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Static reflection

How to read this document The first two sections are devoted to the introduction to reflection and reflective programming, they contain some motivational examples and some experiences with usage of a library-based reflection utility. These can be skipped if you are knowledgeable about reflection. Section 3 contains the rationale for the design decisions. The most important part is the technical specification in section 4, the impact on the standard is discussed in section 5, the issues that need to be resolved are listed in section 7, and section 6 mentions some implementation hints.

Contents

1. Introduction

Reflection and reflective programming can be used for a wide range of tasks such as implementation of serialization-like operations, 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 structures providing basic metadata describing various program constructs. These metaobjects can later be used to implement a library or a set of 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.

The term *reflection* refers to the ability of a computer program to observe and possibly alter its own structure and/or its behavior. This includes building new or altering the existing data structures, doing changes to algorithms or changing the way the program code is interpreted. Reflective programming is a particular kind of *metaprogramming*.

Reflection should follow the principle of *Ontological correspondence*, i.e. should *reflect* the base-level program constructs as closely as possible to a reasonable level. Reflection should not omit existing language features not invent new ones that do not exist at the base-level.

What reflection "looks like" is thefore very language-specific. Reflection for C++ is necessary different from reflection in Smalltalk since these are two quite different languages.

The "reasonability" applies to the level-of-detail of the metadata provided by reflection. It is a tradeoff between the complexity of the reflection system and its usefulness. The "metadata" provided by the currently standard `typeid` operator are rather simple (which may be good), but their usefulness is very limited (which is bad). On the other hand a fictional reflection facility that would allow to inspect the individual instructions of a function could be useful for some specific applications, but this system would also be very complex to implement and use. The proposed reflection system tries to walk a "middle ground" and be usable in many situations without unmanagable complexity.

The advantage of using reflection is in the fact that everything is implemented in a single programming language, and the human-written code can be closely tied with the customizable reflection-based code which is automatically generated by compiler metaprograms, based on the metadata provided by reflection.

The solution proposed in this paper is based on the expirience with *Mirror* reflection utilities [1] and with reflection-based metaprogramming. In the following chapters and appendices several examples of usage of various components of the Mirror library are provided. These are included just to show what can be done with a sufficiently advanced reflection facility. The Mirror library, however *is not* part of the current proposal.

2. Motivation and Scope

2.1. Usefullness of reflection

There is a wide range of computer programming tasks that involve the execution of the same algorithm on a set of types defined by an application or on instances of these types, accessing member variables, calling free or member functions in an uniform manner, converting data between the language's intrinsic representation and external formats, etc., for the purpose of implementing the following:

- serialization or storing of persistent data in a custom binary format or in XML, JSON, XDR, etc.,
- (re-)construction of class instances from external data representations (like those listed above), from the data stored in a relational database, from data entered by a user through a user interface or queried through a web service API,
- automatic generation of a relational schema from the application object model and object-relational mapping (ORM),
- support for scripting
- support remote procedure calls (RPC) / remote method invocation (RMI),
- inspection and manipulation of existing objects via a (graphic) user interface or a web service,
- visualization of objects or data and the relations between objects or relations in the data,
- automatic or semi-automatic implementation of certain software design patterns,
- etc.

There are several aproaches to the implementation of such functionality. The most straightforward and also usually the most error-prone is manual implementation. Many of the tasks listed above are inherently repetitive and basically require to process programming language constructs (types, structures, containers, functions, constructors, class member variables, enumerated values, etc.) in a very uniform way that could be easily transformed into a meta-algorithm.

While it is acceptable (even if not very advantageous) for example, for a design pattern implementation to be made by a human, writing RPC/RMI-related code is a task much better suited for a computer.

This leads to the second, heavily used approach: preprocessing and parsing of the program source text by a (usually very specfic) external program (documentation generation tool, interface definition language compiler for RPC/RMI, web service interface generator, a rapid application development environment with a form designer, etc.) resulting in additional program source code, which is then compiled into the final application binary.

This approach has several problems. First, it requires the external tools which may not fit well into the build system or may not be portable between platforms or be free; second, such tools are task-specific and many of them allow only a limited, if any, customization of the output.

Another way to automate these tasks is to use reflection, reflective programming, metaprogramming and generic programming as explained below.

2.2. Motivational examples

This section describes some of the many possible uses of reflection and reflective programming on concrete real-world examples.

2.2.1. Factory generator

As already said above, it is possible (at least partially) to automate the implementation of several established software design patterns. This example shows how to implement a variant of the *Factory* pattern.

By factory we mean here a class, which can create instances of a *Product* type, but does not require that the caller chooses the manner of the construction (in the programming language) nor supplies the required arguments directly in the C++ intrinsic data representation.

So instead of direct construction of a Product type,

```
// get the values of arguments from the user
int arg1 = get_from_user<int>("Product arg1");
double arg2 = get_from_user<double>("Product arg2");
std::string arg3 = get_from_user<std::string>("Product arg3");
//
// call a constructor with these arguments
Product* pp = new Product(arg1, arg2, arg3);
// default construct a Product
Product p;
// copy construct a Product
Product cp = p;
```

which involves selection of a specific constructor, getting the values of the required arguments and possibly converting them from an external representation and calling the selected constructor with the arguments, factories pick or let the application user pick the Product's most appropriate constructor, they gather the necessary parameters in a generic way and use the selected constructor to create an instance of the Product:

```
// get data necessary for construction in xml
XMLNode xml_node_1 = get_xml_node(...);
XMLNode xml_node_2 = get_xml_node(...);

// make a factory for the product type
Factory<Product, XMLWalker> xml_factory;

// use the factory to create instances of Product
// from the external representation
Product p = xml_factory(xml_node_1);
Product* pp = xml_factory.new_(xml_node_2);
```

One of the interesting features of these factories is, that they separate the caller (who just needs to get an instance of the specified type) from the actual method of creation.

By using a factory, the constructor to be called can be automatically picked depending on the data available only at run-time and not be chosen by the programmer (at least not directly as in the code above). Factory can match the constructor to best fit the data available in the external representation (XML or JSON fragment, dataset resulting from a RDBS query, etc.)

Even more interesting is, that such factories can be implemented semi-automatically with the help of reflection.

Every factory is a composition of two distinct (and nearly orthogonal) parts:

- Product-type-dependent: includes the enumeration of Product's constructors, enumeration of their parameters, information about the context in which a constructor is called, etc. This part is based on reflection and independent on the representation of the input data.
- Data representation-dependent: includes the scanning of the available input data, conversion into C++ intrinsic data representation, and the selection of the best constructor. This part is user-defined and specifies how the input data is gathered and converted into the C++ representation.

These two parts are then tied together into the factory class. Based on the input-data related components, the factory can include a script parser or XML document tree walker or code dynamically generating a GUI for the input of the necessary values and the selection of the preferred constructor. Figure 1 shows such a GUI created by factory automatically generated by the Mirror's *factory generator* utility for a tetrahedron class with the following definition:

```
struct vector
{
```

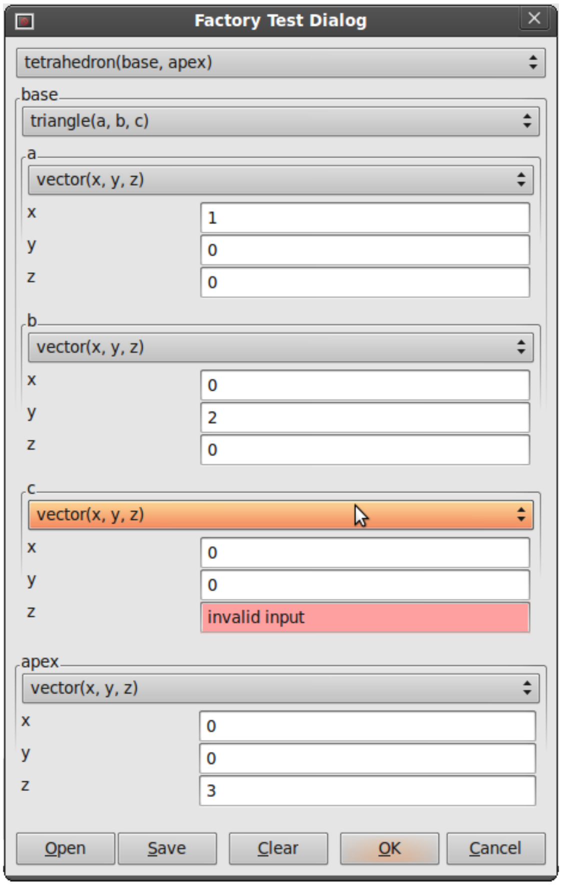


Figure 1: Example of a GUI created by a factory generated by the Mirror's factory generator.

```
double x,y,z;

vector(double _x, double _y, double _z)
 : x(_x), y(_y), z(_z)
{ }

vector(double _w)
 : x(_w), y(_w), z(_w)
{ }

vector(void)
 : x(0.0), y(0.0), z(0.0)
{ }

/* other members */
```

```
};

struct triangle
{
        vector a, b, c;

        triangle(
                const vector& _a,
                const vector& _b,
                const vector& _c
        ): a(_a), b(_b), c(_c)
        { }

        triangle(void){ }

        /* other members */
};

struct tetrahedron
{
        triangle base;
        vector apex;

        tetrahedron(const triangle& _base, const vector& _apex)
         : base(_base), apex(_apex)
        { }

        tetrahedron(
                const vector& a,
                const vector& b,
                const vector& c,
                const vector& d
        ): base(a, b, c), apex(d)
        { }

        /* other members */
};
```

3. Design Decisions

3.1. Desired features

The proposed reflection facility is designed with the following goals in mind:

- *Reusability*: The provided metadata should be reusable in many situations and for many different purposes, not only the obvious ones. This is closely related to *completeness* (below).
- *Flexibility*: The basic reflection and the libraries built on top of it should be designed in a way that they are eventually usable during both compile-time and run-time and under various paradigms (object-oriented, functional, etc.), depending on the application needs.
- *Encapsulation*: The metadata should be accessible through conceptually well-defined interfaces.
- *Stratification*: Reflection should be non-intrusive, and the meta-level should be separated from the base-level language constructs it reflects. Also, reflection should not be implemented in a all-or-nothing manner. Things that are not needed, should not generally be compiled-into the final application.
- *Ontological correspondence*: The meta-level facilities should correspond to the ontology of the base-level C++ language constructs which they reflect. This basically means that all existing language features should be reflected and new ones should not be invented. This rule may have some important exceptions, like the reflection of containers.
- *Completeness*: The proposed reflection facility should provide as much useful metadata as possible, including various specifiers, (like constness, storage-class, access, etc.), namespace members, enumerated types, iteration of namespace members and much more.
- *Ease of use*: Although reflection-based metaprogramming allows to implement very complicated things, simple things should be kept simple.
- *Cooperation with other librares*: Reflection should be usable with the existing introspection facilites (like `type_traits`) already provided by the standard library and with other libraries.

3.2. Layered approach and extensibility

The purpose of this section is to show that a *static* $\rightarrow$ *dynamic* and *basic* $\rightarrow$ *complex* approach in designing reflection can accomodate a wide variety of programming styles and is arguably the "best" one. We do not propose to add all layers described below into the standard library. They are mentioned here only to show that a well designed compile-time reflection is a good foundation for many (if not all) other reflection facilities.

The Mirror reflection utilities [1] on which this proposal is based, implements several distinct components which are stacked on top of each other. From the low-level metadata, through a functional-style compile-time interface to a completely dynamic object-oriented run-time layer (all described in greater detail below).

3.2.1. Basic metaobjects

The very basic metadata, which are in Mirror provided (registered) by the user (or an automated command-line tool) via a set of preprocessor macros. This approach is both inconvenient and error-prone in many situations, but also has its advantages.

We propose that a standard compiler should make these metadata available to the programmer through the static basic metaobject interfaces described below. These should serve as the basis for other (standard and non-standard) higher-level reflection libraries and utilities.

In the Mirror utilities the basic metadata is not used directly by applications.

3.2.2. Mirror

Mirror is a compile-time functional-style reflective programming library, which is based directly on the basic metadata and is suitable for generic programming, similar to the standard `type_traits` library.

Mirror is the original library from which the Mirror reflection utilities started.

It provides a more user-friendly and rich interface than the basic-metaobjects. and a set of metaprogramming utilities which allow to write compile-time meta-programs, which can generate efficient and optimized program code using only those metadata that are required.

The appendix B contains several (rather simple) examples of usage and the functional style of the algorithms based on metadata provided by Mirror.

3.2.3. Puddle

Puddle is an OOP-style (mostly) compile-time interface built on top of Mirror. It copies the metaobject concept hierarchy of Mirror, but provides a more "object-ish" interface as shown below:

Instead of Mirror's:

```
static_assert(
  is_public<
    access_type<
      at_c<
        member_variables<
          reflected<person>
        >,
        0
      >
    >
  >::value,
  "Shoot, persons first mem. variable is not public!"
)
```

Puddle allows to do the following:

```
assert(
  reflected_type<person>()
    member_variables().
      at_c<0>().
        access_type().
          is_public()
);
```

For a more complex use-case see appendix C.

3.2.4. Rubber

Rubber is a OOP-style run-time type erasure utility built on top of Mirror and Puddle. It again follows the metaobject concept hierarchy of Mirror and Puddle. Rubber allows to access and store metaobjects of the same category in a single type, so in contrast to Mirror and Puddle where a meta-type reflecting the `int` type and a meta-type reflecting the `double` type have different types in Rubber they can both be stored in a variable of the same type. Rubber does not use virtual functions but rather pointers to existing functions implemented by Mirror to achieve run-time polymorphism.

For examples of usage see appendix D.

3.2.5. Lagoon

Lagoon defines run-time polymorphic interfaces and classes implementing these interfaces and wrapping the compile-time metaobjects from Mirror and Puddle. While Rubber is more suitable for simple decoupling of reflection-based algorithms from the real types of the metaobjects that the algorithms operate on, Lagoon is full-blown run-time reflection utility that can be even decoupled from the application using it and loaded dynamically on-demand.

See appendix E for examples of usage.

3.3. Class generators

There are situations where the following transformation of scopes (classes, enumerations, etc.) and their members would be very useful. Consider a simple user-defined `struct`s `address` and `person`,

```
struct address
{
        std::string street;
        std::string number;
        std::string postal_code;
        std::string city;
        std::string country;
};

struct person
{
        std::string name;
        std::string surname;

        address residence;

        std::tm birth_date;
};
```

and an object-relational mapping (ORM) library, that would allow automatic generation of SQL queries from strongly typed expressions in a DSEL in C++. It would be advantageous to have some counterparts for all "ORM-aware" classes having members with the same names as the original class, but with different types, like:

```
template <class T>
struct orm_table;

template <>
struct orm_table<address>
 : public base_table
{
        orm_column<std::string> street;
        orm_column<std::string> number;
        orm_column<std::string> postal_code;
```

```
        orm_column<std::string> city;
        orm_column<std::string> country;

        orm_table(orm_param& param)
         : base_table(param)
         , street(this, param)
         , number(this, param)
         , postal_code(this, param)
         , city(this, param)
         , country(this, param)
        { }
};

template <>
struct orm_table<person>
 : public base_table
{
        orm_column<std::string> name;
        orm_column<std::string> surname;
        orm_column<address> residence;
        orm_column<std::tm> birth_date;

        orm_table(orm_param& param)
         : base_table(param)
         , name(this, param)
         , surname(this, param)
         , residence(this, param)
         , birth_date(this, param)
        { }
};
```

Generating such or similar classes can also be achieved with reflection. The Mirror library implements the `by_name` metafunction template and the `class_generator` utility for this purpose.

The *Puddle* layer, described above, uses this functionality and allows access to metadata reflecting member variables of a class or free variables of a namespace through the overloaded `operator ->` of a meta-class or meta-namespace:

```
auto meta_person = puddle::reflected_type<person>();
// access the metavariable reflecting
// the birth_date member of person
assert(meta_person->birth_date().access_type().is_public());
// access the metadata for person::name
// and person::surname by their names
```

```
assert(
        meta_person->name() ==
        meta_person.member_variables().at_c<0>()
);
assert(
        meta_person->surname() !=
        meta_person.member_variables().at_c<0>()
);
```

This functionality could be extended to any scope member and the mechanism is described below.

3.4. Compile-time vs. Run-time reflection

Run-time, dynamic reflection facilities may seem more readily usable, but with the increasing popularity of compile-time metaprogramming, the need for compile-time introspection (already taken care of by `type_traits`) and reflection also increases.

Also, if compile-time reflection is well supported it is relatively easy to implement run-time or even dynamically loadable reflection on top of it. The oposite is not true: One cannot use run-time metaobjects or the value returned by their member functions as template parameters or compile-time constants.

From the performance point of view, algorithms based on static meta-data offer much more possibilities for the compiler to do optimizations.

Thus, taking shortcuts directly to run-time reflection, without compile-time support has obvious drawbacks.

4. Technical Specifications

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.

4.1. Metaobject Concepts

This section conceptualy describes the requirements that various metaobjects need to satisfy in order to be considered models of the individual concepts. There are several ways how the conceptual model can be transformed into the final C++ form. These are discussed in the 4.2 subsection below. For examples of concrete renderings please see Appendix A.

4.1.1. Categorization and Traits

In order to provide means for distinguishing between regular types and metaobjects the `is_metaobject` trait should be added and should "return" `true` for metaobjects (types defined by the compiler providing metadata) and `false` for non-metaobjects (native or user defined types). See the definition of the *Metaobject* concept for further metaobject traits and tags.

4.1.2. String

String is an "object" which can be examined at compile-time that represents constant C-character string storing for example a name of a type, function, namespace, etc. or the keyword of a specifier. It allows compile-time metaprograms to examine and make decisions based on the value of such strings. If necessary, the stored string can be returned as a regular C-string.

One of the use-cases for these strings is the filtering of scope members based on their names if a good naming policy is consistently applied. For example: filter out all scope members whose name starts with an underscore or process only classes with names starting with `DB`, `Persistent`, etc.

Concrete metaobjects modelling *String* must satisfy the following:

- *attribute:* `size_t size` – Specifies the length (in `chars`) of the *String*, not counting any terminating characters.
- *attribute:* `const char* c_str` – The encapsulated constant character string value.

4.1.3. Range {Element}

Range is a static constant parametrized container, containing and providing random-access to elements satisfying the `Element` concept

Concrete metaobjects modelling *Range* must satisfy the following:

- *attribute:* `size_t size` – Specifies the number of elements in the *Range*.
- *element:* `Element at(position)` – Returns the element at the specified `position` in the *Range*.
  - position: The position of the element to be returned.Valid values for this argument are from the range $\{0 \ldots size - 1\}$. For other arguments the result is undefined.

4.1.4. MetaobjectCategory

MetaobjectCategory is a compile-time tag specifying the category of a metaobject.

Instances of the *MetaobjectCategory* concept are listed below.

- *instance:* `namespace` – Indicates that the tagged metaobject satisfies the *Namespace* concept.
- *instance:* `global_scope` – Indicates that the tagged metaobject satisfies the *GlobalScope* concept.
- *instance:* `type` – Indicates that the tagged metaobject satisfies the *Type* concept.
- *instance:* `typedef` – Indicates that the tagged metaobject satisfies the *Typedef* concept.
- *instance:* `class` – Indicates that the tagged metaobject satisfies the *Class* concept.
- *instance:* `function` – Indicates that the tagged metaobject satisfies the *Function* concept.
- *instance:* `constructor` – Indicates that the tagged metaobject satisfies the *Constructor* concept.

- *instance:* `operator` – Indicates that the tagged metaobject satisfies the *Operator* concept.
- *instance:* `overloaded_function` – Indicates that the tagged metaobject satisfies the *OverloadedFunction* concept.
- *instance:* `enum` – Indicates that the tagged metaobject satisfies the *Enum* concept.
- *instance:* `enum_class` – Indicates that the tagged metaobject satisfies the *EnumClass* concept.
- *instance:* `inheritance` – Indicates that the tagged metaobject satisfies the *Inheritance* concept.
- *instance:* `constant` – Indicates that the tagged metaobject satisfies the *Constant* concept.
- *instance:* `variable` – Indicates that the tagged metaobject satisfies the *Variable* concept.
- *instance:* `parameter` – Indicates that the tagged metaobject satisfies the *Parameter* concept.

4.1.5. SpecifierCategory

SpecifierCategory is a compile-time tag specifying an exact C++ specifier.

Instances of the *SpecifierCategory* concept are listed below.

- *instance:* `none` – Indicates missing specifiers; for example a reflected non-const member function would have a `none` constness specifier tag or a variable with automatic storage class would have a `none` storage class specifier, etc. The `keyword` attribute in *Specifier*s with this category tag is an empty *String*.
- *instance:* `extern` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `extern` *storage* or *linkage* specifier.
- *instance:* `static` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `static` *storage* or *linkage* specifier.
- *instance:* `mutable` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `mutable` *storage* or *linkage* specifier.
- *instance:* `register` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `register` *storage* or *linkage* specifier.
- *instance:* `thread_local` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `thread_local` *storage* or *linkage* specifier.

- *instance:* `const` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `const` *constness* specifier.
- *instance:* `virtual` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `virtual` *inheritance type* or *linkage* specifier.
- *instance:* `private` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `private` *access type* specifier.
- *instance:* `protected` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `protected` *access type* specifier.
- *instance:* `public` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `public` *access type* specifier.
- *instance:* `class` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `class` *elaborated type* specifier.
- *instance:* `struct` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `struct` *elaborated type* specifier.
- *instance:* `union` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `union` *elaborated type* specifier.
- *instance:* `enum` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `enum` *elaborated type* specifier.
- *instance:* `enum_class` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `enum_class` *elaborated type* specifier.
- *instance:* `constexpr` – Indicates that the tagged metaobject satisfies the *Specifier* concept and is reflecting the `constexpr` *constness* specifier.

4.1.6. Metaobject

Metaobject is a stateless or (monostate) anonymous type which provides metadata reflecting certain program features.

Concrete metaobjects modelling *Metaobject* must satisfy the following:

- The `is_metaobject` trait inherited from *Metaobject* is true.
- *trait:* *MetaobjectCategory* `category` – A tag specifying the category of the concrete metaobject, which allows metaprograms to do tag dispatching and indicates which concepts the concrete metaobject models.
- *trait:* `bool is_metaobject` – Indicates that the examined metaobject satisfies the *Metaobject* concept.

- *trait:* `bool has_name` – Indicates that the examined metaobject satisfies the *Named* concept.
- *trait:* `bool has_scope` – Indicates that the examined metaobject satisfies the *Scoped* concept.
- *trait:* `bool is_scope` – Indicates that the examined metaobject satisfies the *Scope* concept.
- *trait:* `bool is_class_member` – Indicates that the examined metaobject satisfies the *ClassMember* concept.
- *trait:* `bool has_template` – Indicates that the examined metaobject satisfies the *Instantiation* concept.
- *trait:* `bool is_template` – Indicates that the examined metaobject satisfies the *Template* concept.

4.1.7. Specifier

Specifier is a *Metaobject* which reflects specifiers (like const, static, virtual, etc.) used in the definition the base-level program constructs.

Metaobject ← Specifier

Specifier has these requirements:

- *trait:* *SpecifierCategory* `category` – Refines the category. The resulting tag can be used to identify the concrete specifier reflected by this *Specifier*.
- *attribute:* *String* `keyword` – The C++ keyword of the reflected specifier.

4.1.8. Named

Named is a *Metaobject* that reflects program constructs, which have a name, like namespaces, types, functions, variables, parameters, etc.

Metaobject ← Named

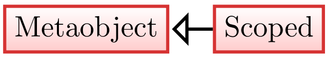
Concrete metaobjects modelling *Named* must satisfy the following:

- The `has_name` trait inherited from *Metaobject* is true.
- *attribute:* *String* `base_name` – The base name of the reflected construct, without the nested name specifier. 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 `std::vector<int>::iterator` it should be `"iterator"`. For derived, qualified types like `volatile std::vector<const foo::bar::fubar*> * const *` it should be `"volatile vector<const fubar*> * const *"`, etc.

4.1.9. Scoped

Scoped is a *Metaobject* reflecting program constructs, which are defined inside of a named *Scope* (global scope, namespace, class, etc.).

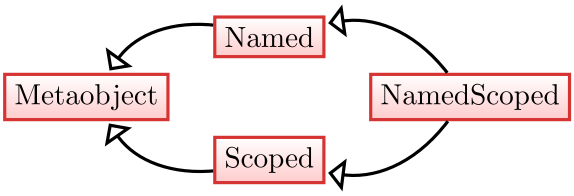


Concrete metaobjects modelling *Scoped* must satisfy the following:

- The `has_scope` trait inherited from *Metaobject* is true.
- *attribute: Scope* `scope` – A *Scope* metaobject reflecting the scope of the scoped object reflected by this *Scoped* metaobject. In concrete metaobjects the result can be a *Namespace*, *GlobalScope*, *Class*, etc.

4.1.10. NamedScoped

Many of the concepts are specializations of both the *Scoped* and *Named* concepts.



Concrete metaobjects modelling *NamedScoped* must satisfy the following:

- *attribute: String* `full_name` – The full name of the reflected construct, with the nested name specifier. 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 c-string literal. 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. For some metaobjects this value may be the same as the `base_name` attribute.
- *template: unspecified* `named_typedef(X)` – A template, instantiation of which should result in a type equivalent to the `struct` in the following pseudo-code:

```
struct unspecified
{
```

```
        typedef X <NAME>;
};
```

The `<NAME>` expression above should be replaced by the name of the reflected named scoped object. This structure could be used to generate new classes with member typedefs having the same names as the members of the scope of the named object reflected by this *NamedScoped* metaobject. One way to combinine the `<NAME>` typedefs from various reflected scope members into a single class would be to let the class inherit from multiple types generated by the `named_typedef` template from the metaobjects obtained by reflection.

  – X: The parameter passed to the `named_typedef` template by the end-user. It is used as the "source" type of the typedef (with the same name as the reflected language construct) in the resulting type.

- *template: unspecified* `named_mem_var(X)` – A template, instantiation of which should result in a type equivalent to the `struct` in the following pseudo-code:

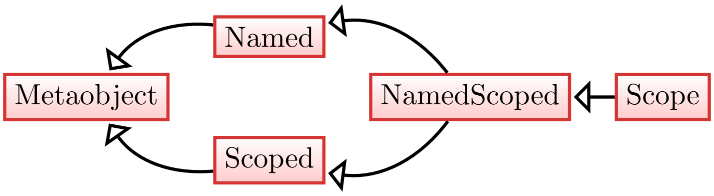
```
struct unspecified
{
        X <NAME>;

        unspecified(void) = default;

        template <typename Param>
        unspecified(Param&& param)
         : <NAME>(std::forward<Param>(param))
        { }
};
```

  The `<NAME>` expression above should be replaced by the name of the reflected named scoped object. This structure could be used to generate new classes with member variables having the same names as the members of the scope of the named object reflected by this *NamedScoped* metaobject. One way to combinine the `<NAME>` member variables from various reflected scope members into a single class would be to let the class inherit from multiple types generated by the `named_mem_var` template from the metaobjects obtained by reflection.

  – X: The parameter passed to the `named_mem_var` template by the end-user. It is used as the type of the member variable (with the same name as the reflected language construct) in the resulting type.

4.1.11. Scope

Scope is a *NamedScoped* which reflects scopes like namespaces, classes, enum classes, etc.

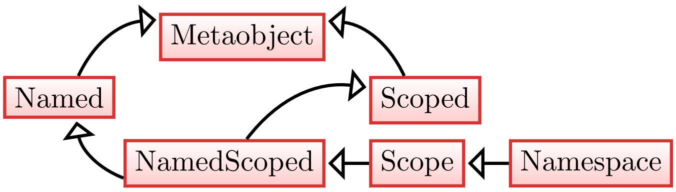


Scope has these requirements:

- The `is_scope` trait inherited from *Metaobject* is true.
- *range: Range* {*Scoped*} `members` – A range of *Scoped* metaobjects reflecting the individual members like types, namespaces, functions, variables, etc. defined inside the scope reflected by this *Scope*.

4.1.12. Namespace

Namespace is a *Scope* which reflects a namespace.

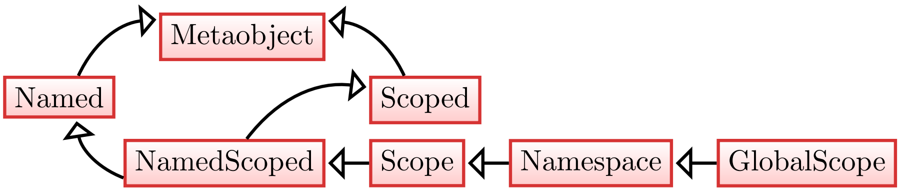


Namespace has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `namespace`.

4.1.13. GlobalScope

GlobalScope is a *Namespace* which reflects the global scope.

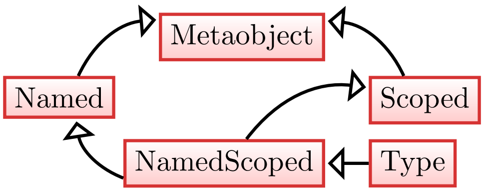


GlobalScope has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `global_scope`.

4.1.14. Type

Type is a *NamedScoped* which reflects types

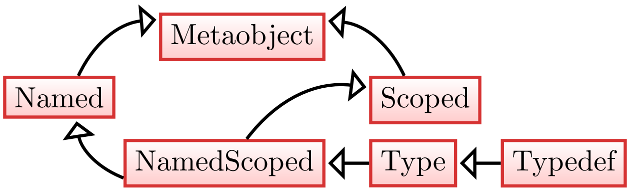


Type has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `type`.
- *attribute: original-type* `original_type` – The original base-level type that this *Type* is reflecting. Note, that if a concept derived from *Type*, for example *Class*, is also a *Template* (i.e. is reflecting a template not a concrete type), then this attribute is not inherited.

4.1.15. Typedef

Typedef is a *Type* which reflects typedefs, i.e. types that were defined as alternate names for other types using the C++ `typedef` expression.

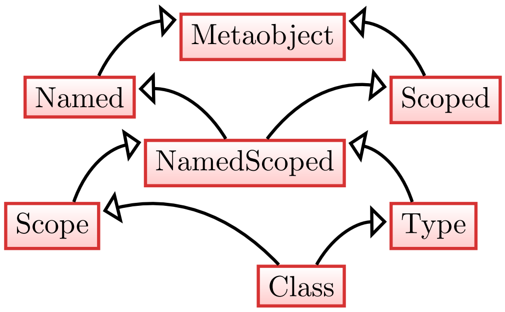


Typedef has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `typedef`.
- *attribute: Type* `typedef_type` – A *Type* metaobject reflecting the "source" type of the typedef.

4.1.16. Class

Class is a *Type* and *Scope* that reflects elaborated types (class, struct, union) or class templates. Note, that if a *Class* is also a *Template*, i.e. is reflecting a class template not a concrete class, then the `original_type` attribute is not inherited from *Type*.



Concrete metaobjects modelling *Class* must satisfy the following:

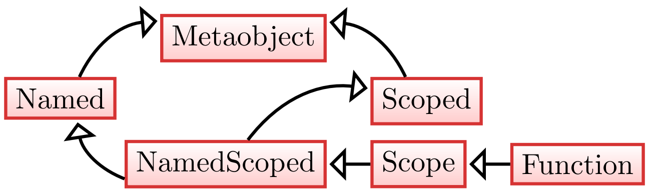
- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `class`.
- *attribute: Specifier* `elaborated_type` – Specifier reflecting the elaborated type specifier used to define the class (`class`, `struct`, `union`).
- *range: Range* {*Inheritance*} `base_classes` – A *Range* of *Inheritance* metaobjects reflecting the base classes that the class reflected by this *Class* inherits from.

4.1.17. Function

Function is a *Scope* reflecting a function or a function template. *Function* metaobjects are not direct members of scopes. Instead, all functions with the same name, even those that are not overloaded in a specific scope are grouped into an *OverloadedFunction*. Individual overloaded *Function*s in the group can be obtained through the interface of *OverloadedFunction*. The same should also apply to *Constructor*s and *Operator*s.

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

The `scope` attribute of an *OverloadedFunction* is the same as the `scope` attribute of all *Function*s grouped by that *OverloadedFunction*.



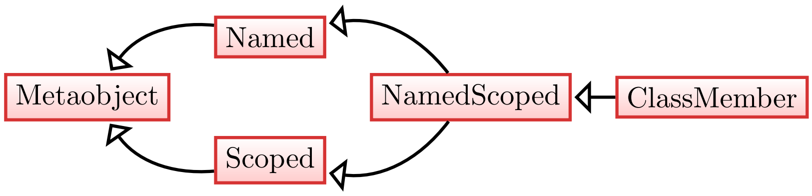
Concrete metaobjects modelling *Function* must satisfy the following:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `function`.
- *attribute: Specifier* `linkage` – *Specifier* reflecting the linkage specifier of the function reflected by this *Function*.

- *attribute:* `bool constexpr` – Indicates if the reflected function is defined as `constexpr`.
- *attribute:* *Type* `result_type` – *Type* reflecting the result type of the function.
- *range:* *Range* {*Parameter*} `parameters` – A *Range* of *Parameter* metaobject reflecting the parameters of the function reflected by this *Function*.
- *attribute:* `bool noexcept` – Indicates if the reflected function is defined as `noexcept`.
- *range:* *Range* {*Type*} `exceptions` – A *Range* of *Type* metaobject reflecting the exception types that the function reflected by this *Function* is allowed to throw.
- *attribute (conditional):* *Specifier* `constness` – *Specifier* reflecting the the constness specifier of the function reflected by this *Function*. This attribute is availabile only if the `is_class_member` trait is true for this *Function*, i.e. when it also satisfies the *ClassMember* concept.
- *attribute (conditional):* `bool pure` – Indicates if the function is a pure virtual function. This attribute is availabile only if the `is_class_member` trait is true for this *Function*, i.e. when it also satisfies the *ClassMember* concept.
- *function:* *unspecified* `call(...)` – Function with the same return value type and the same number and type of parameters as the original function reflected by this *Function*. Calls to this function should be equivalent to the call of the reflected function with the arguments passed to `call`. Additionaly if the reflected function is a member function, then the first of the parameters of `call` should be a reference to the class where the member function is defined and should be used as the `this` argument when calling the member function. If the member function is declared as `const` then the reference to the class should also be `const`.

4.1.18. ClassMember

ClassMember is a *NamedScoped* that reflects a member of a class.

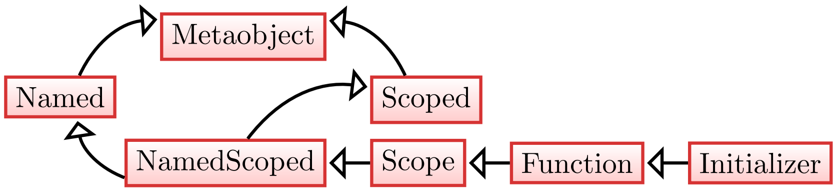


Concrete metaobjects modelling *ClassMember* must satisfy the following:

- The `is_class_member` trait inherited from *Metaobject* is true.
- *attribute:* *Specifier* `access_type` – *Specifier* reflecting the access type specifier of the class member reflected by this *ClassMember*.

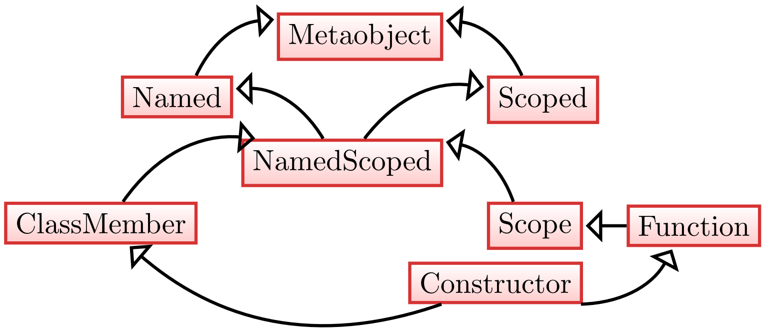
4.1.19. Initializer

Initializer is a *Function* which reflects an initializer (constructor) of a native type.



4.1.20. Constructor

Constructor is a *ClassMember* and *Function* that reflects a constructor.

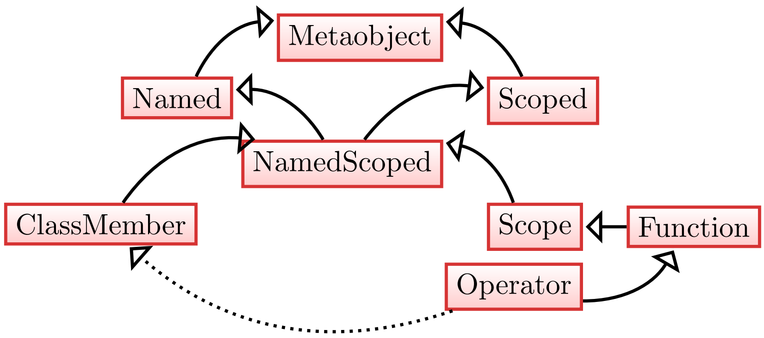


Concrete metaobjects modelling *Constructor* must satisfy the following:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `constructor`.

4.1.21. Operator

Operator is a *Function* and possibly a *ClassMember* reflecting an operator.



Concrete metaobjects modelling *Operator* must satisfy the following:

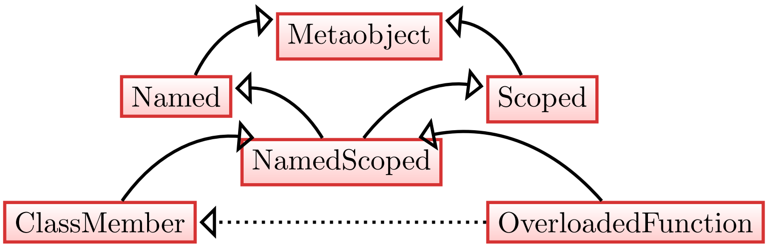
- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `operator`.

4.1.22. OverloadedFunction

OverloadedFunction is a *NamedScoped* and possibly a *ClassMember* reflecting an overloaded function. *Function* metaobjects are not direct members of scopes. Instead, all functions with the same name, even those that are not overloaded in a specific scope are grouped into an *OverloadedFunction*. Individual overloaded *Function*s in the group can be obtained through *OverloadedFunction*. The same should also apply to *Constructor*s and *Operator*s.

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

The `scope` attribute of an *OverloadedFunction* is the same as the `scope` attribute of all *Function*s grouped by that *OverloadedFunction*.

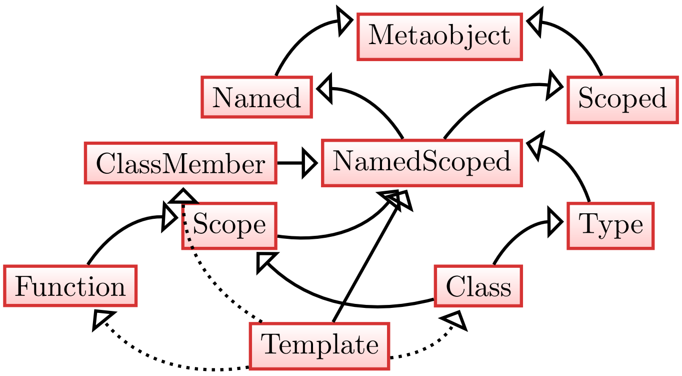


Concrete metaobjects modelling *OverloadedFunction* must satisfy the following:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `overloaded_function`.
- *range:* *Range* {*Function*} `overloads` – A range of *Function* metaobjects reflecting the individual overloaded functions.

4.1.23. Template

Template is a *NamedScoped* and possibly a *Class*, *ClassMember* or *Function* reflecting a class or (member) function template. Note, that the *Template* concept slightly modifies the requirements of the *Class* and *Function* concepts.



Concrete metaobjects modelling *Template* must satisfy the following:

- The `is_template` trait inherited from *Metaobject* is true.
- *range:* *Range* {*TemplateParameter*} `template_parameters` – A range of *TemplateParameter* metaobjects reflecting the individual template parameters.
- *template:* *Instantiation* `instantiation(...)` – A template, instantiation of which should result in the instantiation of the template, reflected by this *Template*, with the specified parameters. The template parameters for the `instantiation` template should be the same as the parameters of the original template.

4.1.24. TemplateParameter

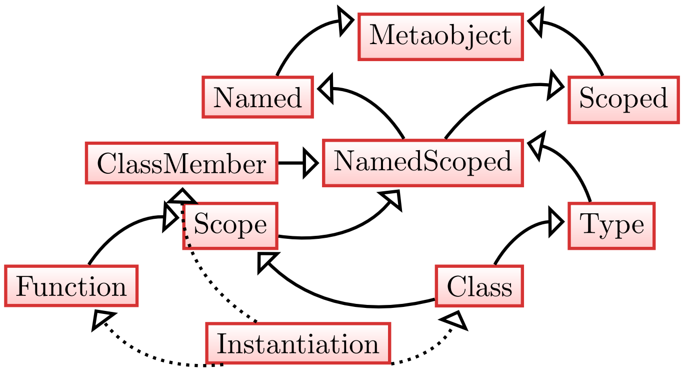
TemplateParameter is a either *Typedef* or *Constant* which reflects a type or non-type template parameter or parameter pack. The `category` tag should be used to distinguish between type and non-type (integral constant) template parameters. The `is_template` trait should be used to distinguish reflected template parameters from typedefs and constants.

TemplateParameter has these requirements:

- *trait:* `bool is_template` – This trait, inherited from *Metaobject*, should return true for template parameters.
- *attribute:* `size_t position` – The position of the template parameter.
- *attribute:* `bool pack` – Indicates whether the reflected parameter is a parameter pack of a variadic template.

4.1.25. Instantiation

Instantiation is a either *Class*, *ClassMember* or *Function* that reflects an instantiation of a class or (member) function template.

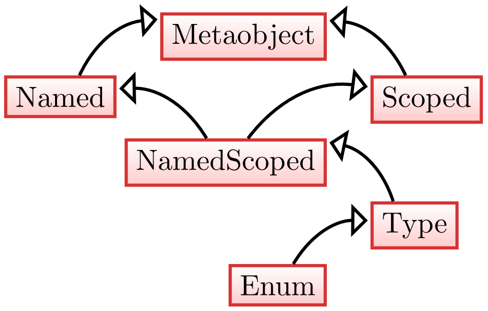


Concrete metaobjects modelling *Instantiation* must satisfy the following:

- The `has_template` trait inherited from *Metaobject* is true.
- *attribute: Template* `template` – A *Template* metaobject reflecting the template that the class or function, reflected by this *Instantiation*, is an instantiation of.

4.1.26. Enum

Enum is a *Type* reflecting an enumeration type. The members of an *Enum* are only *Constant* metaobjects.

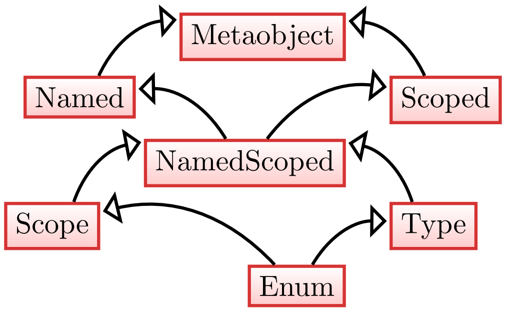


Concrete metaobjects modelling *Enum* must satisfy the following:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `enum`.
- *attribute: Type* `base_type` – A *Type* reflecting the underlying type of the enumeration type.

4.1.27. EnumClass

EnumClass is a *Type* and *Scope* which reflects a strongly typed enumeration. The members of an *EnumClass* are only *Constant* metaobjects.

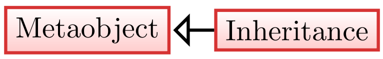


EnumClass has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `enum_class`.
- *attribute: Type* `base_type` – A *Type* reflecting the underlying type of the enumeration type.

4.1.28. Inheritance

Inheritance is a *Metaobject* which reflects a class inheritance.

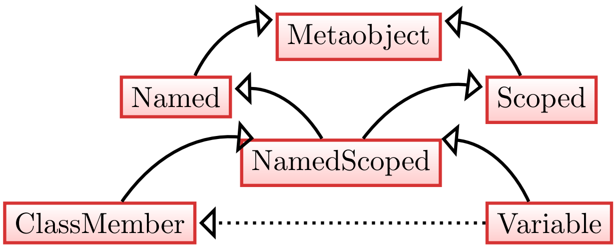


Inheritance has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `inheritance`.
- *attribute: Specifier* `access_type` – *Specifier* that reflects the inheritance access type specifier (`private`, `protected`, `public`).
- *attribute: Specifier* `inheritance_type` – *Specifier* that reflects the inheritance type specifier (`virtual`, non-virtual).
- *attribute: Class* `base_class` – A *Class* reflecting the base-class in the inheritance.
- *attribute: Class* `derived_class` – A *Class* reflecting the derived class in the inheritance.

4.1.29. Variable

Variable is a *NamedScoped* and possibly a *ClassMember* which reflects a variable defined in a namespace, class, function, etc.

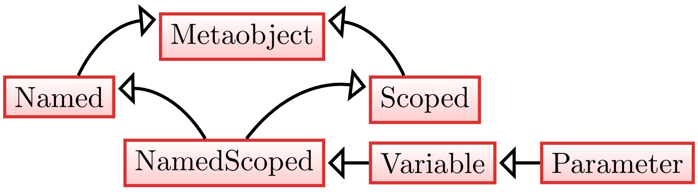


Variable has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `variable`.
- *attribute: Specifier* `storage_class` – *Specifier* that reflects the storage class specifier of the variable.
- *attribute: Type* `type` – A *Type* reflecting the type of the variable.

4.1.30. Parameter

Parameter is a *Variable* which reflects a function parameter or a parameter pack.

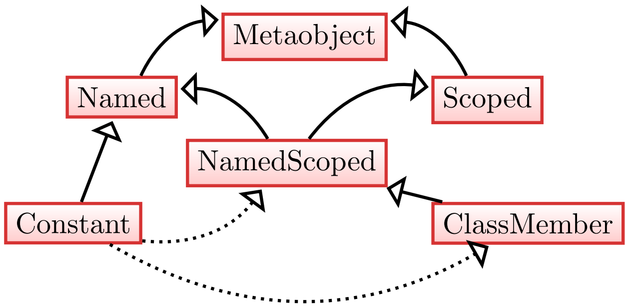


Parameter has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `parameter`.
- *attribute:* `size_t position` – The position of the parameter.
- *attribute:* `bool pack` – Indicates whether the reflected parameter is a parameter pack.
- *attribute: Function* `scope` – This attribute, inherited from *Scoped*, returns the function that the reflected parameter belongs to.

4.1.31. Constant

Constant is a *Named* and possibly a *NamedScoped* or *ClassMember* which reflects a named compile-time constant values, like non-type template parameters and enumeration values.



Constant has these requirements:

- The value of the *MetaobjectCategory* `category` attribute inherited from *Metaobject* is `constant`.
- *attribute:* `unspecified-constant-value value` – The value of the reflected constant.

4.2. Concept transformation

The concepts described above need to be transformed into concrete C++ code in order to be usable to the programmer and there are several possible sets of transformation rules, with various advantages and disadvanateges.

Please see the appendix A for concrete examples of several possible transformations.

Consider a *Concept* with the following requirements:

- *instance:* `some_instance` – Instance of a tag concept.
- *attribute:* `Constant constant_attrib`– Attribute specifying a compile-time constant value.
- *attribute:* `Type type_attrib` – Attribute specifying a base-level type.
- *attribute:* `Concept concept_attrib` – Attributes specifying a metaobject conforming to a concept.
- *trait:* `bool some_trait` – Boolean trait.
- *element:* `Element element(position)` – Unary random access getter for indexed attributes.
- *template:* `some_template(X)` – Class template which when instantiated results in a concrete type.
- *function:* `result_type some_function(...)` – N-ary function.

This logical concept could be transformed into usable C++ as:

- an anonymous structure with member typedefs, functions, constant values, etc.:

```
// definition
struct Concept
{
        static constexpr size_t constant_attrib = /*...*/;

        typedef /*...*/ type_attrib;

        static constexpr AnotherConcept concept_attrib(void);

        static constexpr bool some_trait = /*...*/;

        static Element element(integral_constant<size_t, /*...*/>);

        template <typename X>
        struct some_template { /*...*/ };

        static result_type some_function(/*...*/);
};

// usage
auto metaobject = /* use reflection to get an instance of Concept */
size_t x = metaobject.constant_attrib;
auto y = metaobject.concept_attrib();
// etc.
```

- an anonymous type (with its own identity so that it could be used in function overloads or template specializations) without any internal structure, where the related attributes, etc. would be accessed by free functions or by the means of templates, for example:

```
// by function
// declared as
constexpr size_t constant_attrib(Concept);
constexpr AnotherConcept concept_attrib(Concept);
//
// used as
auto metaobject = /* use reflection to get an instance of Concept */
size_t x = constant_attrib(metaobject);
AnotherConcept y = concept_attrib(metaobject);
result_type some_function(Concept, /*...*/);

// or by template
```

```
// defined as
template <typename Concept>
struct constant_attr
{
        static constexpr size_t value = /*...*/;
};
template <typename Concept>
struct concept_attrib
{
        typedef AnotherConcept type;
};
template <typename Concept, typename X>
struct some_template
{
        /*...*/
};
template <typename Concept>
result_type some_function(/*...*/);

// used as
typedef /* get metaobject */ metaobject;
size_t x = constant_attrib<metaobject>::value;
typedef concept_attrib<metaobject>::type y;
```

The advantage of the first approach is that it does not ”pollute” the `std` (nor any other namespace) with the *getter* functions or templates. Everything necessary to get the metadata from the metaobject is contained in the metaobject itself.

The advantage of the second approach is that the getters for a particular metaobject do not need to be defined all-in-one, which may simplify resolution of circular-dependencies.

4.2.1. Resolving conflicts with C++ keywords

In the concepts defined above, several requirements like instances, attributes, etc. have names which if transformed directly to C++ would conflict with C++ keywords.

There are several ways to resolve these conflicts:

- Changing the letter case or naming convention for example to `ALL_CAPS`, `CamelCase`, etc. – this approach is however inconsistent with the naming convention adopted by the standard library.
- Applying a prefix and/or postfix – the prefixes/suffixes can be meaningful or just underscores, for which there is a precedent in the standard - the placeholders.
- Changing the name to a synonym – this can however lead to confusion.

4.3. Suggested transformation

We suggest the following set of rules to transform the individual requirement kinds to C++ (see appendix A.1 for details).

Concrete metaobjects should be anonymous structures with the attributes, instances, elements, templates, etc. defined as members. If the name is in conflict with a C++ keyword it should be postfixed with an underscore, unless stated otherwise.

4.3.1. Instances of tag concepts

Tag concepts define a set of "instances" tagging other metaobjects. The instances are intended to be used for metaobject classification and tag dispatching of function overloads and template specializations – i.e. they must have their own identity.

Tags can be either types or compile-time constant values, for example the values of a strongly typed enumeration.

We suggest that the instances of the tag concepts are transformed into tag types and in order to avoid conflicts with keywords they should be prefixed with `meta_` (in case of *MetaobjectCategory*) and `spec_` (in case of *SpecifierCategory*) and suffixed with `_tag`.

For example the *namespace* instance of *MetaobjectCategory* should be transformed into:

```
namespace std {
struct meta_namespace_tag { };
} // namespace std
```

and the *static* instance of *SpecifierCategory* should be transformed into:

```
namespace std {
struct spec_static_tag { };
} // namespace std
```

4.3.2. Traits

Concept traits should be transformed to templates similar to `type_traits`. For example the *is_template* trait of *Metaobject* should be transformed:

```
struct _unspecified_instance_of_Metaobject { };

template <typename Metaobject>
struct is_template
 : integral_constant<bool, true-or-false>
{ };
```

4.3.3. Constant value attributes

Attributes specifying a constant value should be transformed to static constexpr data members. For example the *size* attribute of *String* should be transformed into:

```
struct _unspecified_instance_of_String
{
        static constexpr size_t size = /*...*/;
        /*...*/
};
```

4.3.4. Type attributes

Attributes specifying a (base-level not meta-level) type should be transformed to member typedefs. For example the *original_type* attribute of *Type* should be transformed to:

```
struct _unspecified_instance_of_Type
{
        typedef unspecified-type original_type;
        /*...*/
};
```

4.3.5. Concept attributes

Attributes specifying a (meta-level) type conforming to a Concept should be transformed to static constexpr member functions. For example the *scope* attribute of *Scoped* should be transformed to:

```
struct _unspecified_instance_of_Scoped
{
        static constexpr Scope scope(void);
        /*...*/
};
```

The *template* attribute of *Instantiation* that is in conflict with a reserved identifier should be transformed to:

```
struct _unspecified_instance_of_Instantiation
{
        static constexpr Template template_(void);
        /*...*/
};
```

There are cicrular dependencies in the metaobjects and using functions can help to avoid problems when defining the metaobjects.

4.3.6. Range elements

Indexed attributes specifying the i-th element in a *Range* should be transformed to a set of static constexpr functions overloaded for every element in the range. The `integral_constant` template is used at the parameter distinguishing the overloads. For example the *at* element of a *Range* should be transformed to:

```
struct _unspecified_instance_of_Range<Element>
{
        // overloaded for i in (0, 1, ..., N-1) where
        // N is the value of Range::size
        static constexpr Element at(integral_constant<size_t, i>);
        /*...*/
};
```

4.3.7. Templates

Class templates should be transformed to nested member templates. For example the *named_typedef* template in *NamedScoped* should be transformed to:

```
struct _unspecified_instance_of_NamedScoped
{
        template <typename X>
        struct named_typedef
        {
                /*...*/
        };
        /*...*/
};
```

4.3.8. Functions

Functions should be transformed to static member functions. For example the *call* function in *Function* should be transformed into:

```
struct _unspecified_instance_of_Function
{
        static result_type call(/*same as the reflected function*/);
        /*...*/
};
```

4.4. Reflection

The metaobjects can be provided either via a set of overloaded functions or template classes similar to `type_traits` defined in the `std` namespace or by a new operator. Both of these approaches have advantages and disadvantages and both also depend on how the logical concepts are transformed to the C++ types generated by the compiler.

Another important aspect is, whether the metaobjects are returned as types or as objects. This is closely tied to how the logical concepts are transformed to concrete C++ which determines how the metaobjects are used.

4.4.1. Reflection functions

In this approach at least two functions should be defined in the `std` namespace:

- *unspecified-type* `reflected_global_scope(void);` (or alternatively `mirrored_global_scope()`) This function should return a type conforming to the *GlobalScope* concept, reflecting the global scope. The real type of the result is not defined by the standard, i.e. it is an implementation detail. If the caller needs to store the result of this function the `auto` type specifier should always be used.

- `template <typename Type>`
  unspecified-type `reflected(void);` (or alternativelly `mirrored<Type>()`) This function should return a type conforming to the *Type* concept, reflecting the `Type` passed as template argument to this function. The real type of the result is not defined by the standard, i.e. it is an implementation detail. If the caller needs to store the result of this function the `auto` type specifier should always be used.

Several other similar functions could be added to the list above for reflection of templates, enumerated values, etc. without defining new rules for what regular function and template parameters can be. The advantages of using reflection functions are following:

- No need to add a new keyword to the language.

- Reduced chance of breaking existing code. The `reflected_global_scope()` and `reflected<Type>()` (nor `mirrored_global_scope()` and `mirrored<Type>()`) functions are currently not defined in the `std` namespace and therefore should not clash with existing user code.

This approach has the following disadvantages:

- Less direct reflection. Using this approach it is not possible (at least without adding new rules for possible values of template and function parameters) to reflect constructors, overloaded functions and some other things.

4.4.2. Reflection operator

In this approach a new operator (we suggest the name) `mirrored(`*param*`)` (or alternativelly `reflected(`*param*`)`for additional alternatives see below) should be added. Depending on *param* – which could be a type name, namespace name, template name, overloaded function name, enumerated value name, etc. – the operator should return a *Named* metaobject reflecting the specified feature. If the parameter is ommited a type conforming to the *GlobalScope* metaobject concept should be returned. The exact types returned by the operators should be implementation details. For example:

```
//
typedef integral_constant<size_t, 0> _0;
typedef integral_constant<size_t, 1> _1;
typedef integral_constant<size_t, 2> _2;
typedef integral_constant<size_t, 3> _3;
//
// reflect the global scope
// meta_gs conforms to the GlobalScope concept
mirrored() meta_gs;

static_assert(
        meta_gs.member_count() > 0,
        "The global scope has no members!"
);

static_assert(
        meta_gs.base_name().size() == 0,
        "Name of the global scope is not an empty string!"
);


//
// reflect the std namespace
// meta_std conforms to the Namespace concept
mirrored(std) meta_std;

static_assert(
        is_same<
                meta_gs,
                decltype(meta_std.scope())
        >::value,
        "Namespace std is not in the global scope!"
);
```

```
static_assert(
        meta_std.base_name().size() == 3,
        "Name of the std namespace does not have 3 characters!"
);

static_assert(
        meta_std.base_name().at(_0) == 's',
        "Name of the std namespace does not start with 's'!"
);

assert(strcmp(meta_std.base_name().c_str(), "std") == 0);


//
// reflect the errno variable
// meta_errno conforms to the Variable concept
mirrored(errno) meta_errno;

//
// reflect the int type
// meta_int conforms to the Type concept
mirrored(int) meta_int;

//
// reflect the std::string typedef
// meta_std_string conforms to the Typedef concept
mirrored(std::string) meta_std_string;

//
// reflect the std::map template
// meta_std_map conforms to the Template
// and Class concepts
mirrored(std::map) meta_std_map;

//
// reflect the std::map<int, std::string> type
// meta_std_map_int_std_string conforms to Class
// and Instantiation concepts
mirrored(std::map<int, std::string>)
        meta_std_map_int_std_string;

//
// reflect the std::string's (overloaded) constructors
// meta_std_string_string conforms to
```

```
// the OverloadedFunction concept and the individual
// overloads that it allows to traverse conform
// to the Constructor concept
mirrored(std::string::string) meta_std_string_string;

//
// reflect ths std::string's copy constructor
// meta_std_string_string_copy conforms to
// the Constructor concept
mirrored(std::string::string(const std::string&))
        meta_std_string_string_copy;


//
// reflect the std::swap overloaded free function
// meta_std_swap conforms to OverloadedFunction
mirrored(std::swap) meta_std_swap;

// reflect the (local) variable i
// meta_i conforms to Variable
int i = 42;
mirrored(i) meta_i;
```

Alternativelly the `mirrored` keyword could return a value (instead of a type) and would be used as in the following examples:

```
// overloaded constructors of std::string
auto meta_std_string_string = mirrored(std::string::string);
// the first constructor
auto meta_std_string_string_0 = meta_std_string_string.overloads().at(_0);
```

Using a new operator has the following advantages:

- More direct reflection. Even features that could not be reflected by using a (templated) function could be reflected with an operator.
- More consistent reflection. Everything is reflected with a single operator.

and these disadvantages:

- Requires a new keyword or the usage of an existing keyword in a new context or the usage of a character sequence that is currently invalid.
- Increased risk of breaking existing code. Could be resolved by using an existing operator like `%`, `|`, etc., or the use of a currently invalid character or character sequence like `@`, `$` or the usage of a new set of quotations like ` (backtick character). For example:

```
// instead of:
auto meta_std_string = mirrored(std::string);
// use
auto meta_std_string = %std::string;
// or
auto meta_std_string = |std::string;
// or
auto meta_std_string = @std::string;
// or
auto meta_std_string = `std::string`;
// or
auto meta_std_string = [[std::string]];
// or
auto meta_std_string = <<std::string>>;
```

The problem with these may be the reflection of the global scope, which when using some of the above would result in awkward expressions like:

```
// instead of
auto meta_gs = mirrored();
// use
auto meta_gs = %;
auto meta_gs = |;
auto meta_gs = |::;
auto meta_gs = @;
auto meta_gs = @::;
// or
auto meta_gs = ``;
auto meta_gs = `::`;
auto meta_gs = [[]];
auto meta_gs = [[::]];
auto meta_gs = <<>>;
auto meta_gs = <<::>>;
```

5. Impact On the Standard

The impact on the standard and the existing applications depends mainly on the method of reflection (functions vs. operators). Reflection functions pose a very small risk of breaking existing standard-conforming code. The `mirrored` operator on the other hand has a considerable potential of breaking existing applications. This can be alleviated by using existing keywords like `%` as suggested above.

Since compilers already have all the metadata required to generate the proposed metaobjects, making them available to programmers should not pose a big problem to the compiler vendors.

TODO: to be revised/completed

6. Implementation hints

6.1. Generation of metaobjects

The metaobjects should be generated / instantiated by the compiler only when explicitly requested. This also applies to members of the metaobjects. For example when a *Namespace* reflecting the `std` namespace is generated the individual `member(...)` functions (and the resulting metaobjects) should *not* be generated automatically unless the `Scope::member(...)` function is called or its type queried (by `decltype` or otherwise).

This should probably improve the compilation times and avoid reflection-related overhead when reflection is not used.

7. Unresolved Issues

- *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* `Named::base_name()` *and* `NamedScoped::full_name()`*:* The strings returned by the `base_name` and `full_name` functions 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.

8. Acknowledgements

9 References

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

[2] Mirror - Examples of usage, http://kifri.fri.uniza.sk/~chochlik/mirror-lib/html/doxygen/mirror/html/examples.html.

[3] Mirror - The Puddle layer - examples of usage, http://kifri.fri.uniza.sk/~chochlik/mirror-lib/html/doxygen/puddle/html/examples.html.

[4] Mirror - The Rubber layer - examples of usage, http://kifri.fri.uniza.sk/~chochlik/mirror-lib/html/doxygen/rubber/html/examples.html.

[5] Mirror - The Lagoon layer - examples of usage, http://kifri.fri.uniza.sk/~chochlik/mirror-lib/html/doxygen/lagoon/html/examples.html.

[6] Mirror - Compile-time strings http://kifri.fri.uniza.sk/~chochlik/mirror-lib/html/doxygen/mirror/html/d5/d1d/group__ct__string.html.

A. Transforming the concepts to C++

A.1. Concept models – variant 1 (preferred)

A.1.1. String

```
struct String
{
  static constexpr size_t size;

  static constexpr const char* c_str;
};
```

A.1.2. Range

```
template <typename Element>
struct Range
{
  static constexpr size_t size;

  static constexpr Element at(
```

```
    integral_constant<size_t, unspecified> position
  );
};
```

A.1.3. MetaobjectCategory

This concept has the following instances:

```
struct meta_namespace_tag { };
struct meta_global_scope_tag { };
struct meta_type_tag { };
struct meta_typedef_tag { };
struct meta_class_tag { };
struct meta_function_tag { };
struct meta_constructor_tag { };
struct meta_operator_tag { };
struct meta_overloaded_function_tag { };
struct meta_enum_tag { };
struct meta_enum_class_tag { };
struct meta_inheritance_tag { };
struct meta_constant_tag { };
struct meta_variable_tag { };
struct meta_parameter_tag { };
```

A.1.4. SpecifierCategory

This concept has the following instances:

```
struct spec_none_tag { };
struct spec_extern_tag { };
struct spec_static_tag { };
struct spec_mutable_tag { };
struct spec_register_tag { };
struct spec_thread_local_tag { };
struct spec_const_tag { };
struct spec_virtual_tag { };
struct spec_private_tag { };
struct spec_protected_tag { };
struct spec_public_tag { };
struct spec_class_tag { };
struct spec_struct_tag { };
struct spec_union_tag { };
struct spec_enum_tag { };
```

```
struct spec_enum_class_tag { };
struct spec_constexpr_tag { };
```

A.1.5. Metaobject

```
struct Metaobject
{
};

template <>
struct category<Metaobject>
{
  typedef MetaobjectCategory type;
};

template <>
struct is_metaobject<Metaobject>
 : integral_constant<bool, true>
{ };

template <>
struct has_name<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct has_scope<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct is_scope<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct is_class_member<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct has_template<Metaobject>
 : integral_constant<bool, false>
```

```
{ };

template <>
struct is_template<Metaobject>
 : integral_constant<bool, false>
{ };
```

A.1.6. Specifier

```
struct Specifier
{
  static constexpr String keyword(void);
};

template <>
struct category<Specifier>
{
  typedef SpecifierCategory type;
};
```

A.1.7. Named

```
struct Named
{
  static constexpr String base_name(void);
};

template <>
struct has_name<Named>
 : integral_constant<bool, true>
{ };
```

A.1.8. Scoped

```
struct Scoped
{
  static constexpr Scope scope(void);
};

template <>
struct has_scope<Scoped>
```

```
: integral_constant<bool, true>
{ };
```

A.1.9. NamedScoped

```
struct NamedScoped
{
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  static constexpr String full_name(void);

  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };
};
```

A.1.10. Scope

```
struct Scope
{
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
```

```
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  static constexpr Range<Scoped>
  members(void);
};

template <>
struct is_scope<Scope>
 : integral_constant<bool, true>
{ };
```

A.1.11. Namespace

```
struct Namespace
{
  typedef meta_namespace_tag category;
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };
```

```
  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Scope
  static constexpr Range<Scoped>
  members(void);

};
```

A.1.12. GlobalScope

```
struct GlobalScope
{
  typedef meta_global_scope_tag category;
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Scope
  static constexpr Range<Scoped>
```

```
  members(void);

};
```

A.1.13. Type

```
struct Type
{
  typedef meta_type_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  typedef original-type original_type;
};
```

A.1.14. Typedef

```
struct Typedef
{
  typedef meta_typedef_tag category;
```

```
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Type
  typedef original-type original_type;

  static constexpr Type typedef_type(void);
};
```

A.1.15. Class

```
struct Class
{
  typedef meta_class_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);
```

```
  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Type
  typedef original-type original_type;

  // inherited from Scope
  static constexpr Range<Scoped>
  members(void);

  static constexpr Specifier elaborated_type(void);

  static constexpr Range<Inheritance>
  base_classes(void);
};
```

A.1.16. Function

```
struct Function
{
  typedef meta_function_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);
```

```
  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Scope
  static constexpr Range<Scoped>
  members(void);

  static constexpr Specifier linkage(void);

  static constexpr bool constexpr_;

  static constexpr Type result_type(void);

  static constexpr Range<Parameter>
  parameters(void);

  static constexpr bool noexcept_;

  static constexpr Range<Type>
  exceptions(void);

  static constexpr Specifier constness(void);

  static constexpr bool pure;

  static unspecified call(...);};
```

A.1.17. ClassMember

```
struct ClassMember
{
  // inherited from Named
```

```
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  static constexpr Specifier access_type(void);
};

template <>
struct is_class_member<ClassMember>
 : integral_constant<bool, true>
{ };
```

A.1.18. Initializer

```
struct Initializer
{
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);
```

```
// inherited from NamedScoped
template <typename X>
struct named_typedef
{
  typedef unspecified type;
};

// inherited from NamedScoped
template <typename X>
struct named_mem_var
{
  typedef unspecified type;
};

// inherited from Scope
static constexpr Range<Scoped>
members(void);

// inherited from Function
static constexpr Specifier linkage(void);

// inherited from Function
static constexpr bool constexpr_;

// inherited from Function
static constexpr Type result_type(void);

// inherited from Function
static constexpr Range<Parameter>
parameters(void);

// inherited from Function
static constexpr bool noexcept_;

// inherited from Function
static constexpr Range<Type>
exceptions(void);

// inherited from Function
static constexpr Specifier constness(void);

// inherited from Function
static constexpr bool pure;
```

```
  // inherited from Function
  static unspecified call(...);
};
```

A.1.19. Constructor

```
struct Constructor
{
  typedef meta_constructor_tag category;
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from ClassMember
  static constexpr Specifier access_type(void);

  // inherited from Scope
  static constexpr Range<Scoped>
  members(void);

  // inherited from Function
  static constexpr Specifier linkage(void);

  // inherited from Function
```

```
  static constexpr bool constexpr_;

  // inherited from Function
  static constexpr Type result_type(void);

  // inherited from Function
  static constexpr Range<Parameter>
  parameters(void);

  // inherited from Function
  static constexpr bool noexcept_;

  // inherited from Function
  static constexpr Range<Type>
  exceptions(void);

  // inherited from Function
  static constexpr Specifier constness(void);

  // inherited from Function
  static constexpr bool pure;

  // inherited from Function
  static unspecified call(...);
};
```

A.1.20. Operator

```
struct Operator
{
  typedef meta_operator_tag category;
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
```

```
{
  typedef unspecified type;
};

// inherited from NamedScoped
template <typename X>
struct named_mem_var
{
  typedef unspecified type;
};

// inherited from Scope
static constexpr Range<Scoped>
members(void);

// inherited from Function
static constexpr Specifier linkage(void);

// inherited from Function
static constexpr bool constexpr_;

// inherited from Function
static constexpr Type result_type(void);

// inherited from Function
static constexpr Range<Parameter>
parameters(void);

// inherited from Function
static constexpr bool noexcept_;

// inherited from Function
static constexpr Range<Type>
exceptions(void);

// inherited from Function
static constexpr Specifier constness(void);

// inherited from Function
static constexpr bool pure;

// inherited from Function
static unspecified call(...);
// possibly inherited from ClassMember
```

```
  static constexpr Specifier access_type(void);

};
```

A.1.21. OverloadedFunction

```
struct OverloadedFunction
{
  typedef meta_overloaded_function_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);

  static constexpr Range<Function>
  overloads(void);
};
```

A.1.22. Template

```
struct Template
{
  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from Type
  typedef original-type original_type;

  // possibly inherited from Scope
  static constexpr Range<Scoped>
  members(void);

  // possibly inherited from Class
  static constexpr Specifier elaborated_type(void);

  // possibly inherited from Class
  static constexpr Range<Inheritance>
  base_classes(void);

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);
```

```
  // possibly inherited from Function
  static constexpr Specifier linkage(void);

  // possibly inherited from Function
  static constexpr bool constexpr_;

  // possibly inherited from Function
  static constexpr Type result_type(void);

  // possibly inherited from Function
  static constexpr Range<Parameter>
  parameters(void);

  // possibly inherited from Function
  static constexpr bool noexcept_;

  // possibly inherited from Function
  static constexpr Range<Type>
  exceptions(void);

  // possibly inherited from Function
  static constexpr Specifier constness(void);

  // possibly inherited from Function
  static constexpr bool pure;

  // possibly inherited from Function
  static unspecified call(...);
  static constexpr Range<TemplateParameter>
  template_parameters(void);

  template <...>
  struct instantiation
  {
    typedef Instantiation type;
  };
};

template <>
struct is_template<Template>
 : integral_constant<bool, true>
{ };
```

A.1.23. TemplateParameter

```
struct TemplateParameter
{
  // possibly inherited from Named
  static constexpr String base_name(void);

  // possibly inherited from Scoped
  static constexpr Scope scope(void);

  // possibly inherited from NamedScoped
  static constexpr String full_name(void);

  // possibly inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // possibly inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from Type
  typedef original-type original_type;

  // possibly inherited from Typedef
  static constexpr Type typedef_type(void);

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);

  // possibly inherited from Constant
  static constexpr unspecified-constant-value value;

  static constexpr size_t position;

  static constexpr bool pack;
};
```

```
template <>
struct is_template<TemplateParameter>
 : integral_constant<bool, true>
{ };
```

A.1.24. Instantiation

```
struct Instantiation
{
  // possibly inherited from Named
  static constexpr String base_name(void);

  // possibly inherited from Scoped
  static constexpr Scope scope(void);

  // possibly inherited from NamedScoped
  static constexpr String full_name(void);

  // possibly inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // possibly inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from Type
  typedef original-type original_type;

  // possibly inherited from Scope
  static constexpr Range<Scoped>
  members(void);

  // possibly inherited from Class
  static constexpr Specifier elaborated_type(void);
```

```
  // possibly inherited from Class
  static constexpr Range<Inheritance>
  base_classes(void);

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);

  // possibly inherited from Function
  static constexpr Specifier linkage(void);

  // possibly inherited from Function
  static constexpr bool constexpr_;

  // possibly inherited from Function
  static constexpr Type result_type(void);

  // possibly inherited from Function
  static constexpr Range<Parameter>
  parameters(void);

  // possibly inherited from Function
  static constexpr bool noexcept_;

  // possibly inherited from Function
  static constexpr Range<Type>
  exceptions(void);

  // possibly inherited from Function
  static constexpr Specifier constness(void);

  // possibly inherited from Function
  static constexpr bool pure;

  // possibly inherited from Function
  static unspecified call(...);
  static constexpr Template template_(void);
};

template <>
struct has_template<Instantiation>
 : integral_constant<bool, true>
{ };
```

A.1.25. Enum

```
struct Enum
{
  typedef meta_enum_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Type
  typedef original-type original_type;

  static constexpr Type base_type(void);
};
```

A.1.26. EnumClass

```
struct EnumClass
{
  typedef meta_enum_class_tag category;

  // inherited from Named
  static constexpr String base_name(void);
```

```
  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // inherited from Type
  typedef original-type original_type;

  // inherited from Scope
  static constexpr Range<Scoped>
  members(void);

  static constexpr Type base_type(void);
};
```

A.1.27. Inheritance

```
struct Inheritance
{
  typedef meta_inheritance_tag category;

  static constexpr Specifier access_type(void);

  static constexpr Specifier inheritance_type(void);

  static constexpr Class base_class(void);
```

```
  static constexpr Class derived_class(void);
};
```

A.1.28. Variable

```
struct Variable
{
  typedef meta_variable_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from Scoped
  static constexpr Scope scope(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);

  static constexpr Specifier storage_class(void);

  static constexpr Type type(void);
};
```

A.1.29. Parameter

```
struct Parameter
{
  typedef meta_parameter_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // inherited from NamedScoped
  static constexpr String full_name(void);

  // inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);

  // inherited from Variable
  static constexpr Specifier storage_class(void);

  // inherited from Variable
  static constexpr Type type(void);

  static constexpr size_t position;

  static constexpr bool pack;

  static constexpr Function scope(void);
};
```

A.1.30. Constant

```
struct Constant
{
  typedef meta_constant_tag category;

  // inherited from Named
  static constexpr String base_name(void);

  // possibly inherited from Scoped
  static constexpr Scope scope(void);

  // possibly inherited from NamedScoped
  static constexpr String full_name(void);

  // possibly inherited from NamedScoped
  template <typename X>
  struct named_typedef
  {
    typedef unspecified type;
  };

  // possibly inherited from NamedScoped
  template <typename X>
  struct named_mem_var
  {
    typedef unspecified type;
  };

  // possibly inherited from ClassMember
  static constexpr Specifier access_type(void);

  static constexpr unspecified-constant-value value;
};
```

A.2. Concept models – variant 2 (alternative)

A.2.1. String

```
struct String { };

template <>
struct size<String>
```

```
 : integral_constant<size_t, unspecified>
{ };

template <>
struct c_str<String>
{
  static constexpr const char* value;
};
```

A.2.2. Range

```
template <typename Element>
struct Range { };

template <typename Element>
struct size<Range<Element>>
 : integral_constant<size_t, unspecified>
{ };

template <typename Element, size_t Index>
struct at<Range<Element>, integral_constant<size_t, Index>>
{
  typedef Element type;
};
```

A.2.3. MetaobjectCategory

This concept has the following instances:

```
struct meta_namespace_tag { };
struct meta_global_scope_tag { };
struct meta_type_tag { };
struct meta_typedef_tag { };
struct meta_class_tag { };
struct meta_function_tag { };
struct meta_constructor_tag { };
struct meta_operator_tag { };
struct meta_overloaded_function_tag { };
struct meta_enum_tag { };
struct meta_enum_class_tag { };
struct meta_inheritance_tag { };
struct meta_constant_tag { };
```

```
struct meta_variable_tag { };
struct meta_parameter_tag { };
```

A.2.4. SpecifierCategory

This concept has the following instances:

```
struct spec_none_tag { };
struct spec_extern_tag { };
struct spec_static_tag { };
struct spec_mutable_tag { };
struct spec_register_tag { };
struct spec_thread_local_tag { };
struct spec_const_tag { };
struct spec_virtual_tag { };
struct spec_private_tag { };
struct spec_protected_tag { };
struct spec_public_tag { };
struct spec_class_tag { };
struct spec_struct_tag { };
struct spec_union_tag { };
struct spec_enum_tag { };
struct spec_enum_class_tag { };
struct spec_constexpr_tag { };
```

A.2.5. Metaobject

```
struct Metaobject { };


template <>
struct category<Metaobject>
{
  typedef MetaobjectCategory type;
};

template <>
struct is_metaobject<Metaobject>
 : integral_constant<bool, true>
{ };

template <>
struct has_name<Metaobject>
```

```
 : integral_constant<bool, false>
{ };

template <>
struct has_scope<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct is_scope<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct is_class_member<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct has_template<Metaobject>
 : integral_constant<bool, false>
{ };

template <>
struct is_template<Metaobject>
 : integral_constant<bool, false>
{ };
```

A.2.6. Specifier

```
struct Specifier { };

template <>
struct keyword<Specifier>
{
  typedef String type;
};

template <>
struct category<Specifier>
{
  typedef SpecifierCategory type;
};
```

A.2.7. Named

```
struct Named { };

template <>
struct base_name<Named>
{
  typedef String type;
};

template <>
struct has_name<Named>
 : integral_constant<bool, true>
{ };
```

A.2.8. Scoped

```
struct Scoped { };

template <>
struct scope<Scoped>
{
  typedef Scope type;
};

template <>
struct has_scope<Scoped>
 : integral_constant<bool, true>
{ };
```

A.2.9. NamedScoped

```
struct NamedScoped { };

  // inherited from Named
template <>
struct base_name<NamedScoped>
{
  typedef String type;
};

  // inherited from Scoped
```

```
template <>
struct scope<NamedScoped>
{
  typedef Scope type;
};

template <>
struct full_name<NamedScoped>
{
  typedef String type;
};

template <typename X>
struct named_typedef<NamedScoped, X>
{
  typedef unspecified type;
};

template <typename X>
struct named_mem_var<NamedScoped, X>
{
  typedef unspecified type;
};
```

A.2.10. Scope

```
struct Scope { };

  // inherited from Named
template <>
struct base_name<Scope>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Scope>
{
  typedef Scope type;
};

  // inherited from NamedScoped
```

```
template <>
struct full_name<Scope>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Scope, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Scope, X>
{
  typedef unspecified type;
};

template <>
struct members<Scope>
{
  typedef Range<Scoped> type;
};

template <>
struct is_scope<Scope>
 : integral_constant<bool, true>
{ };
```

A.2.11. Namespace

```
struct Namespace { };

template typename <>
struct category<Namespace>
{
  typedef meta_namespace_tag type;
};
  // inherited from Named
template <>
struct base_name<Namespace>
```

```
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Namespace>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Namespace>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Namespace, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Namespace, X>
{
  typedef unspecified type;
};

  // inherited from Scope
template <>
struct members<Namespace>
{
  typedef Range<Scoped> type;
};
```

A.2.12. GlobalScope

```
struct GlobalScope { };
```

```
template typename <>
struct category<GlobalScope>
{
  typedef meta_global_scope_tag type;
};
  // inherited from Named
template <>
struct base_name<GlobalScope>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<GlobalScope>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<GlobalScope>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<GlobalScope, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<GlobalScope, X>
{
  typedef unspecified type;
};

  // inherited from Scope
template <>
struct members<GlobalScope>
{
```

```
  typedef Range<Scoped> type;
};
```

A.2.13. Type

```
struct Type { };

template typename <>
struct category<Type>
{
  typedef meta_type_tag type;
};

  // inherited from Named
template <>
struct base_name<Type>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Type>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Type>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Type, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
```

```
struct named_mem_var<Type, X>
{
  typedef unspecified type;
};

template <>
struct original_type<Type>
{
  typedef original-type type;
};
```

A.2.14. Typedef

```
struct Typedef { };

template typename <>
struct category<Typedef>
{
  typedef meta_typedef_tag type;
};

  // inherited from Named
template <>
struct base_name<Typedef>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Typedef>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Typedef>
{
  typedef String type;
};

  // inherited from NamedScoped
```

```
template <typename X>
struct named_typedef<Typedef, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Typedef, X>
{
  typedef unspecified type;
};

  // inherited from Type
template <>
struct original_type<Typedef>
{
  typedef original-type type;
};

template <>
struct typedef_type<Typedef>
{
  typedef Type type;
};
```

A.2.15. Class

```
struct Class { };

template typename <>
struct category<Class>
{
  typedef meta_class_tag type;
};

  // inherited from Named
template <>
struct base_name<Class>
{
  typedef String type;
};
```

```
  // inherited from Scoped
template <>
struct scope<Class>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Class>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Class, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Class, X>
{
  typedef unspecified type;
};

  // inherited from Type
template <>
struct original_type<Class>
{
  typedef original-type type;
};

  // inherited from Scope
template <>
struct members<Class>
{
  typedef Range<Scoped> type;
};

template <>
struct elaborated_type<Class>
```

```
{
  typedef Specifier type;
};

template <>
struct base_classes<Class>
{
  typedef Range<Inheritance> type;
};
```

A.2.16. Function

```
struct Function { };

template typename <>
struct category<Function>
{
  typedef meta_function_tag type;
};

  // inherited from Named
template <>
struct base_name<Function>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Function>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Function>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
```

```
struct named_typedef<Function, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Function, X>
{
  typedef unspecified type;
};

  // inherited from Scope
template <>
struct members<Function>
{
  typedef Range<Scoped> type;
};

template <>
struct linkage<Function>
{
  typedef Specifier type;
};

template <>
struct constexpr_<Function>
 : integral_constant<bool, >
{ };

template <>
struct result_type<Function>
{
  typedef Type type;
};

template <>
struct parameters<Function>
{
  typedef Range<Parameter> type;
};

template <>
struct noexcept_<Function>
```

```
 : integral_constant<bool, >
{ };

template <>
struct exceptions<Function>
{
  typedef Range<Type> type;
};

template <>
struct constness<Function>
{
  typedef Specifier type;
};

template <>
struct pure<Function>
 : integral_constant<bool, >
{ };

template <>
struct call<Function>
{
  static unspecified apply(...);
};
```

A.2.17. ClassMember

```
struct ClassMember { };

  // inherited from Named
template <>
struct base_name<ClassMember>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<ClassMember>
{
  typedef Scope type;
};
```

```
  // inherited from NamedScoped
template <>
struct full_name<ClassMember>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<ClassMember, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<ClassMember, X>
{
  typedef unspecified type;
};

template <>
struct access_type<ClassMember>
{
  typedef Specifier type;
};

template <>
struct is_class_member<ClassMember>
 : integral_constant<bool, true>
{ };
```

A.2.18. Initializer

```
struct Initializer { };

  // inherited from Named
template <>
struct base_name<Initializer>
{
  typedef String type;
};
```

```
  // inherited from Scoped
template <>
struct scope<Initializer>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Initializer>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Initializer, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Initializer, X>
{
  typedef unspecified type;
};

  // inherited from Scope
template <>
struct members<Initializer>
{
  typedef Range<Scoped> type;
};

  // inherited from Function
template <>
struct linkage<Initializer>
{
  typedef Specifier type;
};

  // inherited from Function
```

```
template <>
struct constexpr_<Initializer>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct result_type<Initializer>
{
  typedef Type type;
};

  // inherited from Function
template <>
struct parameters<Initializer>
{
  typedef Range<Parameter> type;
};

  // inherited from Function
template <>
struct noexcept_<Initializer>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct exceptions<Initializer>
{
  typedef Range<Type> type;
};

  // inherited from Function
template <>
struct constness<Initializer>
{
  typedef Specifier type;
};

  // inherited from Function
template <>
struct pure<Initializer>
 : integral_constant<bool, >
{ };
```

```
  // inherited from Function
template <>
struct call<Initializer>
{
  static unspecified apply(...);
};
```

A.2.19. Constructor

```
struct Constructor { };

template typename <>
struct category<Constructor>
{
  typedef meta_constructor_tag type;
};
  // inherited from Named
template <>
struct base_name<Constructor>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Constructor>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Constructor>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Constructor, X>
{
  typedef unspecified type;
```

```
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Constructor, X>
{
  typedef unspecified type;
};

  // inherited from ClassMember
template <>
struct access_type<Constructor>
{
  typedef Specifier type;
};

  // inherited from Scope
template <>
struct members<Constructor>
{
  typedef Range<Scoped> type;
};

  // inherited from Function
template <>
struct linkage<Constructor>
{
  typedef Specifier type;
};

  // inherited from Function
template <>
struct constexpr_<Constructor>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct result_type<Constructor>
{
  typedef Type type;
};

  // inherited from Function
```

```
template <>
struct parameters<Constructor>
{
  typedef Range<Parameter> type;
};

  // inherited from Function
template <>
struct noexcept_<Constructor>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct exceptions<Constructor>
{
  typedef Range<Type> type;
};

  // inherited from Function
template <>
struct constness<Constructor>
{
  typedef Specifier type;
};

  // inherited from Function
template <>
struct pure<Constructor>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct call<Constructor>
{
  static unspecified apply(...);
};
```

A.2.20. Operator

```
struct Operator { };
```

```
template typename <>
struct category<Operator>
{
  typedef meta_operator_tag type;
};
  // inherited from Named
template <>
struct base_name<Operator>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Operator>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Operator>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Operator, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Operator, X>
{
  typedef unspecified type;
};

  // inherited from Scope
template <>
struct members<Operator>
{
```

```
  typedef Range<Scoped> type;
};

  // inherited from Function
template <>
struct linkage<Operator>
{
  typedef Specifier type;
};

  // inherited from Function
template <>
struct constexpr_<Operator>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct result_type<Operator>
{
  typedef Type type;
};

  // inherited from Function
template <>
struct parameters<Operator>
{
  typedef Range<Parameter> type;
};

  // inherited from Function
template <>
struct noexcept_<Operator>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct exceptions<Operator>
{
  typedef Range<Type> type;
};

  // inherited from Function
```

```
template <>
struct constness<Operator>
{
  typedef Specifier type;
};

  // inherited from Function
template <>
struct pure<Operator>
 : integral_constant<bool, >
{ };

  // inherited from Function
template <>
struct call<Operator>
{
  static unspecified apply(...);
};

  // possibly inherited from ClassMember
template <>
struct access_type<Operator>
{
  typedef Specifier type;
};
```

A.2.21. OverloadedFunction

```
struct OverloadedFunction { };

template typename <>
struct category<OverloadedFunction>
{
  typedef meta_overloaded_function_tag type;
};

  // inherited from Named
template <>
struct base_name<OverloadedFunction>
{
  typedef String type;
};
```

```
  // inherited from Scoped
template <>
struct scope<OverloadedFunction>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<OverloadedFunction>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<OverloadedFunction, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<OverloadedFunction, X>
{
  typedef unspecified type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<OverloadedFunction>
{
  typedef Specifier type;
};

template <>
struct overloads<OverloadedFunction>
{
  typedef Range<Function> type;
};
```

A.2.22. Template

```
struct Template { };

  // inherited from Named
template <>
struct base_name<Template>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Template>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Template>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Template, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Template, X>
{
  typedef unspecified type;
};

  // possibly inherited from Type
template <>
struct original_type<Template>
{
```

```
  typedef original-type type;
};

  // possibly inherited from Scope
template <>
struct members<Template>
{
  typedef Range<Scoped> type;
};

  // possibly inherited from Class
template <>
struct elaborated_type<Template>
{
  typedef Specifier type;
};

  // possibly inherited from Class
template <>
struct base_classes<Template>
{
  typedef Range<Inheritance> type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<Template>
{
  typedef Specifier type;
};

  // possibly inherited from Function
template <>
struct linkage<Template>
{
  typedef Specifier type;
};

  // possibly inherited from Function
template <>
struct constexpr_<Template>
 : integral_constant<bool, >
{ };
```

```
  // possibly inherited from Function
template <>
struct result_type<Template>
{
  typedef Type type;
};

  // possibly inherited from Function
template <>
struct parameters<Template>
{
  typedef Range<Parameter> type;
};

  // possibly inherited from Function
template <>
struct noexcept_<Template>
 : integral_constant<bool, >
{ };

  // possibly inherited from Function
template <>
struct exceptions<Template>
{
  typedef Range<Type> type;
};

  // possibly inherited from Function
template <>
struct constness<Template>
{
  typedef Specifier type;
};

  // possibly inherited from Function
template <>
struct pure<Template>
 : integral_constant<bool, >
{ };

  // possibly inherited from Function
template <>
struct call<Template>
{
```

```
  static unspecified apply(...);
};

template <>
struct template_parameters<Template>
{
  typedef Range<TemplateParameter> type;
};

template <...>
struct instantiation<Template, ...>
{
  typedef Instantiation type;
};

template <>
struct is_template<Template>
 : integral_constant<bool, true>
{ };
```

A.2.23. TemplateParameter

```
struct TemplateParameter { };

  // possibly inherited from Named
template <>
struct base_name<TemplateParameter>
{
  typedef String type;
};

  // possibly inherited from Scoped
template <>
struct scope<TemplateParameter>
{
  typedef Scope type;
};

  // possibly inherited from NamedScoped
template <>
struct full_name<TemplateParameter>
{
  typedef String type;
```

```
};

  // possibly inherited from NamedScoped
template <typename X>
struct named_typedef<TemplateParameter, X>
{
  typedef unspecified type;
};

  // possibly inherited from NamedScoped
template <typename X>
struct named_mem_var<TemplateParameter, X>
{
  typedef unspecified type;
};

  // possibly inherited from Type
template <>
struct original_type<TemplateParameter>
{
  typedef original-type type;
};

  // possibly inherited from Typedef
template <>
struct typedef_type<TemplateParameter>
{
  typedef Type type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<TemplateParameter>
{
  typedef Specifier type;
};

  // possibly inherited from Constant
template <>
struct value<TemplateParameter>
{
  static constexpr unspecified-constant-value value;
};
```

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

template <>
struct pack<TemplateParameter>
 : integral_constant<bool, >
{ };

template <>
struct is_template<TemplateParameter>
 : integral_constant<bool, true>
{ };
```

A.2.24. Instantiation

```
struct Instantiation { };

  // possibly inherited from Named
template <>
struct base_name<Instantiation>
{
  typedef String type;
};

  // possibly inherited from Scoped
template <>
struct scope<Instantiation>
{
  typedef Scope type;
};

  // possibly inherited from NamedScoped
template <>
struct full_name<Instantiation>
{
  typedef String type;
};

  // possibly inherited from NamedScoped
template <typename X>
struct named_typedef<Instantiation, X>
```

```
{
  typedef unspecified type;
};

  // possibly inherited from NamedScoped
template <typename X>
struct named_mem_var<Instantiation, X>
{
  typedef unspecified type;
};

  // possibly inherited from Type
template <>
struct original_type<Instantiation>
{
  typedef original-type type;
};

  // possibly inherited from Scope
template <>
struct members<Instantiation>
{
  typedef Range<Scoped> type;
};

  // possibly inherited from Class
template <>
struct elaborated_type<Instantiation>
{
  typedef Specifier type;
};

  // possibly inherited from Class
template <>
struct base_classes<Instantiation>
{
  typedef Range<Inheritance> type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<Instantiation>
{
  typedef Specifier type;
```

```
};

  // possibly inherited from Function
template <>
struct linkage<Instantiation>
{
  typedef Specifier type;
};

  // possibly inherited from Function
template <>
struct constexpr_<Instantiation>
 : integral_constant<bool, >
{ };

  // possibly inherited from Function
template <>
struct result_type<Instantiation>
{
  typedef Type type;
};

  // possibly inherited from Function
template <>
struct parameters<Instantiation>
{
  typedef Range<Parameter> type;
};

  // possibly inherited from Function
template <>
struct noexcept_<Instantiation>
 : integral_constant<bool, >
{ };

  // possibly inherited from Function
template <>
struct exceptions<Instantiation>
{
  typedef Range<Type> type;
};

  // possibly inherited from Function
template <>
```

```
struct constness<Instantiation>
{
  typedef Specifier type;
};

  // possibly inherited from Function
template <>
struct pure<Instantiation>
 : integral_constant<bool, >
{ };

  // possibly inherited from Function
template <>
struct call<Instantiation>
{
  static unspecified apply(...);
};

template <>
struct template_<Instantiation>
{
  typedef Template type;
};

template <>
struct has_template<Instantiation>
 : integral_constant<bool, true>
{ };
```

A.2.25. Enum

```
struct Enum { };

template typename <>
struct category<Enum>
{
  typedef meta_enum_tag type;
};

  // inherited from Named
template <>
struct base_name<Enum>
{
```

```
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Enum>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Enum>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Enum, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Enum, X>
{
  typedef unspecified type;
};

  // inherited from Type
template <>
struct original_type<Enum>
{
  typedef original-type type;
};

template <>
struct base_type<Enum>
{
  typedef Type type;
};
```

A.2.26. EnumClass

```
struct EnumClass { };

template typename <>
struct category<EnumClass>
{
  typedef meta_enum_class_tag type;
};

  // inherited from Named
template <>
struct base_name<EnumClass>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<EnumClass>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<EnumClass>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<EnumClass, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<EnumClass, X>
{
  typedef unspecified type;
```

```
};

  // inherited from Type
template <>
struct original_type<EnumClass>
{
  typedef original-type type;
};

  // inherited from Scope
template <>
struct members<EnumClass>
{
  typedef Range<Scoped> type;
};

template <>
struct base_type<EnumClass>
{
  typedef Type type;
};
```

A.2.27. Inheritance

```
struct Inheritance { };

template typename <>
struct category<Inheritance>
{
  typedef meta_inheritance_tag type;
};

template <>
struct access_type<Inheritance>
{
  typedef Specifier type;
};

template <>
struct inheritance_type<Inheritance>
{
  typedef Specifier type;
};
```

```
template <>
struct base_class<Inheritance>
{
  typedef Class type;
};

template <>
struct derived_class<Inheritance>
{
  typedef Class type;
};
```

A.2.28. Variable

```
struct Variable { };

template typename <>
struct category<Variable>
{
  typedef meta_variable_tag type;
};

  // inherited from Named
template <>
struct base_name<Variable>
{
  typedef String type;
};

  // inherited from Scoped
template <>
struct scope<Variable>
{
  typedef Scope type;
};

  // inherited from NamedScoped
template <>
struct full_name<Variable>
{
  typedef String type;
};
```

```
  // inherited from NamedScoped
template <typename X>
struct named_typedef<Variable, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Variable, X>
{
  typedef unspecified type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<Variable>
{
  typedef Specifier type;
};

template <>
struct storage_class<Variable>
{
  typedef Specifier type;
};

template <>
struct type<Variable>
{
  typedef Type type;
};
```

A.2.29. Parameter

```
struct Parameter { };

template typename <>
struct category<Parameter>
{
  typedef meta_parameter_tag type;
};
```

```
  // inherited from Named
template <>
struct base_name<Parameter>
{
  typedef String type;
};

  // inherited from NamedScoped
template <>
struct full_name<Parameter>
{
  typedef String type;
};

  // inherited from NamedScoped
template <typename X>
struct named_typedef<Parameter, X>
{
  typedef unspecified type;
};

  // inherited from NamedScoped
template <typename X>
struct named_mem_var<Parameter, X>
{
  typedef unspecified type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<Parameter>
{
  typedef Specifier type;
};

  // inherited from Variable
template <>
struct storage_class<Parameter>
{
  typedef Specifier type;
};

  // inherited from Variable
```

```
template <>
struct type<Parameter>
{
  typedef Type type;
};

template <>
struct position<Parameter>
 : integral_constant<size_t, >
{ };

template <>
struct pack<Parameter>
{
  static constexpr bool value;
};

template <>
struct scope<Parameter>
{
  typedef Function type;
};
```

A.2.30. Constant

```
struct Constant { };

template typename <>
struct category<Constant>
{
  typedef meta_constant_tag type;
};

  // inherited from Named
template <>
struct base_name<Constant>
{
  typedef String type;
};

  // possibly inherited from Scoped
template <>
struct scope<Constant>
```

```
{
  typedef Scope type;
};

  // possibly inherited from NamedScoped
template <>
struct full_name<Constant>
{
  typedef String type;
};

  // possibly inherited from NamedScoped
template <typename X>
struct named_typedef<Constant, X>
{
  typedef unspecified type;
};

  // possibly inherited from NamedScoped
template <typename X>
struct named_mem_var<Constant, X>
{
  typedef unspecified type;
};

  // possibly inherited from ClassMember
template <>
struct access_type<Constant>
{
  typedef Specifier type;
};

template <>
struct value<Constant>
{
  static constexpr unspecified-constant-value value;
};
```

B. Mirror examples

The first example prints some information about the members of selected namespaces to `std::cout`.

```
struct info_printer
{
    template <typename MetaObject>
    void operator()(MetaObject mo) const
    {
        MIRRORED_META_OBJECT(MetaObject) mmo;
        std::cout
            << mmo.construct_name()
            << ": "
            << mo.full_name()
            << std::endl;
    }
};

int main(void)
{
    using namespace mirror;

    // print the info about each of the members
    // of the global scope
    mirror::mp::for_each<
        members<

            // this should be in standard C++
            // be replaced by a specialstandard library
            // function or operator
            MIRRORED_GLOBAL_SCOPE()
        >
    >(info_printer());

    // print the info about each of the members
    // of the std namespace
    mp::for_each<
        members<

            // this should be in standard C++
            // be replaced by a special standard
            // library function or operator
            MIRRORED_NAMESPACE(std)
        >
    >(info_printer());
    //
    return 0;
}
```

This program produces the following output:

```
namespace: std
namespace: boost
type: void
type: bool
type: char
type: unsigned char
type: wchar_t
type: short int
type: int
type: long int
type: unsigned short int
type: unsigned int
type: unsigned long int
type: float
type: double
type: long double
class: std::string
class: std::wstring
class: std::tm
template: std::pair
template: std::tuple
template: std::allocator
template: std::equal_to
template: std::not_equal_to
template: std::less
template: std::greater
template: std::less_equal
template: std::greater_equal
template: std::vector
template: std::list
template: std::deque
template: std::map
template: std::set
```

The next example gets all types in the global scope, applies some `type_traits` modifiers like `std::add_pointer` `std::add_const` and for each of such modified types calls a functor that prints the names of the individual types to the standard output:

```
struct name_printer
{
    template <typename MetaNamedObject>
    void operator()(MetaNamedObject mo) const
    {
```

```
        std::cout << mo.base_name() << std::endl;
    }
};

int main(void)
{
  using namespace mirror;

  // this function calls the name_printer functor passed
  // as the function argument on each element in the
  // range that is passed as the template argument
  mp::for_each<

    // this template transforms the elements in the range
    // passed as the first argument by the unary template
    // passed as the second argument
    mp::transform<

      // this template filters out only those metaobjects
      // that satisfy the predicate passed as the second
      // argument from the range of metaobjects passed
      // as the first argument
      mp::only_if<

        // this template "returns" a range of metaobjects
        // reflecting the members of the namespace
        // (or other scope) that is passed as argument
        members<

          // this macro expands into a class
          // conforming to the Mirror's MetaNamespace
          // concept and provides metadata describing
          // the global scope namespace.
          // in the proposed solution for standard C++
          // this should be relaced by a special stdlib
          // function or by an operator.
          MIRRORED_GLOBAL_SCOPE()
        >,

        // this is a lambda function testing if its first
        // argument falls to the MetaType category
        mp::is_a<
          mp::arg<1>,
          meta_type_tag
```

```
        >
      >,

      // this is a unary lambda function that modifies
      // the type passed as its argument by
      // the add_pointer and add_const type traits
      apply_modifier<
        mp::arg<1>,
        mp::protect<
          std::add_pointer<
            std::add_const<
              mp::arg<1>
            >
          >
        >
      >
    >
  >(name_printer());
  std::cout << std::endl;
  return 0;
}
```

This short program produces the following output:

```
void const *
bool const *
char const *
unsigned char const *
wchar_t const *
short int const *
int const *
long int const *
unsigned short int const *
unsigned int const *
unsigned long int const *
float const *
double const *
long double const *
```

For other examples of usage see [2].

C. Puddle examples

In this example a reflection-based algorithm traverses the global scope namespace and its nested scopes and prints information about their members:

```
struct object_printer
{
  std::ostream& out;
  int indent_level;

  std::ostream& indented_output(void)
  {
    for(int i=0;i!=indent_level;++i)
      out << "  ";
    return out;
  }

  template <class MetaObject>
  void print_details(MetaObject obj, mirror::meta_object_tag)
  {
  }

  template <class MetaObject>
  void print_details(MetaObject obj, mirror::meta_scope_tag)
  {
    out << ": ";
    if(obj.members().empty())
    {
      out << "{ }";
    }
    else
    {
      out << "{" << std::endl;
      object_printer print_members = {out, indent_level+1};
      obj.members().for_each(print_members);
      indented_output() << "}";
    }
  }

  template <class MetaObject>
  void print(MetaObject obj, bool last)
  {
    indented_output()
      << obj.self().construct_name()
```

```
      << " "
      << obj.base_name();
    print_details(obj, obj.category());
    if(!last) out << ",";
    out << std::endl;
  }
  template <class MetaObject>
  void operator()(MetaObject obj, bool first, bool last)
  {
    print(obj, last);
  }

  template <class MetaObject>
  void operator()(MetaObject obj)
  {
    print(obj, true);
  }


int main(void)
{
  object_printer print = {std::cout, 0};
  print(puddle::adapt<MIRRORED_GLOBAL_SCOPE()>());
  return 0;
}
```

which prints the following on the standard output:

```
global scope : {
  namespace std: {
    class string: { },
    class wstring: { },
    template pair,
    template tuple,
    template initializer_list,
    template allocator,
    template equal_to,
    template not_equal_to,
    template less,
    template greater,
    template less_equal,
    template greater_equal,
    template deque,
    class tm: {
      member variable tm_sec,
```

```
        member variable tm_min,
        member variable tm_hour,
        member variable tm_mday,
        member variable tm_mon,
        member variable tm_year,
        member variable tm_wday,
        member variable tm_yday,
        member variable tm_isdst
      },
      template vector,
      template list,
      template set,
      template map
    },
    namespace boost: {
      template optional
    },
    namespace mirror: { },
    type void,
    type bool,
    type char,
    type unsigned char,
    type wchar_t,
    type short int,
    type int,
    type long int,
    type unsigned short int,
    type unsigned int,
    type unsigned long int,
    type float,
    type double,
    type long double
  }
```

For more examples of usage see [3].

D. Rubber examples

The first example shows the usage of type-erased metaobjects with a C++11 lambda function which could not be used with Mirror's or Puddle's metaobjects (because lambdas are not templated):

```
#include <mirror/mirror.hpp>
#include <rubber/rubber.hpp>
#include <iostream>

int main(void)
{
    // use the Mirror's for_each function, but erase
    // the types of the iterated compile-time metaobjects
    // before passing them as arguments to the lambda function.
    mirror::mp::for_each<
        mirror::members<
            MIRRORED_GLOBAL_SCOPE()
        >
    >(
        // the rubber::meta_named_scoped_object type is
        // constructible from a Mirror MetaNamedScopedObject
        [](const rubber::meta_named_scoped_object& member)
        {
            std::cout <<
                member.self().construct_name() <<
                " " <<
                member.base_name() <<
                std::endl;
        }
    );
    return 0;
}
```

This simple application prints the following on the standard output:

```
namespace std
namespace boost
namespace mirror
type void
type bool
type char
type unsigned char
type wchar_t
type short int
type int
type long int
type unsigned short int
type unsigned int
type unsigned long int
type float
```

```
type double
type long double
```

The next example prints different information for different categories of metaobjects:

```
#include <mirror/mirror.hpp>
#include <rubber/rubber.hpp>
#include <iostream>
#include <vector>

int main(void)
{
    using namespace rubber;
    mirror::mp::for_each<
        mirror::members<
            MIRRORED_GLOBAL_SCOPE()
        >
    >(
        eraser<meta_scope, meta_type, meta_named_object>(
            [](const meta_scope& scope)
            {
                std::cout <<
                    scope.self().construct_name() <<
                    " '" <<
                    scope.base_name() <<
                    "', number of members = " <<
                    scope.members().size() <<
                    std::endl;
            },
            [](const meta_type& type)
            {
                std::cout <<
                    type.self().construct_name() <<
                    " '" <<
                    type.base_name() <<
                    "', size in bytes = " <<
                    type.sizeof_() <<
                    std::endl;
            },
            [](const meta_named_object& named)
            {
                std::cout <<
                    named.self().construct_name() <<
                    " '" <<
                    named.base_name() <<
```

```
                    "'" <<
                    std::endl;
            }
        )
    );
    return 0;
}
```

It has the following output:

```
namespace 'std', number of members = 20
namespace 'boost', number of members = 0
namespace 'mirror', number of members = 0
type 'void', size in bytes = 0
type 'bool', size in bytes = 1
type 'char', size in bytes = 1
type 'unsigned char', size in bytes = 1
type 'wchar_t', size in bytes = 4
type 'short int', size in bytes = 2
type 'int', size in bytes = 4
type 'long int', size in bytes = 8
type 'unsigned short int', size in bytes = 2
type 'unsigned int', size in bytes = 4
type 'unsigned long int', size in bytes = 8
type 'float', size in bytes = 4
type 'double', size in bytes = 8
type 'long double', size in bytes = 16
```

For more examples of usage see [4].

E. Lagoon examples

This example queries the meta-types reflecting types in the global scope, orders them by the value of `sizeof` and prints their names:

```
#include <mirror/mirror.hpp>
#include <lagoon/lagoon.hpp>
#include <lagoon/range/extract.hpp>
#include <lagoon/range/sort.hpp>
#include <lagoon/range/for_each.hpp>
#include <iostream>

int main(void)
{
```

```
    using namespace lagoon;
    typedef shared<meta_named_scoped_object> shared_mnso;
    typedef shared<meta_type> shared_mt;
    //
    // traverses the range of meta-objects passed as
    // the first argument and on each of them executes
    // the functor passed as the second argument
    for_each(

        // sorts the range passed as the first argument
        // using the functor passed as the second argument
        // for comparison
        sort(

            // extracts only those having the meta_type
            // interface
            extract<meta_type>(

                // gets all members of the global scope
                reflected_global_scope()->members()
            ),

            // compares two meta-types on the value
            // of sizeof(reflected-type)
            [](const shared_mt& a, const shared_mt& b)
            {
                return a->size_of() < b->size_of();
            }
        ),

        // prints the full name of a type
        [](const shared_mt& member)
        {
            std::cout << member->full_name() << std::endl;
        }
    );
    return 0;
}
```

This application prints the following on the standard output:

```
void
bool
char
unsigned char
```

```
short int
unsigned short int
wchar_t
int
long int
unsigned int
unsigned long int
float
double
long double
```

The following example is more complex and shows the usage of Lagoon's object factories, in this case a factory using a text-script similar to C++ uniform initializers to provide input data from which a set of instances is constructed:

```cpp
#include <mirror/mirror_base.hpp>
#include <mirror/pre_registered/basic.hpp>
#include <mirror/pre_registered/class/std/vector.hpp>
#include <mirror/pre_registered/class/std/map.hpp>
#include <mirror/utils/quick_reg.hpp>
#include <lagoon/lagoon.hpp>
#include <lagoon/utils/script_factory.hpp>
#include <iostream>

namespace morse {

// declares an enumerated class for morse code symbols
enum class signal : char { dash = '-', dot = '.' };

// declares a type for a sequence of morse code symbols
typedef std::vector<signal> sequence;

// declares a type for storing morse code entries
typedef std::map<char, sequence> code;

} // namespace morse

MIRROR_REG_BEGIN

// registers the morse namespace
MIRROR_QREG_GLOBAL_SCOPE_NAMESPACE(morse)
// registers the signal enumeration
MIRROR_QREG_ENUM(morse, signal, (dash)(dot))

MIRROR_REG_END
```

```
int main(void)
{
    try
    {
        using namespace lagoon;

        // a factory builder class provided by Lagoon
        // that can be used together with a meta-type
        // to build a factory
        c_str_script_factory_builder builder;

        // a class storing the input data for the factory
        // built by the builder
        c_str_script_factory_input in;

        // the input data for the factory
        auto data = in.data();

        // polymorphic meta-type reflecting the morse::code type
        auto meta_morse_code = reflected_class<morse::code>();

        // a polymorphic factory that can be used to construct
        // instances of the morse::code type, that is built by
        // the builder and the meta-type reflecting morse::code.
        auto morse_code_factory = meta_morse_code->make_factory(
            builder,
            raw_ptr(&data)
        );

        // the input string for this factory
        const char input[] = "{" \
            "{'A', {dot, dash}}," \
            "{'B', {dash, dot, dot, dot}}," \
            "{'C', {dash, dot, dash, dot}}," \
            "{'D', {dash, dot, dot}}," \
            "{'E', {dot}}," \
            "{'F', {dot, dot, dash, dot}}," \
            "{'G', {dash, dash, dot}}," \
            "{'H', {dot, dot, dot, dot}}," \
            "{'I', {dot, dot}}," \
            "{'J', {dot, dash, dash, dash}}," \
            "{'K', {dash, dot, dash}}," \
            "{'L', {dot, dash, dot, dot}}," \
```

```
        "{'M', {dash, dash}}," \
        "{'N', {dash, dot}}," \
        "{'O', {dash, dash, dash}}," \
        "{'P', {dot, dash, dash, dot}}," \
        "{'Q', {dash, dash, dot, dash}}," \
        "{'R', {dot, dash, dot}}," \
        "{'S', {dot, dot, dot}}," \
        "{'T', {dash}}," \
        "{'U', {dot, dot, dash}}," \
        "{'V', {dot, dot, dot, dash}}," \
        "{'W', {dot, dash, dash}}," \
        "{'X', {dash, dot, dot, dash}}," \
        "{'Y', {dash, dot, dash, dash}}," \
        "{'Z', {dash, dash, dot, dot}}," \
        "{'1', {dot, dash, dash, dash, dash}}," \
        "{'2', {dot, dot, dash, dash, dash}}," \
        "{'3', {dot, dot, dot, dash, dash}}," \
        "{'4', {dot, dot, dot, dot, dash}}," \
        "{'5', {dot, dot, dot, dot, dot}}," \
        "{'6', {dash, dot, dot, dot, dot}}," \
        "{'7', {dash, dash, dot, dot, dot}}," \
        "{'8', {dash, dash, dash, dot, dot}}," \
        "{'9', {dash, dash, dash, dash, dot}}," \
        "{'0', {dash, dash, dash, dash, dash}}" \
"}";

// passes the input data to the factory
in.set(input, input+sizeof(input));

// use the factory built above to create
// a new instance of the morse::code type
raw_ptr pmc = morse_code_factory->new_();

// cast of the raw pointer returned by the factory
// to the concrete type (morse::code)
morse::code& mc = *raw_cast<morse::code*>(pmc);

// the morse::code type is just a map of char to
// a vector of morse signals, this prints them
// to cout in a standard way
for(auto i = mc.begin(), e = mc.end(); i != e; ++i)
{
    std::cout << "Morse code for '" << i->first << "': ";
    auto j = i->second.begin(), f = i->second.end();
```

```
            while(j != f)
            {
                std::cout << char(*j);
                ++j;
            }
            std::cout << std::endl;
        }

        // uses the meta-type reflecting morse::code to delete
        // the instance constructed by the factory
        meta_morse_code->delete_(pmc);
    }
    catch(std::exception const& error)
    {
        std::cerr << "Error: " << error.what() << std::endl;
    }
    //
    return 0;
}
```

This application has the following output:

```
Morse code for '0': -----
Morse code for '1': .----
Morse code for '2': ..---
Morse code for '3': ...--
Morse code for '4': ....-
Morse code for '5': .....
Morse code for '6': -....
Morse code for '7': --...
Morse code for '8': ---..
Morse code for '9': ----.
Morse code for 'A': .-
Morse code for 'B': -...
Morse code for 'C': -.-.
Morse code for 'D': -..
Morse code for 'E': .
Morse code for 'F': ..-.
Morse code for 'G': --.
Morse code for 'H': ....
Morse code for 'I': ..
Morse code for 'J': .---
Morse code for 'K': -.-
Morse code for 'L': .-..
Morse code for 'M': --
```

```
Morse code for 'N': -.
Morse code for 'O': ---
Morse code for 'P': .--.
Morse code for 'Q': --.-
Morse code for 'R': .-.
Morse code for 'S': ...
Morse code for 'T': -
Morse code for 'U': ..-
Morse code for 'V': ...-
Morse code for 'W': .--
Morse code for 'X': -..-
Morse code for 'Y': -.--
Morse code for 'Z': --..
```

For more examples of usage see [5].