the reflection subsystem and remain invalid in the core language:

```
mirrored(std::current_thread); // OK - MetaNamespace
std::current_thread; // error - not a primary expression

mirrored(std::sin); // OK - MetaOverloadedFunction
std::sin; // error - cannot resolve overload

mirrored(std::sin(double)); // OK - MetaFunction
std::sin(double); // error - invalid expression
//etc.
```

Second reason is access to private and protected members. There are many use-cases where access to non-public class members through reflection is desired. If reflection was done through type traits directly on the class members, it would be either impossible to reflect non-public members or the access rules would have to be changed to somehow allow access in reflection expressions:

```
class C
{
private:
        typedef int T;
public:
};
```

```
assert(some_trait<C::T>::value); //OK, we are reflecting so we have access
```

but not outside:

```
C::T x = 0; // Error, C::T is private
```

With the reflection operator like `mirrored(X)`, the access rules would have to be updated only to allow the reflection operator to have access to everthing. At the first glance, the following two expressions;

```
some_trait<C::T>::value
```

and

```
mirrored(C::T)
```

look similar and so the changes to the access rules could seem similar too, but that is not the case. The (single) `mirrored` operator would have special status, on the other hand type traits are regular templates (with some magic inside) and all (several dozens of them) would need to be distinguished from all the other templates in the `std` namespace, which should not have private access.

Having said that, we do not object to extending the type traits where it does make sense.

One other reason for having a new reflection operator is, that there already is an existing (very limited) reflection operator, namely `typeid` which "returns" a compiler-generated "metaobject" – `std::type_info`. We are aware that there are differences between `typeid` and `mirrored`, but the basic idea is similar.

5.2. Why are the metaobjects anonymous?

Q: *Why should the metaobjects be anonymous types as opposed to types with well defined and standardized names or concrete template classes, (possibly with some special kind of parameter accepting different arguments than types and constants)?*

A: We wanted to avoid defining a specific naming convention, because it would be difficult to do so and very probably not user friendly (see C++ name mangling). There already is a precedent for anonymous types – for example C++ *lambdas*.

Another option would be to define a concrete set of template classes like:

```
namespace std {

template <typename T>
class meta_type /* Model of MetaType */
{ };

}
```

which could work with types, classes, etc., but would not work with namespaces, constructors, etc. (see also the Q/A above):

```
namespace std {

template <something X> //<- Problem
class meta_constructor /* Model of MetaConstructor */
{ };

template <something X> //<- Problem
class meta_namespace /* Model of MetaNamespace */
{ };

}

typedef std::meta_namespace<std> meta_std; //<- Problem
```

Instead of this, the metaobjects are anonymous and their (internal) identification is left to the compiler. From the users POV, the metaobject can be distinguished by the means of the metaobject traits and tags as described above.

5.3. Why this rendering of metaobjects?

Q: *Why were the metaobject concepts from n3996 transformed into a set of types with external template classes operating on them?*

A: N3996 defined a set of abstract metaobject concepts including their instances, traits, attributes and functions. Then two possible concrete transformations into valid C++ were shown in the appendices.

1. Structures where the attributes were constexpr static member variables and the functions were constexpr static member functions.

2. Types where the traits, attributes and functions are implemented as specializations of class templates defined on namespace-level.

In this proposal the second option was picked for several reasons:

- It is closer to standard type traits and to popular metaprogramming libraries like *Boost.MPL*, etc.

- It should require less resources and time to compile, since the implementation of various metafunctions (class templates) like `base_name`, `scope` or `position` and especially those returning *MetaobjectSequence*s, like `members`, `overloads`, `base_classes` etc. for concrete metaobjects can be instantiated individually and need to be instantiated only if they are actually used in the code. It would probably be harder to do so if they were implemented as (non-template) class members.

6. Known issues

- Some better name for the `template_` metafunction template class.
- *Something similar to source contexts from D3972:* Should *Metaobject* contain information about the source file, line and possibly line column or function name where the base-level construct reflected by the *Metaobject* was defined ?
- *Normalization of names returned by* `MetaNamed base_name()` *and* `MetaNamedScoped full_name()`*:* The strings returned by the `base_name` and `full_name` metafunctions should be implementation-independent and the same on every platform/compiler.
- *The reflection of C++11/14 features not covered by this proposal.*
- *Explicit specification of what should be reflected.* It might be useful to have the ability to explicitly specify either what to reflect or what to hide from reflection. For example the "whitelisting" (explicitly specifying of what should be reflected) of namespace or class members could simplify reflective meta-algorithms so that they would not have to implement complicated filters when traversing scope members, to hide implementation details and to improve compilation times. It is important that this functionality is decoupled from the scope member declarations, since it would allow applications to cherry-pick what should be reflected even in third-party libraries.

7. Acknowledgements

Thanks to Fabio Fracassi for presenting the n3996 proposal at the Rapperswil meeting.

8 References

[1] Chochlík M., N3996 - Static reflection, 2014, https://isocpp.org/files/papers/n3996.pdf.

[2] Mirror C++ reflection utilities (C++11 version), http://kifri.fri.uniza.sk/~chochlik/mirror-lib/html/.

A. Examples

This section contains multiple examples of usage of the additions proposed above. The examples assume that the `mirrored` operator (described above) is used to obtain the metaobjects and the types, templates, etc. are defined in the `std::meta` namespace.

For the sake of brevity

```
using namespace std;
```

is assumed.

A.1. Basic traits

Usage of the `is_metaobject` trait on non-metaobjects:

```
static_assert(not(is_metaobject<int>()), "");
static_assert(not(is_metaobject<std::string>()), "");
static_assert(not(is_metaobject<my_class>()), "");
static_assert(not(meta::is_class_member<meta_gs>()), "");
```

A.2. Global scope reflection

```
// reflected global scope
typedef mirrored(::) meta_gs;

static_assert(is_metaobject<meta_gs>(), "");

// Is a MetaNamed
static_assert(meta::has_name<meta_gs>(), "");
// Is a MetaScoped
static_assert(meta::has_scope<meta_gs>(), "");
// Is a MetaScope
static_assert(meta::is_scope<meta_gs>(), "");
// Is not a MetaTemplate
static_assert(not(meta::is_template<meta_gs>()), "");
// Is not a MetaInstantiation
static_assert(not(meta::has_template<meta_gs>()), "");
// Is not a MetaClassMember
static_assert(not(meta::is_class_member<meta_gs>()), "");

// Is a MetaGlobalScope
static_assert(
    is_base_of<
        meta::global_scope_tag,
        metaobject_category<meta_gs>
    >(), ""
);

// Global scope is its own scope
```

```
static_assert(
    is_base_of<
        meta_gs,
        meta::scope<meta_gs>
    >(), ""
);

// Empty base and full name
assert(strlen(meta::base_name<meta_gs>()) == 0);
assert(strcmp(meta::base_name<meta_gs>(), "") == 0);

assert(strlen(meta::full_name<meta_gs>()) == 0);
assert(strcmp(meta::full_name<meta_gs>(), "") == 0);

// the sequence of members
typedef meta::members<meta_gs>::type meta_gs_members;

static_assert(
    meta::size<meta_gs_members>() == 20, // YMMV
    ""
);
```

A.3. Namespace reflection

```
// reflected namespace std
typedef mirrored(std) meta_std;

static_assert(is_metaobject<meta_std>(), "");

// Is a MetaNamed
static_assert(meta::has_name<meta_std>(), "");
// Is a MetaScoped
static_assert(meta::has_scope<meta_std>(), "");
// Is a MetaScope
static_assert(meta::is_scope<meta_std>(), "");
// Is not a MetaTemplate
static_assert(not(meta::is_template<meta_std>()), "");
// Is not a MetaInstantiation
static_assert(not(meta::has_template<meta_std>()), "");
// Is not a MetaClassMember
static_assert(not(meta::is_class_member<meta_std>()), "");

// Is a MetaNamespace
```

```
static_assert(
    is_base_of<
        meta::namespace_tag,
        metaobject_category<meta_std>
    >(), ""
);

// The scope of namespace std is the global scope
static_assert(
    is_base_of<
        meta_gs,
        meta::scope<meta_std>
    >(), ""
);

// The base and full name
assert(strlen(meta::base_name<meta_std>()) == 3);
assert(strcmp(meta::base_name<meta_std>(), "std") == 0);
assert(strlen(meta::full_name<meta_std>()) == 3);
assert(strcmp(meta::full_name<meta_std>(), "std") == 0);
```

A.4. Type reflection

```
// reflected type unsigned int
typedef mirrored(unsigned int) meta_uint;

static_assert(is_metaobject<meta_uint>(), "");

// Is a MetaNamed
static_assert(meta::has_name<meta_uint>(), "");
// Is a MetaScoped
static_assert(meta::has_scope<meta_uint>(), "");
// Is not a MetaScope
static_assert(not(meta::is_scope<meta_uint>()), "");
// Is not a MetaTemplate
static_assert(not(meta::is_template<meta_uint>()), "");
// Is not a MetaInstantiation
static_assert(not(meta::has_template<meta_uint>()), "");
// Is not a MetaClassMember
static_assert(not(meta::is_class_member<meta_uint>()), "");

// Is a MetaType
static_assert(
```

```
    is_base_of<
        meta::type_tag,
        metaobject_category<meta_uint>
    >(), ""
);

// The scope of unsigned int is the global scope
static_assert(
    is_base_of<
        meta_gs,
        meta::scope<meta_uint>
    >(), ""
);

// The original type
static_assert(
    is_same<
        unsigned int,
        meta::original_type<meta_uint>::type
    >(), ""
);

assert(strlen(meta::base_name<meta_uint>()) == 12);
assert(strcmp(meta::base_name<meta_uint>(), "unsigned int") == 0);
assert(strlen(meta::full_name<meta_uint>()) == 12);
assert(strcmp(meta::full_name<meta_uint>(), "unsigned int") == 0);
```

A.5. Typedef reflection

```
// reflected typedef std::size_t
typedef mirrored(std::size_t) meta_size_t;

static_assert(is_metaobject<meta_size_t>(), "");

static_assert(meta::has_name<meta_size_t>(), "");
static_assert(meta::has_scope<meta_size_t>(), "");
static_assert(not(meta::is_scope<meta_size_t>()), "");
static_assert(not(meta::is_template<meta_size_t>()), "");
static_assert(not(meta::has_template<meta_size_t>()), "");
static_assert(not(meta::is_class_member<meta_size_t>()), "");

// Is a MetaTypedef
static_assert(
```

```
    is_base_of<
        meta::typedef_tag,
        metaobject_category<meta_size_t>
    >(), ""
);

// The scope of std::size_t is the namespace std
static_assert(
    is_base_of<
        meta_std,
        meta::scope<meta_size_t>
    >(), ""
);

// The original type
static_assert(
    is_same<
        std::size_t,
        meta::original_type<meta_size_t>::type
    >(), ""
);

// the "source" type of the typedef
typedef meta::type<meta_size_t>::type meta_size_t_type;
static_assert(
    is_base_of<
        meta::type_tag,
        metaobject_category<meta_size_t_type>
    >(), ""
);

// The original type
static_assert(
    is_same<
        std::size_t,
        meta::original_type<meta_size_t_type>::type
    >(), ""
);

assert(strlen(meta::base_name<meta_size_t>()) == 6);
assert(strcmp(meta::base_name<meta_size_t>(), "size_t") == 0);
assert(strlen(meta::full_name<meta_size_t>()) == 11);
assert(strcmp(meta::full_name<meta_size_t>(), "std::size_t") == 0);
// YMMV
```

```
assert(strlen(meta::base_name<meta_size_t_type>()) == 12);
assert(strcmp(meta::base_name<meta_size_t_type>(), "unsigned int") == 0);
```

A.6. Class reflection

```
struct A
{
    int a;
};

class B
{
private:
    bool b;
public:
    typedef int T;
};

class C
 : public A
 , virtual protected B
{
public:
    static constexpr char c = 'C';

    struct D : A
    {
        static double d;
    } d;
};

union U
{
    long u;
    float v;
};

typedef mirrored(A) meta_A;
typedef mirrored(B) meta_B;
typedef mirrored(C) meta_C;
typedef mirrored(C::D) meta_D;
typedef mirrored(B::T) meta_T;
typedef mirrored(U) meta_U;
```

```
// classes are scopes
static_assert(meta::is_scope<meta_A>(), "");
static_assert(meta::is_scope<meta_B>(), "");
static_assert(meta::is_scope<meta_C>(), "");
static_assert(meta::is_scope<meta_D>(), "");
static_assert(meta::is_scope<meta_U>(), "");

// A, B, C, C::D and U are all elaborated types
assert(is_base_of<meta::class_tag, metaobject_category<meta_A>>());
assert(is_base_of<meta::class_tag, metaobject_category<meta_B>>());
assert(is_base_of<meta::class_tag, metaobject_category<meta_C>>());
assert(is_base_of<meta::class_tag, metaobject_category<meta_D>>());
assert(is_base_of<meta::class_tag, metaobject_category<meta_U>>());

static_assert(!meta::is_class_member<meta_A>(), "");
static_assert(!meta::is_class_member<meta_B>(), "");
static_assert(!meta::is_class_member<meta_C>(), "");
static_assert( meta::is_class_member<meta_D>(), "");
static_assert( meta::is_class_member<meta_T>(), "");
static_assert(!meta::is_class_member<meta_U>(), "");

// typenames
assert(strcmp(meta::base_name<meta_A>(), "A") == 0);
assert(strcmp(meta::base_name<meta_B>(), "B") == 0);
assert(strcmp(meta::full_name<meta_D>(), "C::D") == 0);

// reflected laborated type specifiers for A, B and U
typedef meta::elaborated_type_specifier<meta_A>::type meta_A_ets;
typedef meta::elaborated_type_specifier<meta_B>::type meta_B_ets;
typedef meta::elaborated_type_specifier<meta_U>::type meta_U_ets;

// specifier keywords
assert(strcmp(meta::keyword<meta_A_ets>(), "struct") == 0);
assert(strcmp(meta::keyword<meta_B_ets>(), "class") == 0);
assert(strcmp(meta::keyword<meta_U_ets>(), "union") == 0);

// specifier tags
assert(is_base_of<meta::struct_tag, meta::specifier_category<meta_A_ets>>());
assert(is_base_of< meta::class_tag, meta::specifier_category<meta_B_ets>>());
assert(is_base_of<meta::union_tag, meta::specifier_category<meta_U_ets>>());

// reflected sequences of members of the A,B and C classes
typedef meta::members<meta_A>::type meta_A_members;
```

```
typedef meta::members<meta_B>::type meta_B_members;
typedef meta::members<meta_C>::type meta_C_members;

static_assert(meta::size<meta_A_members>() == 1, ""); // A::a
static_assert(meta::size<meta_B_members>() == 2, ""); // B::b,B::T
static_assert(meta::size<meta_C_members>() == 3, ""); // C::c,C::D,C::d

// reflected members of B and C
typedef meta::at<meta_B_members, 0>::type meta_B_b;
typedef meta::at<meta_B_members, 1>::type meta_B_T;
typedef meta::at<meta_C_members, 0>::type meta_C_c;
typedef meta::at<meta_C_members, 1>::type meta_C_D;
typedef meta::at<meta_C_members, 2>::type meta_C_d;

assert(is_base_of<meta::variable_tag, metaobject_category<meta_B_b>>());
assert(is_base_of<meta::typedef_tag, metaobject_category<meta_B_T>>());
assert(is_base_of<meta::class_tag, metaobject_category<meta_C_D>>());

// MetaClassMembers
static_assert( meta::is_class_member<meta_B_b>(), "");
static_assert( meta::is_class_member<meta_B_T>(), "");
static_assert( meta::is_class_member<meta_C_D>(), "");
static_assert( meta::is_class_member<meta_C_d>(), "");

// access specifiers
typedef meta::access_specifier<meta_B_B>::type meta_B_b_access;
typedef meta::access_specifier<meta_C_D>::type meta_C_D_access;

// specifier keywords
assert(strcmp(meta::keyword<meta_B_b_access>(), "private") == 0);
assert(strcmp(meta::keyword<meta_C_D_access>(), "public") == 0);

// sequence of base classes of C
typedef meta::base_classes<meta_C>::type meta_C_bases;

static_assert(meta::size<meta_C_bases>() == 2, ""); // A, B

// MetaInheritances of C->A and C->B
typedef meta::at<meta_C_bases, 0>::type meta_C_base_A;
typedef meta::at<meta_C_bases, 1>::type meta_C_base_B;

// inheritance specifiers
typedef meta::inheritance_specifier<meta_C_base_A>::type meta_C_base_A_it;
typedef meta::inheritance_specifier<meta_C_base_B>::type meta_C_base_B_it;
```

```
// access specifiers
typedef meta::access_specifier<meta_C_base_A>::type meta_C_base_A_acc;
typedef meta::access_specifier<meta_C_base_B>::type meta_C_base_B_acc;

// specifier keywords
assert(strcmp(meta::keyword<meta_C_base_A_it>(), "") == 0);
assert(strcmp(meta::keyword<meta_C_base_B_it>(), "virtual") == 0);
assert(strcmp(meta::keyword<meta_C_base_A_acc>(), "public") == 0);
assert(strcmp(meta::keyword<meta_C_base_B_acc>(), "protected") == 0);

// specifier tags
static_assert(
    is_base_of<
        meta::none_tag,
        meta::specifier_category<meta_C_base_A_it>
    >(), ""
);
static_assert(
    is_base_of<
        meta::virtual_tag,
        meta::specifier_category<meta_C_base_B_it>
    >(), ""
);
static_assert(
    is_base_of<
        meta::public_tag,
        meta::specifier_category<meta_C_base_A_acc>
    >(), ""
);

// base classes
static_assert(
    is_base_of<
        meta_A,
        meta::base_class<meta_C_base_A>
    >(), ""
);
static_assert(
    is_base_of<
        meta_B,
        meta::base_class<meta_C_base_B>
    >(), ""
);
```