Metaclasses: Generative C++

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Reply-to: Herb Sutter (hsutter@microsoft.com)
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Contents

Major changes in R3: Switched to function-style declaration syntax per SG7 direction in Albuquerque (old: `$class M` → new: `constexpr void M(meta::type target, const meta::type source)`). Simplified some examples.

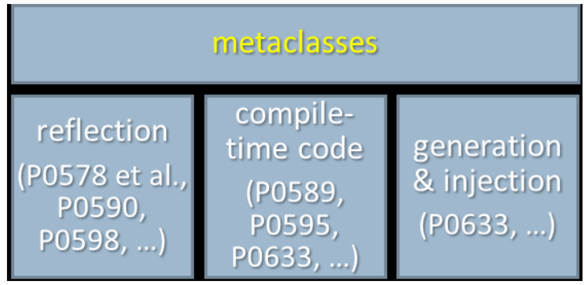
Abstract

The only way to make a language more powerful, but also make its programs simpler, is by *abstraction*: adding well-chosen abstractions that let programmers replace manual code patterns with saying directly what they mean. There are two major categories:

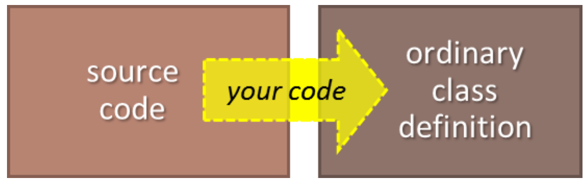
> **Elevate coding patterns/idioms into new abstractions built into the language.** For example, in current C++, range-`for` lets programmers directly declare "for each" loops with compiler support and enforcement.
>
> **(major, this paper) Provide a new abstraction authoring mechanism so programmers can write new kinds of user-defined abstractions that encapsulate behavior.** In current C++, the function and the `class` are the two mechanisms that encapsulate user-defined behavior. In this paper, metaclasses enable defining categories of `class`es that have common defaults and generated functions, and formally expand C++'s type abstraction vocabulary beyond `class`/`struct`/`union`/`enum`.

Also, §3 shows a set of common metaclasses, many of which are common enough to consider for `std::`. This paper begins by demonstrating how to implement Java/C# `interface` as a 10-line C++ `std::` metaclass – with the same usability, expressiveness, diagnostic quality, and performance of the built-in feature in such languages, where it is specified as ~20 pages of "standardese" text specification.

1 Overview



This paper assumes that C++ adds support for static reflection and compile-time programming to C++ along the lines of P0578 and P0633, and focuses on the next-level layer of abstraction we could build on top of that. This paper will not extensively describe those proposals, which are still evolving; see those papers for details. This paper hopes to provide "what we want to be able to write" use cases for using features in the related work, and this paper's prototype implementation also implements most of those other proposals since they are necessary for metaclasses.



Metaclasses (provisional name) let programmers write a new kind of efficient abstraction: a user-defined named subset of `class`es that share common characteristics – including user-defined rules, defaults, and generated functions – by writing a custom transformation from normal C++ source code to a normal C++ class definition. There is no type system bifurcation; the generated class is a normal `class`.

Primary goals:

- Expand C++'s abstraction vocabulary beyond `class`/`struct`/`union`/`enum` which are the type categories hardwired into the language.
- Enable providing longstanding best practices as reusable libraries instead of English guides/books, to have an easily adopted vocabulary (e.g., `interface`, `value`) instead of lists of rules to be memorized (e.g., remember this coding pattern to write an abstract base class or value type, relying on tools to find mistakes).
- Enable writing compiler-enforced patterns for any purpose: coding standards (e.g., many Core Guidelines "enforce" rules), API requirements (e.g., rules a class must follow to work with a hardware interface library, a browser extension, a callback mechanism), and any other pattern for classes.
- Enable writing many new "specialized types" features (e.g., as we did in C++11 with `enum class`) as ordinary library code instead of pseudo-English standardese, with equal usability and efficiency, so that they can be unit-tested and debugged using normal tools, developed/distributed without updating/shipping a new compiler, and go through LEWG/LWG as code instead of EWG/CWG as standardese. As a consequence, enable standardizing valuable extensions that we'd likely never standardize in the core language because they are too narrow (e.g., `interface`), but could readily standardize as a small self-contained library.
- Eliminate the need to invent non-C++ "side languages" and special compilers, such as Qt moc, COM MIDL, and C++/CX, to express the information their systems need but cannot be expressed in today's C++ (such as specialized types for properties, event callbacks, and similar abstractions).

Primary intended benefits:

- For users: Don't have to wait for a new compiler. Can write "new class features" as "just code" so they can be put in namespaces, shared as libraries and on GitHub, and so on like any other code.
- For standardization: More features as testable libraries ⇒ easier evolution, higher quality proposals. Common metaclasses (like common classes) can be standardized as `std::` libraries.
- For C++ implementations: Fewer new language features ⇒ less new compiler work and more capacity to improve tooling and quality for existing features. Over time, can deprecate and eventually remove many nonstandard extensions.

A Clang-based prototype is available at *github.com/asutton/clang* (source) and R2 of this paper linked to some live examples on *cppx.godbolt.org*. See §1.3 for in-progress notes regarding in-progress work (not yet up on godbolt).

1.1 Design principles

Note These principles apply to all design efforts and aren't specific to this paper. Please steal and reuse.

The primary design goal is conceptual integrity [Brooks 1975], which means that the design is coherent and reliably does what the user expects it to do. Conceptual integrity's major supporting principles are:

- **Be consistent:** Don't make similar things different, including in spelling, behavior, or capability. Don't make different things appear similar when they have different behavior or capability. – For example, in metaclasses we use normal class declaration syntax instead of inventing novel syntax.
- **Be orthogonal:** Avoid arbitrary coupling. Let features be used freely in combination. – For example, in these papers `for` can be used to process a reflected collection of items (e.g., all the member functions of a class), without having a distinct special-purpose `for_each<>` on a reflected collection.
- **Be general:** Don't restrict what is inherent. Don't arbitrarily restrict a complete set of uses. Avoid special cases and partial features. – For example, this paper prefers to avoid creating a special-purpose syntax to define metaclasses, and instead lets programmers use normal class scope declaration syntax plus the general features of reflection and compile-time programming. Also, metaclasses are just code, that can appear wherever code can appear – written inside namespaces to avoid name collisions (including putting common ones in `std::`), and shared via `#include` headers or via modules.

These also help satisfy the principles of least surprise and of including only what is essential, and result in features that are additive and so directly minimize concept count (and therefore also redundancy and clutter).

1.2 Strawman syntax notes

This paper assumes concepts, general compile-time programming along the lines proposed in P0633 and related papers, and underlying reflection facilities along the lines in P0194, P0385, P0578 and related papers. This paper is tracking the evolution of those compile-time facilities, whose syntax is still undergoing change.

The strawman syntax for a metaclass is to write it as a compile-time `constexpr` function that takes `meta::type` parameters, which are passed with reference semantics (like `shared_future`):

```
constexpr void my_metaclass(meta::type target, const meta::type source);
```

Note The current prototype implementation has not yet been merged with the value-based reflection implementation, and in the meantime such a function is written as a template:

```
template<typename T, typename S>
constexpr void my_metaclass(T target, S source);
```

In addition, a `constexpr{}` block can appear in normal code, including at class or namespace scope, and contain compile-time code as in a metaclass function.

The current strawman syntax to reflect is prefix `$`. For example, the expression `$void` returns a `meta::type` object that represents `void`. The current strawman syntax to extend a `meta::type m` with an additional entity (e.g., another `meta::` object such as a `meta::function`, or member declarations) is `->(m)`. When injecting member declarations, `meta::` objects in the surrounding scope can be accessed and injected using suffix `$` (projection).

In addition, this paper proposes compiler-integrated diagnostics, where `compiler.error("message", m)` directs the compiler to emit the diagnostic message with `m.source_location()`, which is intended to be integrated with the compiler's native diagnostics, including in visual style and control options. For example:

```
for (auto f : source.functions())          // for each member function f in source
    if (f.is_copy() || f.is_move())        // let's say we want to disallow copy/move
        compiler.error("this type may not have a copy or move function", f);
        // note: passing f will use f.source_location() for this diagnostic message
```

For convenience, `compiler.require(cond, "message", source_location)` is equivalent to `if constexpr(!cond) compiler.error("message", source_location);`. So the above is equivalent to:

```
for (auto f : source.functions())
    compiler.require(!f.is_copy() && !f.is_move()),
                     "this type may not have a copy or move function", f);
```

Note The current prototype implementation does not yet allow a `source_location`, so that has been temporarily removed from this paper's examples to make it easier to cut-and-paste examples from here into the prototype compiler. The `source_location` will be added so that diagnostics can have precise source line and column information.

1.3 Current prototype delta notes

The Clang-based prototype is tracking this proposal and has been updated to reflect SG7 feedback in Albuquerque. Where work is still in progress, here are current known deltas needed to make the examples shown in this paper work in the current prototype as of this writing.

1.3.1 Value-based reflection and metaclass function declarations

The prototype has not yet merged with the value-based reflection implementation. This means that for now each reflected type still creates a distinct compile time type; with value-based reflection all reflected types will have the single type `meta::type`.

In the meantime, when you see this declaration in this paper:

```
constexpr void my_metaclass(meta::type target, const meta::type source) { /*...*/ }
```

for now instead write this declaration in the prototype:

```
template<typename T, typename S>
constexpr void my_metaclass(T target, const S source) { /*...*/ }
```

1.3.2 Compile-time for loop syntax

The prototype is temporarily still using a differently-named `for...` rather than just ordinary `for` in compile-time code.

In the meantime, when you see this in this paper:

```
for (auto f : source.member_functions()) {
```

for now instead write this in the prototype:

```
for... (auto f : source.member_functions()) {
```

1.3.3 Injection and projection

The current prototype does not support the `->(target)` syntax. Instead, the syntax to inject an additional entity (e.g., function, class fragment) into a `meta::type m` is `__extend(m)`. Like this paper's `->` it can be followed by a `meta::` object, or by member declarations. However, the syntax for such member declarations is a class fragment written as `class{/*…*/}`, and instead of using suffix $ for projection to inject a meta:: object value, the prototype uses `__inject` to inject the entire entity (e.g., `__inject(func.parameters())`) or `idexpr()` to create an identifier (e.g., `idexpr(v)`) or `typename()` to create a type name (e.g., `typename(mytype)`).

For example, here is a metaclass function in the current prototype's syntax that takes every member function of `source`, changes its return type to `HRESULT`, and if the original return type `R` was not `void` appends an `R*` parameter (moving the return type to be instead an out pointer parameter):

```
template<typename T, typename S>
constexpr void my_metaclass(T target, const S source) {

  for (auto f : in.member_functions()) {

    auto ret = f.return_type();
    if (ret == $void) {
      __extend(target) class {
        virtual HRESULT idexpr(f)(__inject(f.parameters())) = 0;
      };
    }

    else {
      __extend(target) class {
        virtual HRESULT idexpr(f)(__inject(f.parameters()), typename(ret)* retval) = 0;
      };
    }

  }

}
```

1.3.4 Querying changes made on a local copy

Making changes to a `meta::` object's state and then querying it does not always show the new information yet. For example, this assertion can fail, and should not:

```
for (auto f : source.member_functions()) {
    f.make_public();
    compiler.require(f.is_public(), "interface functions must be public");
```

The assertion should never fail, since we just made `f` be public, and this bug will be fixed. However, the bug is of interest because it highlights an implementation detail in the prototype: A variable like `f` has value semantics, but for efficiency (to avoid proliferating short-lived types in the compile-time computation, which can be difficult to prune/collect) under the covers the implementation of `f` stores essentially a pointer to the original member function `meta::` object and a list of local pending changes (diffs) that is only materialized if and when `f` is used to actually declare something else (e.g., if a copy of `f` is injected into another class). This implementation preserves the zero-overhead rule by not incurring compile-time cost of creating objects in the AST except for entities actually declared by the programmer, and not for such temporary variables. However, the current prototype has a bug where when querying the object's state (such as `f.is_public()` above) we currently forget to look at the list of diffs first, and look only at the original copied-from `meta::function` object, and so if that original object had not already been public the test will incorrectly fail until we fix this bug.

1.3.5 Applying metaclasses

The prototype currently requires writing `class()` around the metaclass name when using a metaclass name to define a type.

In the meantime, when you see this in this paper to use a metaclass name (here `interface`) to define a type:

```
interface Shape { /*...*/ };
```

for now instead write this in the prototype:

```
class(interface) Shape { /*...*/ };
```

1.3.6 Concepts

Examples that use concepts will not compile yet in the Clang-based prototype compiler because Clang does not yet support concepts.

1.4 Acknowledgments

Special thanks to Andrew Sutton and Bjarne Stroustrup for their review feedback on several drafts of this paper and other major contributions to C++. They are two of the primary designers of the current Concepts TS. Andrew Sutton is also the first implementer of the Concepts TS (in GCC 6), and the first implementer of this proposal (in a Clang-based prototype). This paper would be poorer without their insightful feedback, including Stroustrup's characterization of metaclasses as 'constructive concepts,' or concepts that can be used to define types.

Thanks also to the ACCU 2017 attendees for their enthusiastic reception and feedback after the talk on this topic at their conference, and to the organizers for holding the video until we could also report the results of the initial presentation to the ISO C++ committee in July 2017 and produce the post-Toronto R1 revision of this paper.

Thanks also to the following experts for their comments in discussions and/or on pre-R0 drafts of this paper: Louis Brandy, Chandler Carruth, Casey Carter, Matúš Chochlík, Marshall Clow, Lawrence Crowl, Pavel Curtis, Christopher Di Bella, Louis Dionne, Gabriel Dos Reis, Joe Duffy, Thomas Heller, Howard Hinnant, Kenny Kerr, Nicolai Josuttis, Aaron Lahman, Scott Meyers, Axel Naumann, Gor Nishanov, Stephan T. Lavavej, Andrew Pardoe, Sean Parent, Jared Parsons, David Sankel, Richard Smith, Jeff Snyder, Mike Spertus, Mads Torgersen, Daveed Vandevoorde, Tony Van Eerd, JC van Winkel, Ville Voutilainen, and Titus Winters.

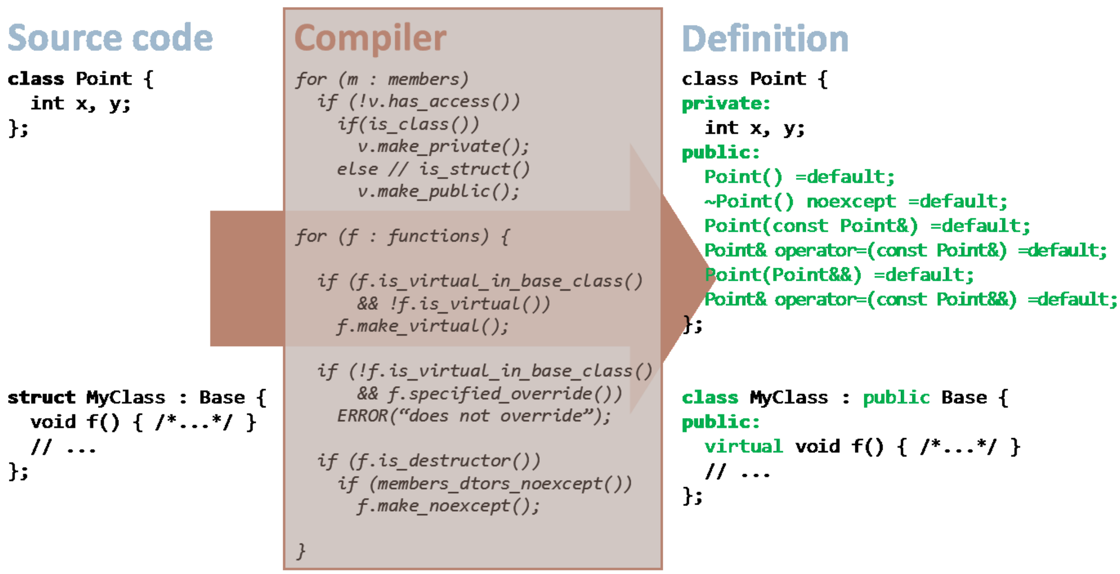
Thanks also to the following for further discussion, corrections, and other feedback since the R0 draft: Andras Agocs, Jonathan Boccara, Marco Foco, Alexandre Folle de Menezes, Barry Revzin.

2 Language: Metaclasses

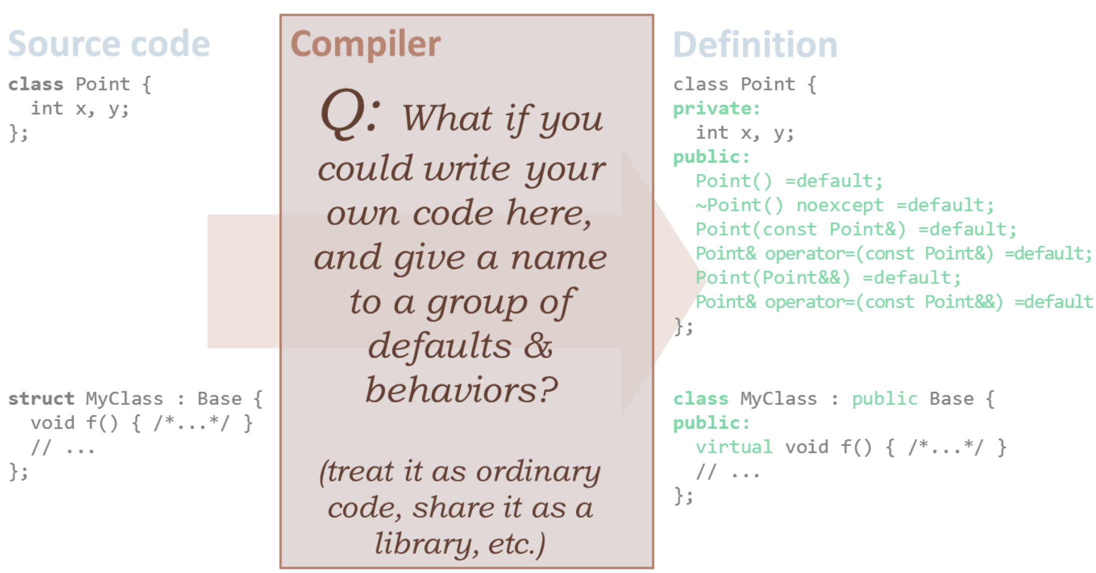
"Classes can represent almost all the concepts we need… Only if the library route is genuinely infeasible should the language extension route be followed." — B. Stroustrup (D&E, p. 181)

This paper relies on C++ classes's already being general and unified. Stroustrup resisted all attempts to bifurcate the type system, such as to have `struct` and `class` be different kinds of types. The result is that the C++ `class` can express virtually every kind of type. – The goal of metaclasses is to fully preserve that, while also being able to define different kinds of types as reusable code by providing a narrow targeted hook: the ability to write compile-time code that participates in how the compiler interprets source code and turns it into a class definition.

Today's language has rules to interpret source code and applies defaults and generates special member functions (SMFs). Here is a pseudocode example to illustrate how the compiler interprets `class` and `struct`:



Today, the contents of the "compiler" box is specified in English-like standardese and hardwired into compiler implementations. The generalization in this paper is to ask one narrowly targeted question:



The intent is to "view `struct` and `class` as the first two metaclasses,"[1] except that today their semantics are baked into the language and written inside C++ compiler implementations, instead of being an extensibility point that can be written as ordinary C++ code.

This hook helps to solve a number of existing problems caused by the fact that "different kinds of types" are not supported by the language itself. For example, today we rely on coding patterns such as abstract base classes ("ABCs") and "regular types" instead of giving names to language-supported features like "interface" or "value" that would let users easily name their design intent and get the right defaults, constraints, and generated functions for *that* kind of type. And the fact that there is only one kind of "class" means that the language's defaults (e.g., all members private by default for classes and public for structs, functions that are virtual in a base class are virtual by default in the derived class) and generated special member functions (SMFs) (e.g., generate move assignment under these conditions) must be specified using a single heuristic for all conceivable types, which guarantees that they will be wrong for many types, and so when the heuristic fails we need tools like `=delete` to suppress an incorrectly generated SMF and `=default` to opt back in to a desired incorrectly suppressed SMF.

A **metaclass** allows programmers to write compile-time code that executes while processing the definition of class. In a nutshell, the goal is to:

- **name a subset** of the universe of C++ classes whose members share **common characteristics**;
- express that subset and its characteristics using **compile-time code** (which can be unit-tested, put in namespaces, shared in libraries, etc. like any other code); and
- **make classes easier to write** by letting class authors **use the name as a single-word "generalized opt-in"** to get that whole package of characteristics.

The goal is to elevate idiomatic conventions into the type system as compilable and testable code, and in particular to write all of the same diverse kinds of class types we already write today, but more cleanly and directly.

Metaclasses complement (and rely on) concepts and reflection, which are about *querying* capabilities – based on "does this expression compile" and "does this member/signature exist," respectively. Metaclasses are about *defining* types – participating in interpreting the meaning of source code to generate the class definition.

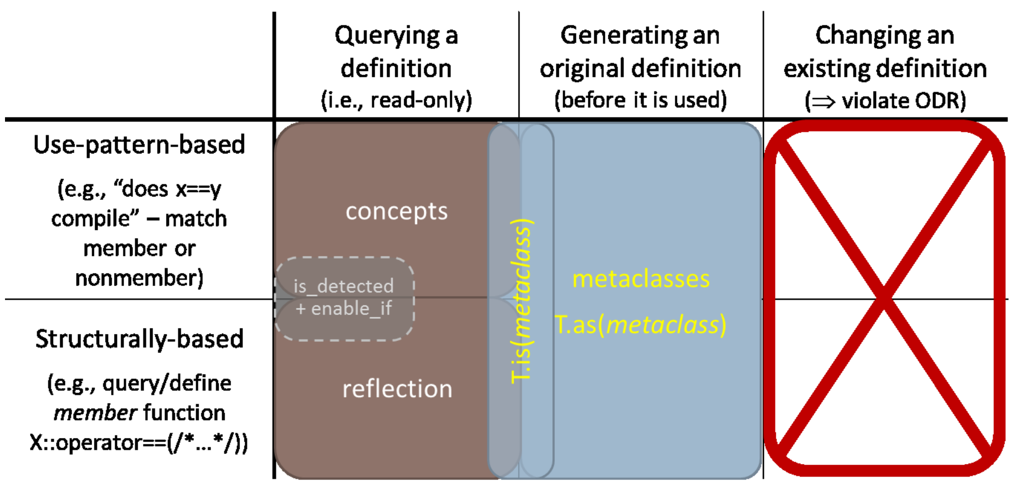


Figure 1: How the pieces fit

[1] And `union` and `enum` as the next two, though the latter has slightly different syntax than a `class`.

2.1 What and how: "Constructive" concepts

A metaclass is defined as `constexpr` function that transforms a read-only source `meta::type` to one or more generated target `meta::type`s, and can express constraints, defaults, and more. For example:

```
namespace std::experimental {
    constexpr void interface(meta::type target, const meta::type source) {
        // we will describe how to write code to:
        //  - apply "public" and "virtual" to member functions by default
        //  - require all member functions be public and virtual
        //  - require no data members, copy functions, or move functions
        //  - generate a pure virtual destructor (if not user-supplied)
    };
}
```

A metaclass function name can be written in place of `class` to more specifically define a type in terms of "what it is." The compile-time code is run when it is used to define an ordinary class:

```
interface Shape {                          // let Shape be-an interface
    int area() const;
    void scale_by(double factor);
};

// result:
//   class Shape {
//   public:
//       virtual int area() const = 0;
//       virtual void scale_by(double factor) = 0;
//       virtual ~Shape() noexcept = 0;
//       using prototype = /*impl-defined-&-unique*/::Shape; // original source
//   };
```

In the code `interface Shape { /*...*/ };`, the semantics are:

- Metaclass `interface` is used in place of the unspecialized keyword `class` to state that the characteristics associated with `interface` apply to `Shape`.
- The code the user writes as the body of `Shape` is the source prototype class.
- The compiler: (a) moves the prototype class into an unspecified and unique namespace that contains no other functions: (b) generates a new class `Shape` in the original namespace that has the same name and is empty except for a `prototype` alias to the new location of the prototype; (c) invokes `interface($Shape, $Shape::prototype)`; and (d) invokes `__metaclass_finalization($Shape)`. When this is complete, `Shape` is a normal fully defined class type.

> **Note** Unlike in Java/C#, the type system is not bifurcated; there is still only one kind of `class`, and every interface is still a `class`. A metaclass simply gives a name to a subset of classes that share common characteristics and makes them easier to write correctly.

A metaclass's code is fully general and so can express anything computable. There are four common uses:

- **Provide defaults:** Implicit meanings, such as "an interface's functions are `public` and `virtual` by default" without the author of a particular interface type having to specify the default.

- **Generate members:** Default declarations and implementations for members that all classes conforming to the metaclass must have, such as "a `value` always has copy and move, and memberwise definitions are generated by default if copy and move are not explicitly written by hand."
- **Enforce rules:** Constraints, such as "an `interface` contains only public virtual functions and is not copyable." Use concepts to express usage-based patterns, and use reflection to query specific entities; together these enable a constraint to express anything computable about a type.
- **Perform transformations:** Changes to declared entities, such as "an `rt_interface` must have an `HRESULT` return type, and a non-`void` return type must be changed to an additional `[[out, retval]]` parameter instead," or "a `variant` type replaces all of the data members declared in the protoclass with an opaque buffer in the fully defined class."

Notes One result is that metaclasses provide "generalized opt-in" for generated functions. A metaclass replaces the built-in `class` special member function generation rules because the metaclass is taking over responsibility for all generation.

C++ provides only a few "special" generated functions for all classes, and more are desirable (e.g., comparisons). They are difficult to manage and extend because today C++ has only a monolithic universe of all classes, with no way to name subsets of classes. So, each compiler-generated "special member function" has to be generated based on a general heuristic that must work well enough *for all conceivable classes* to decide whether the function would likely be desired. But no heuristic is correct for all types, so this led to bugs when a special function was generated or omitted inappropriately (the heuristic failed), which led to the need for ways to "opt back out" and turn off a generated function when not desired (`=delete`) or to "opt back in" and use the default function semantics when the heuristic did not generate them (manual declaration followed by `=default`). Any new generated functions, such as comparisons, would need their own heuristics and face the same problems if the same rule is forced to apply to all possible classes.

Metaclasses provide a way to name a group of classes (a subset of the universe of all classes), and an extensible way to give that subset appropriate generated functions. Because the generated functions are provided by the metaclass, the metaclass name is the natural "opt-in" to get everything it provides. In turn, because generated functions are provided exactly and only when asked for, metaclasses remove the need to reinstate/suppress them – because we opted in, the functions the metaclass generates cannot logically be suppressed because if we didn't want them we wouldn't have opted into the metaclass (thus no need for `=delete` for generated functions), and because they are never suppressed by a heuristic we never need to reinstate them (thus no need to `=default` them).

Of course, `=default` and `=delete` are still useful for other things, such as a convenient way to get default bodies (see P0515) or to manage overload sets, respectively. The point here is only that, when using metaclasses, they are no longer needed to override an overly general heuristic that guesses wrong.

In a metaclass the following defaults apply, and are applied in metaclass finalization:

- Functions are public by default, and data members are private by default (if not already specified).
- The only implicitly generated function is a public nonvirtual default destructor (if not declared).

These are applied by the default metaclass program that runs the following at the end of the class definition after all other compile-time metaclass code (using __ because this is in the language implementation):

```
constexpr void __metaclass_finalization(meta::type t) {
    for (auto o : t.variables())
        if (!o.has_access()) o.make_private();    // make data members private by default
    bool __has_declared_dtor = false;
    for (auto f : t.functions()) {
        if (!f.has_access()) f.make_public();     // make functions public by default
        __has_declared_dtor |= f.is_destructor(); // and find the destructor
    }
    if (!__has_declared_dtor)                     // if no dtor was declared, then
        -> { public: ~this_class() { } }          // make it public nonvirtual by default
}
```

2.2 Metaclass bird's-eye overview: Usage and definition examples

To illustrate, here is an overview of some equivalent code side by side. In each case, the code on the right is just a more convenient way to write exactly the code on the left and so has identical performance, but the code on the right offers stronger abstraction and so eliminates classes of errors and is more robust under maintenance.

<table>
<tr><th>C++17 style</th><th>This paper (proposed)</th></tr>
<tr><td colspan="2">Applying a reusable abstraction with custom defaults and constraints = Medium improvement</td></tr>
<tr><td><pre>class Shape {
public:
    virtual int area() const =0;
    virtual void scale_by(double factor) =0;
    // ... etc.
    virtual ~Shape() noexcept { };
    // be careful not to write nonpublic/nonvirtual function
}; //   or copy/move function or data member; no enforcement</pre></td><td><pre>interface Shape { // see §3.1
    int area() const;
    void scale_by(double factor);
    // ... etc.
};

// see below in this table for the
// definition of interface</pre></td></tr>
<tr><td colspan="2">Applying a reusable abstraction that additionally has custom generated functions = Large improvement</td></tr>
<tr><td><pre>class Point {
    int x = 0;
    int y = 0;
public:
    // ... behavior functions ...
    Point() = default;
    friend bool operator==(const Point& a, const Point& b)
        { return a.x == b.x && a.y == b.y; }
    friend bool operator< (const Point& a, const Point& b)
        { return a.x < b.x || (a.x == b.x && a.y < b.y); }
    friend bool operator!=(const Point& a, const Point& b) { return !(a == b); }
    friend bool operator> (const Point& a, const Point& b) { return b < a; }
    friend bool operator>=(const Point& a, const Point& b) { return !(a < b); }
    friend bool operator<=(const Point& a, const Point& b) { return !(b < a); }
};</pre></td><td><pre>value Point {   // see §3.5
    int x = 0;
    int y = 0;
    // ... behavior functions ...
};</pre></td></tr>
</table>

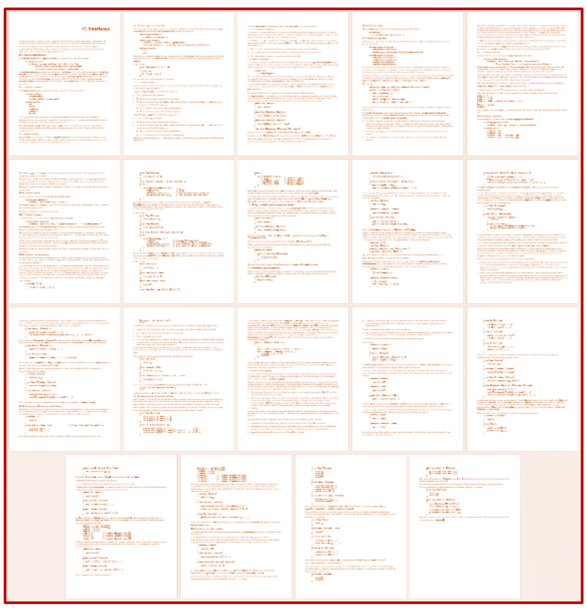
Applying a reusable abstraction with defaults, generated functions, and **custom semantics** = XL improvement

```
template <class T1, class T2>
struct pair {
   using first_type  = T1;
   using second_type = T2;
   T1 first;
   T2 second;
   template <class... Args1, class... Args2>
     pair(piecewise_construct_t,
          tuple<Args1...> args1,
          tuple<Args2...> args2);
   constexpr pair();
   pair(const pair&) = default;
   pair(pair&&) = default;
   pair& operator=(const pair& p);
   pair& operator=(pair&& p) noexcept(see below);
   void swap(pair& p) noexcept(see below);
   explicit constexpr pair(const T1& x, const T2& y);
   template<class U, class V>
     explicit constexpr pair(U&& x, V&& y);
   template<class U, class V>
     explicit constexpr pair(const pair<U, V>& p);
   template<class U, class V>
     explicit constexpr pair(pair<U, V>&& p);
   template<class U, class V>
     pair& operator=(const pair<U, V>& p);
   template<class U, class V>
     pair& operator=(pair<U, V>&& p);
};

template <class T1, class T2>
  constexpr bool operator==
    (const pair<T1,T2>& x, const pair<T1,T2>& y);
template <class T1, class T2>
  constexpr bool operator<
    (const pair<T1,T2>& x, const pair<T1,T2>& y);
template <class T1, class T2>
  constexpr bool operator!=
    (const pair<T1,T2>& x, const pair<T1,T2>& y);
template <class T1, class T2>
  constexpr bool operator>
    (const pair<T1,T2>& x, const pair<T1,T2>& y);
template <class T1, class T2>
  constexpr bool operator>=
    (const pair<T1,T2>& x, const pair<T1,T2>& y);
template <class T1, class T2>
  constexpr bool operator<=
    (const pair<T1,T2>& x, const pair<T1,T2>& y);
template<class T1, class T2>
  void swap(pair<T1, T2>& x, pair<T1, T2>& y)
    noexcept(noexcept(x.swap(y)));
template <class T1, class T2>
  constexpr pair<V1, V2>
    make_pair(T1&& x, T2&& y);
```

```
template<class T1, class T2>
aggregate pair {
    T1 first;
    T2 second;
};

// note: section 3 shows code for
// all metaclasses mentioned in the
// paper except for aggregate
```

Writing **as-if a new ‘language’ feature** using compile-time code + adding expressive power = XXL improvement

```
// C# language spec: ~20 pages of nontestable English
```



```
// User code (today’s Java or C#)
interface Shape {
    int area();
    void scale_by(double factor);
}
```

```
// (Proposed) C++ library: ~10 lines of testable code
constexpr void
interface(meta::type target, const meta::type source) {
   compiler.require(source.variables().empty(),
      "interfaces may not contain data");
   for (auto f : source.functions()) {
      compiler.require(!f.is_copy() && !f.is_move(),
         "interfaces may not copy or move; consider"
         " a virtual clone() instead");
      if (!f.has_access()) f.make_public();
      compiler.require(f.is_public(),
         "interface functions must be public");
      f.make_pure_virtual();
      ->(target) f;
   }
   ->(target) { virtual ~(source.name()$)() noexcept {} }
};
```

```
// User code (proposed C++)
interface Shape {
    int area() const;
    void scale_by(double factor);
};
```

Notes Re “interface”: C++ has always been able to express “interfaces” in a manual ad-hoc manner and even gave the idiomatic convention a name (ABCs, for abstract base classes). There should be a way for class authors to express their intent more directly with a name that is actual code.

Re “pair”: Specifying the “simple” type `std::pair` has been embarrassingly complex. For years, I have been asking the world’s most experienced C++ language and library experts to describe what is missing from C++ to enable expressing `std::pair` as simply as

```
template <class T1, class T2> struct pair { T1 first; T2 second; };
```

but I never received an answer. As far as I know, this is the first proposal that achieves that goal, changing “struct” to a metaclass name (herein I call it `aggregate`) that can then be reused directly to just as simply define other similar types (e.g., `std::tuple`, users’s own literal value types).

2.3 Example: `interface`

The previous page shows the code for an example, `interface`, that could be a candidate for the standard library, and that has the same expressiveness, efficiency and usability as the same feature hardwired into other languages.

Note The concept of an “interface” exists in many languages as a built-in feature, specified in all those languages as pages of human-language specification and implemented in a compiler. I believe that the above specification and implementation is as good (and sometimes better) in every respect, including in strength of abstraction, expressiveness, error diagnostic quality, testability, debuggability, run-time performance, and (to be proven) compile-time performance.

`source.functions()` includes all functions in `source`, including functions it inherited from any of its base classes. The `interface` metaclass function:

- **Implicitly generates** a pure virtual destructor. In this case we can just implicitly declare the pure virtual destructor without any additional checks to see whether the user declared it the same way explicitly, because if the user did declare it explicitly then this declaration is just redundant. (In other cases, we’ll first check to see what the user declared, and then supply generated functions only if the user did not.)
- **Applies defaults** via compile-time code to make all functions public and pure virtual. This applies to all functions in the type including the required function that it declares itself (the destructor).
- **Applies constraints**: If the author of the type applying `interface` explicitly declared any nonpublic or nonvirtual function, copy/move function, or data member, they get a compile-time error message.

2.3.1 Applying `interface`

So now we can use `interface` in place of `class` when defining a new type, to get its defaults and generated functions, and to apply its requirements at compile time.

```
// see §3.1

interface drawable {                // this is an interface
    int draw(canvas& c);            // draw now defaults to public pure virtual
    // ...
};
```

And user code gets high-quality diagnostics when it violates constraints. For example, if this class is modified during maintenance by a programmer who forgets that it should consist of only public pure virtual functions, today the code could silently compile, but with `interface` the compiler helps robustly maintain the class author’s declared intent:

```
interface drawable {                // attempted modification during maintenance...
    int draw(canvas& c);            // ok

private:
    void scale(double factor);      // ERROR: “interface functions must be public”
    string data;                    // ERROR: “interfaces may not contain data”
};
```

Of course, if the maintainer really wants to add a nonpublic function or data member, they can still do that – they just need to change `interface` to a more suitable metaclass name, or just `class`, to document that this is no longer an `interface`. The change is simple, but not silent (it wouldn't be silent for class users in any event!), so that the maintainer cannot violate the original class author's intent by accident.

2.4 Metaclass definition

A metaclass is written as a compile-time `constexpr` function that takes `meta::type` parameters, which are passed with reference semantics (like `shared_future`):

```
constexpr void my_metaclass(meta::type target, const meta::type source) { /*...*/ }
```

To add a declaration to `target`, use `->(target)` to add an object `m` of a `meta::` type, or a class fragment:

```
->(target) m;
->(target) { /*ordinary declaration syntax*/ };
```

In the latter form, it can be used to use the values or abstract state of objects of `meta::` type. For example:

```
constexpr void x(meta::type target, const meta::type source) {

    // for each source function
    for (auto f : source.functions()) {

        // first echo the function into target
        ->(target) f;

        // and then create a no-op overload with an extra “int” parameter
        ->(target) { void f.name()$ ( f.parameters()$, int ) { } };
    }
};
```

Metaclass functions can invoke each other. Here are two examples, one drawn from §3.5:

```
constexpr void io_and_comparable(meta::type target, const meta::type source) {
    iostreamable(target, source);          // this kind of type is both streamable
    comparable(target, source);            // and comparable
    // ... with additional defaults/constraints/generation/etc. ...
}

constexpr void value(meta::type target, const meta::type source) {
    basic_value(target, source);           // a value is-a basic_value
    ordered(target, source);               // that is ordered
    // ... with additional defaults/constraints/generation/etc. ...
};
```

A metaclass function can require concepts. For example, given a concept `Z`, we can add it to the requirements list via `compiler.require` and instantiating it with a `meta::type`:

```
constexpr void value(meta::type target, const meta::type source) {
    basic_value(target, source);           // a value is-a basic_value
    ordered(target, source);               // that is ordered
    compiler.require(Regular<source>,      // and Regular
        "a value type must be Regular");

    // ... with additional defaults/constraints/generation/etc. ...
};
```

2.5 `.is` and `.as`

2.5.1 `.is` to match

We can perform ad-hoc duck typing to test whether a class implicitly satisfies the requirements of a metaclass `M`. In this proposal, `$T.is(M)` evaluates to `true` if and only if:

- applying `M` to `T` (as-if the definition of `T` had specified `M`) succeeds; and
- the resulting type has no new members not already present in `T`.

For example, this test uses the `copyable_pointer` metaclass function defined in §0:

```
static_assert ($shared_ptr<widget>.is(copyable_pointer<widget>));
```

For example, consider `Shape` written equivalently by hand vs. using the `interface` metaclass:

```
class Shape1 {                      // written by hand as in C++17
public:
    virtual void draw() = 0;
    virtual ~Shape1() noexcept = 0;
};

interface Shape2 {                  // same written using a metaclass
    void draw();
};
```

Both types satisfy `.is(interface)`:

```
static_assert ($Shape1.is(interface));
static_assert ($Shape2.is(interface));
```

This loop prints the names of all interfaces in namespace `N`:

```
for (auto t : $N.types())
    if (t.is(interface))
        cout << t.name() << endl;
```

2.5.2 `.as` to apply

Additionally, we can use a class as-if it had been declared with a metaclass, including to apply defaults and generated functions. `$T.as(M)` generates a type that is identical to `T` but is additionally defined using the named metaclass function `M`. Here is an example using a metaclass function `ordered` (see §3.4):

```
struct legacy_point { int x; int y; };             // this is not comparable
set<legacy_point> s;                               // and so this is an error

using ordered_point = $legacy_point.as(ordered);  // ... but this is ordered
set<ordered_point> s;                              // and so this is ok
```

Interestingly, the above example illustrates how strong typedefs could fall out naturally from `.as` …

2.5.3 Strong typedefs via `using` … `as`

To enable general strong typedefs via `using` … `as`, we first define an empty metaclass, which requires and adds nothing to the type. Let's call it `new_type` because that's how programmers will use it:

```
constexpr void new_type(meta::type, const meta::type) { }; // no-op metaclass fn
```

Then the following is a spelling for "strong typedef of `T`":

```
using my_T = $T.as(new_type);
```

There are two impediments to this generalization:

- It will easily pick up member functions, but might require special treatment for non-member functions in the same namespace to ensure the ones that directly mention the type are recognized and copied.
- In the case when `T` is a fundamental type, whether reflection reflects the language-generated operations (e.g., `operator+` for `int`s).

Assuming both of those are supported, this could cover common motivating cases for strong typedefs, namely new `int` and `string` types that work the same as the originals but are distinct types for overloading and do not implicitly convert to/from the original type by default.

```
using handle = $int.as(new_type);  // better than "enum class handle : int { };"

using score  = $unsigned.as(new_type);

using player = $string.as(new_type);
```

2.6 Concepts + metaclasses

Concepts and metaclasses are complementary. Metaclasses can be viewed as "constructive concepts" in that they go beyond concepts to define new types. Metaclass functions often use both concepts and reflection:

- Metaclasses use *concepts* to ask "can class `T` be used this way" via use-pattern constraints.
- Metaclasses use *reflection* to ask "does class T have these contents" via inspection.

Because both concepts and metaclasses have requirements and constraints, we should allow the complementary applications, which both involve replacing the keyword `class`.

First, concepts allow class *uses* to be constrained by replacing `class` with a concept name:

```
template <class     T> // unconstrained – any type will do

template <Sequence  S> // constrained – requires Sequence<S>
```

So we propose that a metaclass also be allowed to replace `class` here with `.is` meaning:

```
template <interface I> // constrained – requires $I.is(interface)
```

Second, metaclasses allow class *definitions* to be constrained by replacing `class` with a metaclass name:

```
class     X { /*…*/ }; // unconstrained – "just some type"
interface I { /*…*/ }; // constrained – is-an interface
```

So we propose that a concept also be allowed to replace `class` here with the meaning of checking that the complete type must satisfy the concept:

```
Sequence  S { /*…*/ }; // constrained – requires Sequence<S>
```

Note Casey Carter has asked for this feature in the past, and reports that this capability would be used widely in the Ranges TS implementation.

There is currently no way to enforce these conditions for specializations of a template. Here is the essence of the problem:

```
template<typename T>
struct S {
    // ...
    static_assert(Regular<S>);   // always fails, S is incomplete
};

static_assert(Regular<S<???>>);  // what goes in ???
```

The above proposal provides a way to express an annotation in `S` that can be extracted and applied after instantiation:

```
template<typename T>
Regular S {
    // ...
};
```

Alternatively, writing an explicit `requires` is useful in combination with conditional compile-time programming. For example:

```
template<typename T>
struct vector {

    // ...

    constexpr {
        if (Copyable<T>)
            compiler.require(Copyable<vector>,
               "if T is Copyable, then vector<T> is also Copyable");
    }
};
```

However, note that this is just a requirement check; it does not make `vector` model `Copyable`. This is a minor extension of modern Concepts TS concepts; it is not moving towards C++0x concepts, Haskell typeclasses, Rust traits, etc. by injecting anything into the class.

3 Library: Example metaclasses

This section shows how to use metaclasses to define powerful abstractions as libraries, often only in a few lines, without loss of efficiency, expressiveness, usability, diagnostics, or debuggability compared to languages that support them as language features baked into their compilers.

This paper proposes considering the following subset as `std::` standard libraries:

- `interface`, an abstract base `class` with all public virtual functions and no copy/move or data members;
- `base_class`, a `class` designed to be inherited from with no copy/move or data members;
- `ordered` et al., each a `class` that supports a comparison category (e.g., total ordering, equality comparison);
- `value`, a `class` that is a "regular" type with default construction, destruction, copy/move, and comparison (memberwise by default), and no virtual functions or protected members;
- `plain_struct` (what we usually mean when we write "struct"), and `flag_enum`.

3.1 `interface`

"… an abstract base class defines an interface…"—Stroustrup (D&E § 12.3.1)

An `interface` is a `class` where all functions are public and pure virtual, both by requirement and by default, and there is a virtual destructor and no data or copying. The definition is as we saw earlier.

```
constexpr void interface(meta::type target, const meta::type source) {
    compiler.require(source.variables().empty(), "interfaces may not contain data");
    for (auto f : source.functions()) {
        compiler.require(!f.is_copy() && !f.is_move(),
            "interfaces may not copy or move; consider a virtual clone() instead");
        if (!f.has_access()) f.make_public();
        compiler.require(f.is_public(), "interface functions must be public");
        f.make_pure_virtual();
        ->(target) f;
    }
    ->(target) { virtual ~(source.name()$)() noexcept {} }
}
```

We can then use this to define classes, including to use access/virtual defaults and enforce rules:

```
interface Shape {
    int area() const;
    void scale_by(double factor);
    // int x;                     // would be error, no data allowed
    // private: void g();         // would be error, no private functions allowed
    // Shape(const Shape&);   // would be error, no copying allowed
};
```

In this interface, `area` and `scale_by` are implicitly public and pure virtual because nothing else is allowed. Trying to make a function explicitly public or virtual would be fine but redundant. Trying to make a function explicitly nonpublic or nonvirtual would be an error, as would adding copy/move functions or data members.

3.2 base_class

A pure base_class is a class that has no instance data, is not copyable, and whose a destructor is either public and virtual or protected and nonvirtual. Unlike an interface, it can have nonpublic and nonvirtual functions. Also, implemented interfaces are public by default.

```
constexpr void base_class(meta::type target, const meta::type source) {
    for (auto f : source.functions()) {
        if (f.is_destructor() &&
            !((f.is_public() && f.is_virtual())
              || (f.is_protected() && !f.is_virtual())))
            compiler.error("base class destructors must be public and"
                           " virtual, or protected and nonvirtual");
        compiler.require(!f.is_copy() && !f.is_move()),
            "base classes may not copy or move; consider a virtual clone() instead");
        if (!f.has_access()) f.make_public();
        ->(target) f;
    }
    for (auto b : source.bases()) {
        if (!b.has_access()) b.make_public();
        ->(target) b;
    }
    compiler.require(source.variables().empty(), "pure base classes may not contain data");
}
```

These can be used to write types that match that metaclass:

```
base_class Rectangle : Shape {
    int  area() const override { /*...*/ }
    void scale_by(double factor) override { /*...*/ }
};
```

3.3 final

A final type is a class that cannot be further included in another type (aka derived from).

```
constexpr void final(meta::type target, const meta::type source) {
    for (auto m : source.members_and_bases())
        ->(target) m;
    target.can_derive = false;             // can’t derive from this
}
```

For example:

```
final circle : shape {
    override void draw(canvas& c) { /*...*/ }
};
```

3.4 ordered

Notes Up to this point, we have only used metaclasses (a) to apply defaults to declared functions and variables, and (b) to enforce requirements. Now we're going to take another step: additionally using them to implement custom default-generated functions. C++17 already does this for the special member functions; the difference here is that no functions are "special" (this works for any function we want to both require to exist and generate a suitable default implementation for) and it's not hardwired into the language.

In this section and the next, we'll cover the most familiar generated functions—default construction, copy construction, copy assignment, move construction, and move assignment—and comparisons which is where we'll begin.

For simpler exposition, this section assumes that all comparisons are done using C++20 `<=>`. A production implementation would also look for types that have user-written two-way comparisons, either instead of or in addition to `<=>`.

A totally `ordered` type is a `class` that requires operator`<=>` that returns `std::strong_ordering`. If the function is not user-written, a lexicographical memberwise implementation is generated by default. In this example, we detect the function using a concepts requires clause.

```
constexpr void ordered(meta::type target, const meta::type source) {

    if (! requires(ordered a) { a <=> a; })
        ->(target) { std::strong_ordering operator<=>(const ordered&) const = default; }

}
```

Note We could call this metaclass function `strong_ordered`, but I prefer to give the nicest prefix-free name to the common case. The same applies to (strong) `equal` below.

The author of a totally ordered type can just apply `ordered` to get all comparisons with memberwise semantics:

```
// using ordered (but prefer "value", see §3.5 -- this is for illustration)
ordered Point { int x; int y; /*copying etc. */ };      // no user-written comparison

Point p1{0,0}, p2{1,1};
assert (p1 == p1);                  // ok, == works
assert (p1 != p2);                  // ok, != works

set<Point> s;                       // ok, less<> works
s.insert({1,2});                    // ok, < works
```

Similarly, we provide the other four:

```
constexpr void weakly_ordered(meta::type target, const meta::type source) {

    if (! requires(source$ a) { a <=> a; })
        ->(target) { std::weak_ordering operator<=>(const ordered&) const = default; }

}

constexpr void partially_ordered(meta::type target, const meta::type source) {

    if (! requires(source$ a) { a <=> a; })
        ->(target) { std::partial_ordering operator<=>(const ordered&) const = default; }
```

```
}

constexpr void equal(meta::type target, const meta::type source) {
    if (! requires(source$ a) { a <=> a; })
        ->(target) { std::strong_equality operator<=>(const ordered&) const = default; }
}

constexpr void weakly_qual(meta::type target, const meta::type source) {
    if (! requires(source$ a) { a <=> a; })
        ->(target) { std::weak_equality operator<=>(const ordered&) const = default; }
}
```

However, most code will use metaclass functions like `ordered` indirectly because they are useful reusable pieces of stronger metaclass concepts. Which brings us to **`value`**, an important workhorse…

3.5 `value` types (regular types)

A `value` is a `class` that is a regular type. It must have all public default construction, copy/move construction/assignment, and destruction, all of which are generated by default if not user-written; and it must not have any protected or virtual functions (including the destructor).

`basic_value` carries the common defaults and constraints that apply to regular value types:

```
constexpr void basic_value(meta::type target, const meta::type source) {
    for (auto m : source.members_and_bases())
        ->(target) m;

    if (find_if(source.functions(), [](auto x){ return x.is_default_ctor(); }) != source.functions().end())
        ->(target) { source.name()$() = default; }

    if (find_if(source.functions(), [](auto x){ return x.is_copy_ctor(); }) != source.functions().end())
        ->(target) { source.name()$ (const source.name()$& that) = default; }

    if (find_if(source.functions(), [](auto x){ return x.is_move_ctor(); }) != source.functions.end())
        ->(target) { source.name()$ (source.name()$&& that) = default; }

    if (find_if(source.functions(), [](auto x){ return x.is_copy_assignment(); }) != source.functions.end())
        ->(target) { source.name()$& operator=(const source.name()$& that) = default; }

    if (find_if(source.functions(), [](auto x){ return x.is_move_assignment(); }) != source.functions.end())
        ->(target) { source.name()$& operator=( source.name()$ && that) = default; }

    for (auto f : source.functions()) {
        compiler.require(!f.is_protected() && !f.is_virtual(),
                         "a value type must not have a protected or virtual function");
        compiler.require(!f.is_destructor() || !f.is_public()), "a value type must have a public destructor");
    }
}
```

A `value` is a totally ordered `basic_value`:

```
constexpr void value(meta::type target, const meta::type source) {
```

```
    ordered(target, source);
    basic_value(target, source);
}
```

Now we can use `value` to have this meaning strictly. To write a type that self-documents this intent, we can write for example:

```
value Point {
    int x, y;                           // implicitly private
    void translate(int dx, int dy);     // implicitly public

    // virtual void f();                // would be an error
    // private: Point(const Point&);    // would be an error
};

Point p1;                               // ok, default construction works
Point p2 = p1;                          // ok, copy construction works

assert (p1 == p1);                      // ok, == works
assert (p1 >= p2);                      // ok, >= works

set<Point> s;                           // ok, less<> works
s.insert({1,2});
```

And similarly we can provide the other four convenience names:

```
constexpr void weakly_ordered_value(meta::type target, const meta::type source) {
    weakly_ordered(target, source);
    basic_value(target, source);
}

constexpr void partially_ordered_value(meta::type target, const meta::type source) {
    partially_ordered(target, source);
    basic_value(target, source);
}

constexpr void equal_value(meta::type target, const meta::type source) {
    equal(target, source);
    basic_value(target, source);
}

constexpr void weakly_ordered_value(meta::type target, const meta::type source) {
    weakly_equal(target, source);
    basic_value(target, source);
}
```

Note Again, I like to give the nice name (`value`) to the default that should be encouraged. If someone is trying to author a `partially_ordered_value` type, the metaclass still makes that simple (they only need to write that one word) but the uglier name is also visible and harder to write by accident.

3.6 plain_struct

"By definition, a `struct` is a class in which members are by default public; that is,

`struct s { …`   is simply shorthand for   `class s { public: …`

*… Which style you use depends on circumstances and taste. **I usually prefer to use `struct` for classes that have all data public.**" — B. Stroustrup (C++PL3e, p. 234)*

A `plain_struct` is a `basic_value` with only public bases, objects, and functions, no virtual functions, and no user-defined constructors (i.e., no invariants) or assignment or destructors.

```
constexpr void plain_struct(meta::type target, const meta::type source) {
    basic_value(target, source);            // a plain_struct is-a basic_value

    for (auto f : src.functions()) {
        compiler.require(f.is_public() && !f.is_virtual(),
                         "a plain_struct function must be public and nonvirtual");

        compiler.require(!(f.is_constructor() || f.is_destructor()
                              || f.is_copy() || f.is_move())
                           || f.is_defaulted(),
                         "a plain_struct can't have a user-defined "
                         "constructor, destructor, or copy/move");
        ->(target) f;
    }

    for (auto o : src.variables()) {
        if (!o.has_access()) o.make_public();
        compiler.require(o.is_public(), "plain_struct members must be public");
        ->(target) o;
    }

    for (auto b : src.bases()) {
        if (!b.has_access()) b.make_public();
        compiler.require(b.is_public(), "plain_struct base classes must be public");
        ->(target) b;
    }
}
```

Now we can use `plain_struct` to have this meaning strictly, without relying on it being just a personal convention. To write a type that self-documents this intent, we can write for example:

```
plain_struct mydata {
    int i;                          // implicitly public
    string s;

    // virtual void f();            // would be an error
    // mydata(const mydata&);       // would be an error
};

mydata a, b, c;                     // ok, because values are default-constructible

if (a == b && c > a) { }            // ok, ordered because all members are ordered
```

3.7 copyable_pointer

A `copyable_pointer` is a `value` that has at least one type parameter and overloads `*` to return an lvalue of that parameter and `->` to return a pointer to that parameter.

```
template<class T>
constexpr void copyable_pointer(meta::type target, const meta::type source) {

    value(target, source);                  // a copyable_pointer is-a value

    ->(target) {
        T.name()$& operator* () const;      // require * and -> operators
        T.name()$* operator->() const;
    }
}
```

Now we can use `copyable_pointer` both to tell if a type is a smart pointer, and to write new smart pointers.

```
static_assert ($shared_ptr<widget>.type.is(copyable_pointer<widget>));

copyable_pointer<gadget> my_ptr {
    // ... can't forget to write copying and both indirection operators ...
};
```

3.8 enum_class and flag_enum

"C enumerations constitute a curiously half-baked concept. … the cleanest way out was to deem each enumeration a separate type."—[Stroustrup, D&E §11.7]

"An enumeration is a distinct type (3.9.2) with named constants"—[ISO C++ standard]

An `enum_class` is a totally ordered `value` type that stores a value of its enumerators's type, and otherwise has only public member variables of its enumerators's type, all of which are naturally scoped because they are members of a type.

```
constexpr void basic_enum(meta::type target, const meta::type source) {

    value(target, source);                  // a basic_enum is-a value

    compiler.require(source.variables().size() > 0, "an enum cannot be empty");
    if (src.variables().front().type().is_auto())
         ->(target) { using U = int; }       // underlying type
    else ->(target) { using U = (src.variables().front().type())$; }

    for (auto o : source.variables()) {
        if (!o.has_access())   o.make_public();
        if (!o.has_storage())  o.make_constexpr();
        if (o.has_auto_type()) o.set_type(U);
        compiler.require(o.is_public(),    "enumerators must be public");
        compiler.require(o.is_constexpr(), "enumerators must be constexpr");
        compiler.require(o.type() == U,    "enumerators must use same type");
        ->(target) o;
    }

    ->(target) {
```

```
        U value;                    // the instance value
    }

    compiler.require(source.functions().empty(), "enumerations must not have functions");
    compiler.require(source.bases().empty(), "enumerations must not have base classes");
}
```

Note A common request is to be able to get string names of enums (e.g., [StackOverflow example]). It is tempting to provide that as a function on `basic_enum` that is always available, which would be easy to provide. But we must not violate C++'s zero-overhead principle by imposing overhead (here in the object/executable image) by default on programs that don't use it. Making this available always or by default, such as automatically generating string names for the members of a `basic_enum`, would be a step down the slippery slope toward always-on/default-on run-time metadata.

However, making it opt-in would be fine. One way would be have a specific metaclass that adds the desired information. A better way would be to write a general constrained function template:

```
template<basic_enum E>        // constrained to enum types
std::string to_string(E e) {
    switch (value) {
        constexpr {
            for (const auto o : $E.variables())
                if (!o.default_value.empty())
                    -> { case o.default_value()$: return std::string(o.name()$); }
        }
    }
}
```

Because templates are only instantiated when used, this way the information is generated (a) on demand at compile time, (b) only in the calling code (and only those calling programs) that actually use it, and (c) only for those enum types for which it is actually used.

There are two common uses of enumerations. First, `enum` expresses an enumeration that stores exactly one of the enumerators. The enumerators can have any distinct values; if the first enumerator does not provide a value, its value defaults to `0`; any subsequent enumerator that does not provide a value, its value defaults to the previous enumerator's value plus `1`. Multiple enumerators can have the same value.

```
constexpr void enum_class(meta::type target, const meta::type source) {

    meta::type src;
    basic_enum(src, source);                    // an enum is-a basic_enum

    src.type("U")$ next_value = 0;
    for (auto o : src.variables()) {
        if (o.is_constexpr() && !o.has_default_value())
            o.set_default_value(next_value);
        next_value = o.get_default_value()++;
        ->(target) o;
    }

}
```

Here is a `state` enumeration that starts at value `1` and counts up:

```
enum_class state {
    auto started = 1, waiting, stopped;          // type is int
};

state s = state::started;
while (s != state::waiting) {
    // ...
}
```

Here is a different enumeration using a different value type and setting some values while using incremented values where those are useful:

```
enum_class skat_games {
    char diamonds = 9, hearts /*10*/, spades /*11*/, clubs /*12*/, grand = 24;
};
```

Second, `flag_enum` expresses an enumeration that stores values corresponding to bitwise-or'd enumerators. The enumerators must be powers of two, and are automatically generated; explicit values are not allowed. A `none` value is provided, with an explicit conversion to `bool` as a convenience test for "not none." Operators `|` and `&` are provided to combine and extract values.

```
constexpr void flag_enum(meta::type target, const meta::type source) {

    meta::type src;
    basic_enum(src, source);                        // an enum is-a basic_enum

    src.type("U")$ next_value = 1;                  // generate powers-of-two values
    compiler.require(src.objects.size() <= 8*sizeof(next_value),
                     "there are " + src.objects.size() + " enumerators but only room for " +
                     to_string(8*sizeof(next_value)) + " bits in the underlying type";
    compiler.require(!numeric_limits<U>.is_signed,
                     "a flag_enum value type must be unsigned");

    for (auto o : src.variables()) {
        compiler.require(o.is_constexpr() && !o.has_default_value(),
            "flag_enum enumerator values are generated and cannot be specified explicitly");
        o.set_default_value(next_value);
        next_value *= 2;
        ->(target) o;
    }

    ->(target) {
        source.name()$  operator&  (const source.name()$& that) { return value & that.value; }
        source.name()$& operator&= (const source.name()$& that) { value &= that.value; return *this; }
        source.name()$  operator|  (const source.name()$& that) { return value | that.value; }
        source.name()$& operator|= (const source.name()$& that) { value |= that.value; return *this; }
        source.name()$  operator^  (const source.name()$& that) { return value ^ that.value; }
        source.name()$& operator^= (const source.name()$& that) { value ^= that.value; return *this; }

        source.name()$()         { value  = none; }      // default initialization
        explicit operator bool() { value != none; }      // test against no-flags-set
```

```
        U none = 0;
    }
}
```

Here is an `ios_mode` enumeration that starts at value `1` and increments by powers of two:

```
flag_enum openmode {
    auto in, out, binary, ate, app, trunc;        // values 1 2 4 8 16 32
};

openmode mode = openmode::in | openmode::out;
assert (mode != openmode::none);
assert (mode & openmode::out);                    // exercise explicit conversion to bool
```

Note There is a recurring need for a "flag enum" type, and writing it in C++17 is awkward. After I wrote this implementation, [Overload 132](https://accu.org/index.php/journals/c358) (April 2016) came out with Anthony Williams's article on "Using Enum Classes as Bitfields." That is a high-quality C++17 library implementation, and illustrates the limitations of authoring not-the-usual-class types in C++: Compared to this approach, the C++17 design is harder to implement because it relies on TMP and SFINAE; it is harder to use because it requires flag-enum type authors to opt into a common trait to enable bitmask operations; and it is more brittle because the flag-enum type authors must still set the bitmask values manually instead of having them be generated. In C++17, there is therefore a compelling argument to add this type because of its repeated rediscovery and usefulness—but to be robust and usable it would need to be added to the core language, with all of the core language integration and wordsmithing that implies including to account for feature interactions and cross-referencing; in a future C++ that had the capabilities in this proposal, it could be added as a small library with no interactions and no language wording.

3.9 bitfield

A `bitfield` is a value that allows treating a sequence of contiguous bits as a sequence of values of trivially copyable types. Each value can be get or set by copy, which the implementation reads from or writes to the value bits. To signify padding bits, set the type to `void` or leave the name empty. It supports equality comparison.

Note Also, treating a bitfield as an object is truer to the C++ memory model. The core language already says (though in standardese English) that a sequence of bitfield variables is treated as a single object for memory model purposes. That special case falls out naturally when we model a sequence of bits containing multiple values as a single object.

To guide the design, let's start with a target use case. A `bitfield` metaclass function could pass each member's size as an attribute (e.g., `int member [[3]];`), but since we already have the bitfield-specific C grammar available, let's use it:

```
bitfield game_stats {
    int      score_difference : 3;
    void     _                : 2;   // padding
    unsigned counter          : 6;
} example;
```

Note Up to this point, we've seen (a) applying defaults, (b) enforcing requirements, (c) combining metaclasses, (d) reflecting on members and computing characteristics such as selectively combining metaclasses, and (e) generating additional data members. Now we'll go further and not just generate new data members, but actually remove the existing declared data members and replace them.

Here is the code:

```
constexpr void bitfield(meta::type target, const meta::type source) {
    final(target, source);                      // no derivation
    value(target, source);                      // copyable, ordered

    auto objects = source.variables();          // take a copy of the class's objects
    size_t size  = 0;                           // first, calculate the required size

    for (auto o : objects) {
        size += (o.bit_length == default ? o.type.size*CHAR_BITS : o.bit_length;

        if (!o.has_storage()) o.make_member();
        compiler.require(o.is_member(), "bitfield members must not be static");

        compiler.require(is_trivially_copyable_v<o.T>,
            "bitfield members must be trivially copyable");

        compiler.require(!(o.name() == "_") || o.T == $void,
            "anonymous _ bitfield members must have type void");

        compiler.require(o.type != $void || o.name() == "_",
            "void bitfield members must have anonymous name _");

        if (o.type != $void) ->(target) {  // generate accessors for non-empty members
            o.T$ o.name$ () { return /*bits of this member cast to T*/; }
            set_(o.name)$(const o.T$& val) { /*bits of this value*/ = val; }
        }
    }

    ->(target) {

        byte data[ (size/CHAR_BITS)+1 ]; } // allocate that much storage

        bitfield() {                       // default ctor inits non-pad members
            constexpr {
                for (auto o : objects)
                    if (o.type != $void)
                        -> { /*set bits of each value to its default value*/ };
            }
        }

        ~bitfield() {                      // cleanup goes here
            constexpr {
                for (auto o : objects)
                    if (o.type != $void)
                        -> { o.name$.~(o.type.name$)(); }
            }
        }
```

```
        bitfield(const bitfield& that) : bitfield() {   // copy constructor
            *this = that;                  // just delegate to default ctor + copy =
        } // you could also directly init each member by generating a mem-init-list

        bitfield& operator=(const bitfield& that) {     // copy assignment operator
            constexpr {
                for (auto o : objects)                  // copy each non-pad member
                    if (o.type != $void)                // via its accessor
                        -> { set_(o.name$)( that.(o.name)$() ); }
            }
        }

        auto operator<=>(const bitfield& that) const = default;
    }
}
```

For example, this bitfield fits in two bytes, and holds two integers separated by two bits of padding:

```
bitfield game_stats {
    int      score_difference : 3;
    void     _                : 2;  // padding
    unsigned counter          : 6;
} example;

example.set_score_difference(-3);   // sadly, the home team is behind
unsigned val = example.counter();   // read value back out
```

Note that in computing the size, the metaclass defaults to the natural size if the number of bits is not explicitly specified. For example, the following two are the same on systems where `int` is 32 bits:

```
bitfield sample { char c : 7;  int i : 32; };

bitfield sample { char c : 7;  int i; };
```

And here is a 7-bit character as an anonymous `bitfield` type:

```
bitfield { char value : 7 } char_7;

char_7.set_value('a');
```

Of course, if we can transform the declared members to lay them out successively, we could also transform the declared members to overlap them in suitably aligned storage, which brings us to `Union` with similar code…

Note Unlike C and C++17, special language support is not necessary, packing is guaranteed, and because a value's bits are not exposed there is no need to specially ban attempting to take its address.

When adding the concurrency memory model to C++11, we realized that we had to invent a language rule that "a set of contiguous bitfields is treated as one object" for the purposes of the machine memory model. That doesn't need saying here; contiguous bitfield values *are* one object naturally. Further, in C++11 we had to add the wart of a special "`:0`" syntax to demarcate a division in a series of bitfields to denote that this was the location to start a new byte and break a series of successive bitfields into groups each so that each group could be treated as its own object in the memory model. Again, that doesn't need saying here; each `bitfield` variable is already an object, so if you want two groups of them to be two objects, just do that: Use two `bitfield` objects.

3.10 safe_union

A safe_union is a class where at most one data member is active at a time, and let's just say equality comparison is supported. The metaclass demonstrates how to replace the declared data members with an active discriminant and a data buffer of sufficient size and alignment to store any of the types. There is no restriction on the number or types of members, except that the type must be copy constructible and copy assignable.

For simpler exposition only (not as a statement on how a variant type should behave), this sample safe_union follows the model of having a default empty state and the semantics that if setting the union to a different type throws then the state is empty. A safe_union with exactly the C++17 std::variant semantics is equally implementable.

```
constexpr void safe_union(meta::type target, const meta::type source) {
    final(target, source);                            // no derivation
    value(target, source);                            // copyable, ordered

    size_t size  = 1;                                 // first, calculate the required size
    size_t align = 1;                                 //   and alignment for the data buffer
    for (auto o : source.variables()) {
        size  = max(size,  sizeof (o.type));
        align = max(align, alignof(o.type));
        if (o.storage.has_default()) o.make_member();

        compiler.require(o.is_member(), "safe_union members must not be static");
        compiler.require(is_copy_constructible_v<o.type$> && is_copy_assignable_v<o.type$>,
            "safe_union members must be copy constructible and copy assignable");
        }

        ->(target){ alignas(align) byte data[size]; } // inject buffer instead of vars
    }

    ->(target) {

        int active;                                   //   and a discriminant

        safe_union() { active = 0; }                  // default constructor

        void clear() {                                // cleanup goes here
            switch (active) {
                constexpr {
                    for (auto o : source.variables()) // destroy the active object
                        -> { case o.num$: o.name$.~(o.type.name$)(); }
            }
            active = 0;
        }

        ~safe_union() { clear(); }            // destructor just invokes cleanup

        safe_union(const safe_union& that)    // copy construction
            : active{that.active}
        {
            switch (that.active) {
                constexpr {
```

```
                for (auto o : objects)    // just copy the active member
                    -> { case o.num$: o.name$() = that.(o.name)$(); }
            }                             // via its accessor, defined next below
        }
    }

    safe_union& operator=(const safe_union& that) {     // copy assignment
        clear();                          // to keep the code simple for now,
        active = that.active;             //   destroy-and-construct even if the
        switch (that.active) {            //   same member is active
            constexpr {
                for (auto o : objects)    // just copy the active member
                    -> { case o.num$: o.name$() = that.(o.name)$(); }
            }                             // via its accessor, defined next below
        }
    }

}

for (auto o : source.variables()) ->(target) {   // for each original member

    auto o.name$() {                      // generate an accessor function
        assert (active==o.num);           // assert that the member is active
        return (o.type$&)data;
    }                                     // and cast data to the appropriate type&

    void operator=(o.type$ value){        // generate a value-set function
        if (active==o.num)
            o.name$() = value;            // if the member is active, just set it
        else {
            clear();                      // otherwise, clean up the active member
            active = o.num;               //   and construct a new one
            try { new (&data[0]) o.type.name$(value); }
            catch { active = 0; }         // failure to construct implies empty
        }
    }

    bool is_(o.name)$() {                 // generate an is-active query function
        return (active==o.num);
    }

}

->(target) {

    auto operator<=>(const safe_union& that) const {
                                          // (we'll get != from 'comparable_value')
        if (active != that.active)        // different active members => not equal
            return std::not_equal;
        if (active == 0)                  // both empty => equal
            return std::equal;
        switch (that.active) {
            constexpr {
```

```
                    for (auto o : objects)    // else just compare the active member
                        -> { case o.num$: return o.name$() <=> that.(o.name)$(); }
                }
            }
        }
        bool is_empty() { return active == 0; }
    }
}
```

Here is code that defines and uses a sample `safe_union`. The usage syntax is identical to C and C++17.

```
safe_union U {
    int i;
    string s;
    map<string, vector<document>> document_map;
};
```

Notes I would be interested in expressing `variant` in this syntax, because I think it's better than writing `variant<int, string, map<string, vector<document>>>` for several reasons, including:

it's easier to read, using the same syntax as built-in unions;

we can give `U` a type that is distinct from the type of other unions even if their members are of the same type;

we get to give nice names to the members, including to access them (instead of `get<0>`).

That we can implement `union` as a library and even get the same union definition syntax for members is only possible because of Dennis Ritchie's consistent design choice: When he designed C, he wisely used the same syntax for writing the members of a `struct` and a `union`. He could instead have gratuitously used a different syntax just because they were (then) different things, but he didn't, and we continue to benefit from that design consistency. Thanks again, Dr. Ritchie.

```
U u;

u = "xyzzy";                              // constructs a string
assert (u.is_s());
cout << u.s() << endl;                    // ok
```

Note I love today's `std::variant`, but I wouldn't miss writing the anonymous and pointy `get<0>`.

```
u = map<string, vector<document>>;        // destroys string, moves in map
assert (u.is_document_map());
use(u.document_map());                    // ok

u.clear();                                        // destroys the map
assert (u.is_empty());
```

3.11 namespace_class

"In this respect, namespaces behave exactly like classes."—[Stroustrup, D&E §17.4.2]

"It has been suggested that a namespace should be a kind of class. I don't think that is a good idea because many class facilities exist exclusively to support the notion of a class being a user-defined type. For example, facilities for defining the creation and manipulation of objects of that type has little to do with scope issues. The opposite, that a class is a kind of namespace, seems almost obviously true. A class is a namespace in the sense that all operations supported for namespaces can be applied with the same meaning to a class unless the operation is explicitly prohibited for classes. This implies simplicity and generality, while minimizing implementation effort."—[Stroustrup, D&E §17.5]

"Functions not intended for use by applications are in boost::math::detail."—[Boost.Math]

A `namespace_class` is a `class` with only static members, and `static public` members by default.

First, let's define a separately useful `reopenable` metaclass – any type that does not define nonstatic data members can be treated as incomplete and reopenable so that a subsequent declaration can add new members:

```
constexpr void reopenable(meta::type target, const meta::type source) {
    compiler.require(source.member_variables().empty(),
                     "a reopenable type cannot have member variables");
    target.make_reopenable();
};
```

A `namespace_class` is `reopenable`:

```
constexpr void namespace_class(meta::type target, const meta::type source) {

    reopenable(target, source);

    for (auto m : $reopenable.members()) {
        if (!m.has_access ()) m.make_public();
        if (!m.has_storage()) m.make_static();
        compiler.require(m.is_static(), "namespace_class members must be static");
    }
};
```

These can be used to write types that match that metaclass. Using Boost's Math library as an example:

<table>
<tr><th>C++17 style</th><th>Using a metaclass</th></tr>
<tr><td>
<pre>
namespace boost {
namespace math {

    // public contents of boost::math

    namespace detail {
    // implementation details of boost::math
    // go here; function call chains go in/out
    // of this nested namespace, and calls to
    // detail:: must be using'd or qualified
    }
}
}
</pre>
</td><td>
<pre>
namespace_class boost {
namespace_class math {

    // public contents of boost::math

private:
    // implementation details of boost::math
    // go here and can be called normally
};
};
</pre>
</td></tr>
</table>

Notes In C++11, we wanted to add a more class-like `enum` into the language, and called it `enum class`. This has been a success, and we encourage people to use it. Now we have an opportunity to give a similar upgrade to namespaces, but this time without having to hardwire a new `enum class`-like type into the core language and plumb it through the core standardese.

This implementation of the `namespace` concept applies generality to enable greater expressiveness without loss of functionality or usability. Note that this intentionally allows a `namespace_class` to naturally have `private` members, which can replace today's hand-coded `namespace detail` idiom.

4 Applying metaclasses: Qt moc and C++/WinRT

Today, C++ framework vendors are forced resort to language extensions that require side compilers/languages and/or extended C++ compilers/languages (in essence, tightly or loosely integrated code generators) only because C++ cannot express everything they need. Some prominent current examples are:

- **Qt moc (meta-object compiler) (see Figure 1):** One of Qt's most common FAQs is "why do you have a meta-object compiler instead of just using C++?" [2] This issue is contentious and divisive; it has caused spawning forks like CopperSpice and creating projects like Verdigris, which are largely motivated by trying to eliminating the moc extensions and compiler (Verdigris was created by the Qt moc maintainer).
- **Multiple attempts at Windows COM or WinRT bindings, lately C++/CX (of which I led the design) and its in-progress replacement C++/WinRT (see Figures 2 and 3):** The most common FAQ about C++/CX was "why all these language extensions instead of just using C++?" [3] Again the issue is contentious and divisive: C++/WinRT exists because its designer disliked C++/CX's reliance on language extensions and set out to show it could be done as just a C++ library; he created an approach that works for consuming WinRT types, but still has to resort to extensions to be able to express (author) the types, only the extensions are in a separate .IDL file instead of inline in the C++ source.

The side/extended languages and compilers exist to express things that C++ cannot express sufficiently today:

- Qt has to express **signals/slots**, **properties**, and **run-time metadata** baked into the executable.
- C++/CX and C++/WinRT has to express **delegates/events**, **properties**, and **run-time metadata** in a separate .winmd file.

Note The C++ static reflection proposal by itself helps the run-time metadata issue, but not the others. For example, see "Can Qt's moc be replaced by C++ reflection?" in 2014 by the Qt moc maintainer.

There are two aspects, illustrated in Figures 1-3:

- **Side/extended language:** The extra information has to go into source code somewhere. The two main choices are: (1) Nonportable extensions in the C++ source code; this is what Qt and C++/CX do, using macros and compiler extensions respectively. (2) A side language and source file, which requires a more complex build model with a second compiler and requires users to maintain parallel source files consistently (by writing in the extended language as the primarily language and generating C++ code, or by hand synchronization); this is what classic COM and C++/WinRT do.
- **Side/extended compiler:** The extra processing has to go into a compiler somewhere. The same choices are: (1) Put it in nonportable extensions in each C++ compiler; this is what C++/CX does. (2) Put it in a side compiler and use a more complex build model; this is what Qt and classic COM and C++/WinRT do.

---

[2] The Qt site devotes multiple pages to this. For example, see:

- "Moc myths debunked / … you are not writing real C++"
- "Why Does Qt Use Moc for Signals and Slots"
- "Why Doesn't Qt Use Templates for Signals and Slots?"
- "Can Qt's moc be replaced by C++ reflection?"

[3] C++/CX ended up largely following the design of C++/CLI, not by intention (in fact, we consciously tried not to follow it) but because both had very similar design constraints and forces in their bindings to COM and .NET respectively, which led to similar design solutions. We would have loved nothing better than to do it all in C++, but could not. Still, the "all these language extensions" issue with C++/CLI was contentious enough that I had to write "A Design Rationale for C++/CLI" in 2006 to document the rationale, which is about the C++/CLI binding to CLI (.NET) but applies essentially point-for-point to the C++/CX binding to COM and WinRT.

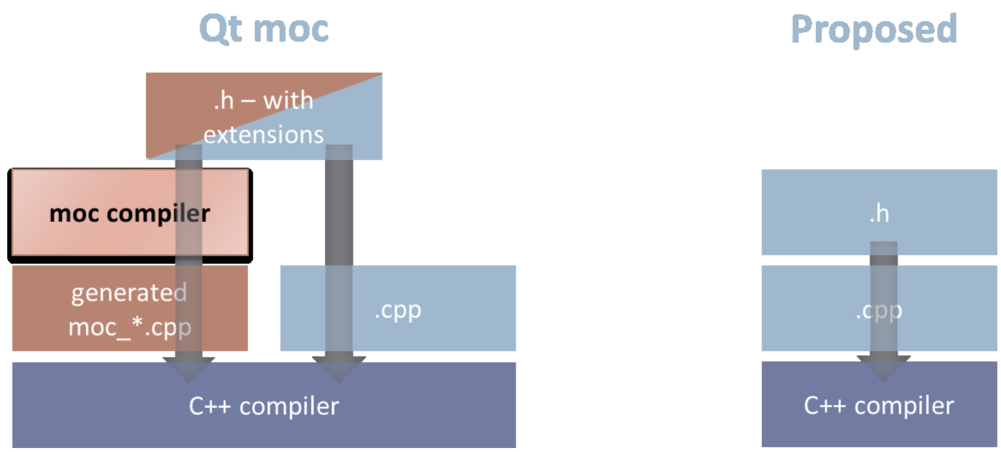


*Figure 2: Qt **extended** language + **side** compiler – build model vs. this proposal*

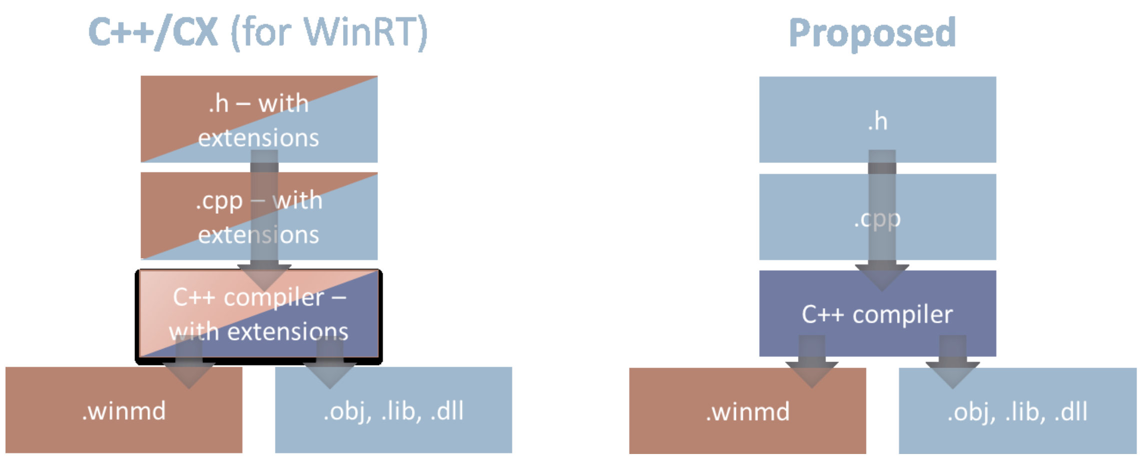


*Figure 3: C++/CX **extended** language + **extended** compiler – build model vs. this proposal*

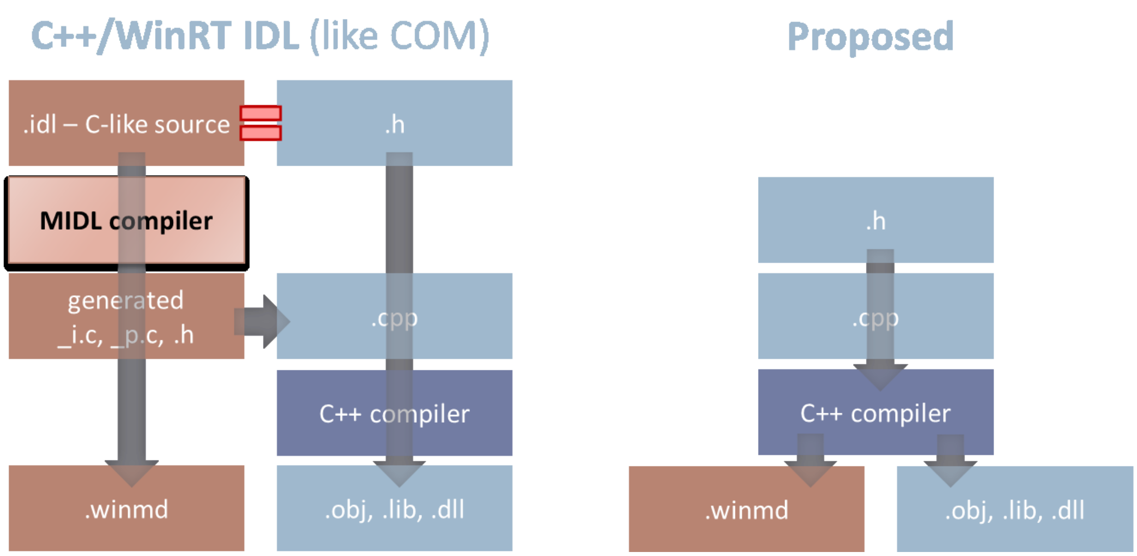


*Figure 4: C++/WinRT **side** language + **side** compiler – build model vs. this proposal*

4.1 Qt moc → metaclasses (sketch)

This section sketches an approach for how Qt moc could be implemented in terms of metaclass functions.

The approach centers on writing metaclasses to encapsulate Qt conventions. In particular:

Feature	Qt moc style	Proposed
Qt class	`: public QObject` `Q_OBJECT` macro	`QClass` metaclass
Signals and slots	`signals:` access specifier `slots:` access specifier Both are grammar extensions	`qt::signal` type `qt::slot` type No grammar extensions
Properties	`Q_PROPERTY` macro	`property<>` metaclass (note: not necessarily specific to Qt)
Metadata	Generated by moc compiler	Generated in `QClass` metaclass code, or separately by reflection

Consider this example, which uses a simple property for which it's easy to provide a default (as do C# and other languages), and a simple signal (outbound event notification) and slot (inbound event notification):

Qt moc style

```
class MyClass : public QObject {
    Q_OBJECT
public:
    MyClass( QObject* parent = 0 );
    Q_PROPERTY(int value READ get_value WRITE set_value)
    int  get_value() const { return value; }
    void set_value(int v)  { value = v; }
private:
    int value;
signals:
    void mySignal();
public slots:
    void mySlot();
};
```

This paper (proposed)

```
QClass MyClass {
    property<int> value { };
    signal mySignal();
    slot mySlot();
};
```

4.2 `QClass` metaclass function

`QClass` is a metaclass function that implements the following requirements and defaults:

- Implicitly inherits publicly from `QObject`.
- Generates a constructor that takes `QObject*` with a default value of `nullptr`.
- Performs all the processing currently performed by the `QOBJECT` macro.
- For each nested type declared `property<T>` (see below), "inline" the nested type by moving its data member(s) and function(s) into the scope of this class.

- For each function whose return type is `qt::signal<T>` (see below), change its return type to `T` and treat it as a signal function.
- For each function whose return type is `qt::slot<T>` (see below), change its return type to `T` and treat it as a slot function.
- Performs all the processing currently performed by the `Q_ENUMS` macro to every nested `enum` type.
- (etc. for other `Q_` macros)
- Apply any Qt class rules (e.g., on accessibility of signals and slots).

Note These techniques allow adding "language extensions" that don't change the C++ grammar:

(1) Using a well-known marker class type as a contextual keyword. By using a well-known type such as `signal` or `slot` as a marker type (for a variable, or a function parameter or return type), a metaclass like `QClass` can assign special semantics and processing to that type when it encounters it in the specially recognized position, essentially turning the type into a contextual keyword but without disturbing the C++ grammar. (The same can be done with variable and function names.)

(2) Using a well-known marker metaclass as a contextual keyword and abstraction. For `property`, we need a little more because it is intended to be an abstraction encapsulating multiple components. Because the C++ grammar already allows nested abstractions (classes), and we are now adding metaclasses, we can simply use a well-known metaclass such as `property` to define a nested class that represents the abstraction. (Processing that is reusable in other places the nested type's metaclass (e.g., `property`) is useful can be done inside that metaclass, and the combining or post-processing to integrate it into the enclosing `QClass` can be done in `QClass`.)

4.2.1 `signal` and `slot` types

The types `qt::signal` and `qt::slot` are ordinary empty types that do nothing on their own, but are used as markers recognized by the `QClass` metaclass.

```
template<class Ret = void> class signal { };

template<class Ret = void> class slot { };
```

These are templates because Qt has some support for non-`void` signal and slot return types. A non-`void` return type can be specified by the template parameter:

```
signal<int> mySignalThatReturnsInt();

slot<Priority> mySlotThatReturnsPriority();
```

Otherwise, a C++17 deduction guide offers nice default syntax without `< >` brackets, as in this section's example:

```
signal mySignal();              // signal<void>

slot mySlot();                  // signal<void>
```

Note Qt itself rarely makes use of non-`void` return types in signal-slot calls. However, slots can also be called like normal functions, so they can return values. For now I'll leave in this generality of using a template for the return type intact for both signals and slots as it helps to underscore the flexibility that is available with metaclasses; if the generality is not needed for signals, it's easily removed.

4.2.2 `property` metaclass function

A Qt "property" is modeled as a nested class defined using the metaclass template `qt::property`:

```
template<class T>
constexpr void property(meta::type target, const meta::type source) {
    // ...
};
```

This metaclass implements the following requirements and defaults (note: strawman that follows the published Qt rules):

- We recognize as a "get" any function that is `const` and returns `T` or `T const&`.
- We recognize as a "set" any function that is non-`const` and takes exactly one parameter of type `T`, `T&`, or `T const&`.
- We recognize as a "notify" any function declaration that is a `signal` function in the same class.
- Apply any other Qt property rules.

Note We could design a more general "property" that could be standardized and used both here and in the following C++/WinRT section. For now this just illustrating how to create a binding to Qt.

For convenience, an empty `property` that has no user-declared data member or functions:

```
property<T> xxx { };
```

generates the following if `T` is default-constructible:

- a data member named `xxx` of type `T`;
- a "get" function `T get_xxx() { return value; }`; and
- if `T` is not `const`, a "set" function `void set_xxx(const T& value) { xxx = value; }`;.

A property can have customizable contents, for example have a different internal type (if Qt allows this):

```
property<string> blob {
    DBQuery q;
    string get_blob() const          { return q.run("SELECT blob_field FROM /*...*/"); }
    void   set_blob(const string& s) { q.run("UPDATE blob_field /*... using s ...*/"); }
};
```

After the `property` metaclass has been run to define the property's data and functions as a nested class, the `QClass` metaclass then "inlines" the nested class into the main class so that its data and functions can be used normally by other class members and users.

Note The above shows how to support the basic `Q_PROPERTY` options of `MEMBER`, `READ`, and `WRITE`. To fully support `Q_PROPERTY` semantics, `qt::property` should also support the other options – `RESET`, `NOTIFY`, `DESIGNABLE`, etc.

4.2.3 Generating metadata

Finally, generating metadata is largely enabled by just the reflection proposal on its own, but aided in accuracy by metaclasses. Because we are going to automate Qt conventions using metaclasses such as `QClass`, the source code directly identifies exactly which types are Qt types.

- As each such type is defined by applying the metaclass, the metaclass's code can use reflection at the time each `QClass` is processed to generate compile-time data structures for metadata.

- Alternatively, a `generate_metadata` function could reflect over the whole program to identify and inspect Qt types and generate metadata only for those; that function can be built and invoked as a separate executable. This keeps the metadata generator code outside the metaclass code, if that is desirable.

In both cases, all processing is done inside the C++ program and C++ compiler.

5 Alternatives for source→definition transform syntax

This section explores some alternative ways to express the source→definition transformation. Note that the code within the metaclass is structurally the same under these alternatives. In this section:

- the *source class* (input) means the class as written by the user in source code interpreted without any special rules being applied, not even the usual rules for `class` and `struct` (e.g., the default accessibility of all members is "none," neither private nor public); and
- the *defined class* (output) means the class that is generated as a result of applying the metaclass's logic to the source class.

Note Any metaclass can still inject additional output classes, free functions, etc. under any option.

5.1 Class style, modify-in-place semantics (original R0)

Note Discouraged by SG7 at 2017.11 meeting (Albuquerque). For reference, this section is available in the R2 version of this paper.

5.2 Class style, read-only input semantics

Note Discouraged by SG7 at 2017.11 meeting (Albuquerque). For reference, this section is available in the R2 version of this paper.

5.3 Functional style, take `const meta::type` + return `meta::type`

Summary: Expressed as a compile-time function that returns a new `type` by value.

Semantics:

- The source is a read-only input parameter of type `meta::type`.
- The target generated class definition is a return value of type `meta::type`.
- Inside injection blocks in particular, we use `this_class` to refer to the name of the type itself, for example to mention the name as a function name for the special member functions, or as a parameter type.
- The code needs to inject each item into the target as it goes.
- `meta::type` parameters passed by value have reference semantics.

Drawbacks:

- Requires creating a local `meta::type target(source.name());` initialized with the source class's name string, and `return target;` at the end, as required boilerplate that should not be written differently by the user.
- Requires allowing assignment to "modify" a `meta::type`, for example `target = helper(target);`). This is slightly ugly because the interface of `meta::type` deliberately allows adding and replacing members, but not removing members (to avoid problems with dangling pointers into ASTs). We could still implement such a modifying assignment without the member removal problem, by under the covers actually creating a new type and assigning to that and abandoning the original, but this will cause litter of types in the implementation. We would prefer not to ask C++ compilers to implement litter collection for discarded intermediate types.

In this example, we build up a type in several steps, and have factored out some common reusable logic:

```
constexpr auto factored_helper_1(const meta::type source) {
    meta::type target(source.name());
    if (/*some characteristic about t*/) { /* do something to t */ }
    return target;
}
constexpr auto factored_helper_2(const meta::type source) {
    meta::type target(source.name());
    if (/*some characteristic about t*/) { /* do something to t */ }
    return target;
}
constexpr auto my_metaclass(const meta::type source) constexpr {
    meta::type target(source.name());
    // ...start building up target, using source ...
    target = factored_helper_1(target);      // reuse some common code at this step
    // ... continue building up target ...
    target = factored_helper_2(target);      // reuse some other common code at this step
    // ... finish building up target
    return target;
}
```

5.4 Functional style, take `const meta::type` + fill `meta::type`

Summary: Similar to previous, but fill the destination type via in-out parameter.

Semantics:

- Same as previous section, except that the target generated class definition is an in-out parameter.

Advantages:

- Avoids both drawbacks in the previous section.

In this example, we build up a type in several steps, and have factored out some common reusable logic:

```
constexpr void factored_helper_1(meta::type target, const meta::type source) {
    if (/*some characteristic about t*/) { /* do something to t */ }
}
constexpr void factored_helper_2(meta::type target, const meta::type source) {
    if (/*some characteristic about t*/) { /* do something to t */ }
}
constexpr void my_metaclass(meta::type target, const meta::type source) constexpr {
    // ...start building up target, using source ...
    factored_helper_1(target);               // reuse some common code at this step
    // ... continue building up target ...
    factored_helper_2(target);               // reuse some other common code at this step
    // ... finish building up target
}
```

6 Alternatives for applying the transform

This section explores some alternative ways to apply the source→definition transformation. Note that the code within the class being defined is structurally the same under these alternatives.

In this section "metaclass" means the name given to the transformation.

Unlike the previous section, these alternatives are not mutually exclusive.

6.1 Natural terse syntax: In place of `class`

Summary: One metaclass name can appear in place of `class`.

Note: The rest of this section assumes that this syntax is supported regardless of which of the other syntaxes that follow in are also pursued. Those other syntaxes should be in addition to, not instead of, this syntax.

Advantages:

- Clarity for code authors and readers: This is the "terse syntax" for applying metaclasses, and important for all the reasons the terse syntax is important for applying concepts.
- No parsing ambiguity.

Limitations:

- Allows exactly one metaclass name to be applied to a class definition. If this were the only style supported, a class that wants to apply multiple unrelated metaclasses must define a new metaclass to give a name to a combination of the metaclasses. Personally, I do not view this as an important limitation because it is normally both self-documenting and reuse-promoting to give a name to the combined metaclass; naming it captures the intent of the combiner, and promotes using the name again.
- (Of course, this limitation goes away if other styles in this section are supported as well.)

Example:

```
// to apply one metaclass named interface
interface myclass {
    // ... etc. ...
};

// workaround to apply multiple metaclasses M1 and M2
constexpr void M1M2(meta::type target, const meta::type source)
    { M1(target, source); M2(target,source); }
M1M2 myclass {
    // ... etc. ...
};
```

6.2 As adjectives before `class`

Summary: A whitespace-delimited list of metaclass names appear as adjectives before `class`.

Semantics:

- The terse syntax `M myclass{};` could be allowed as a shorthand for `M class myclass{};`.

Advantages:

- Clarity for code authors and readers: Preserves the “terse syntax” of keeping the more-specialized word of power up front, albeit with a bit of “syntax boilerplate.”
- Allows multiple metaclasses to be listed.
- Extends the naming pattern of C++11’s own `enum class`. Secondarily, we have experience that commercial nonstandard extensions like C++/CLI’s and C++/CX’s `interface class` and `ref class` are adoptable by users, and that users like them (except for their nonstandardness, but not as far as we know because of their naming convention).

Drawbacks:

- If we seriously want to explore this, we should do a UX study to see how users react to the “redundant boilerplate,” because we know C++ developers actively complain about the boilerplate the language already requires.

Example:

```
// to apply one metaclass named interface
interface class myclass {
    // ... etc. ...
};

// maybe: to apply multiple metaclasses M1 and M2
M1 M2 class myclass {
    // ... etc. ...
};
```

6.3 As “specializations” of `class<>`

Summary: The metaclass name appears as a `<>`-enclosed comma-delimited list after `class`.

Advantages:

- Allows multiple metaclasses to be listed.
- Similarity to specialization syntax, which suggests that the metaclass name(s) are specializations of the general “class” concept which is true in that the generated class is “still just a class.”

Drawbacks:

- Similarity to specialization syntax, which suggests that the metaclass name(s) are specializations of the general “class” concept, which is untrue in the detail that the default “metaprogram for class” that applies rules like “default private,” “implicit virtual,” etc. is not run, we are running this metaclasses’s rules instead.

Example:

```
// to apply one metaclass named interface
class<interface> myclass {
    // ... etc. ...
};

// to apply multiple metaclasses M1 and M2
```

```
class<M1,M2> myclass {
    // ... etc. ...
};
```

There are variations, such as to use `()`:

```
class(interface) myclass {
    // ... etc. ...
};
class(M1,M2) myclass {
    // ... etc. ...
};
```

6.4 In the class body (primarily motivated by transitional uses)

Summary: The metaclass name can be applied under some syntax within the class body.

Advantages:

- Allows multiple metaclasses to be listed.
- Allows existing macro-based language extensions to (e.g., Qt macros) to change their existing macros to apply metaclasses to existing code as a transitional tool (e.g., within `Q_OBJECT`). That permits code written using the existing macros targeting a separate proprietary compiler to be recompiled without source changes in a metaclass-based implementation.

Drawbacks:

- Naturally supports for conditional composition (`if(something) $other_metaclass`).
- To be useful in migration of existing code such as Qt macros, which uses macros like `Q_OBJECT` typically at the top, we would probably be forced to make the position of the directive not matter and apply to all declarations including those following the directive.

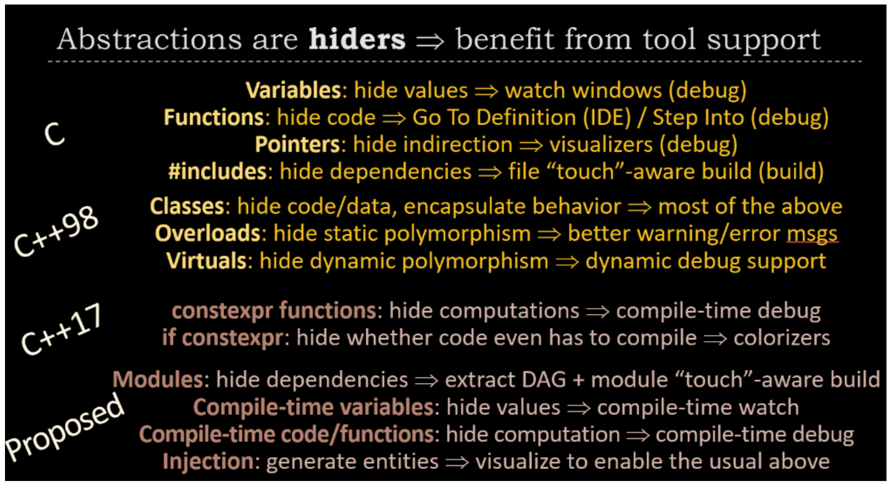
Example:

```
// to apply one metaclass named interface
class myclass {
    constexpr{ __apply(interface); }        // placeholder for some other syntax
    // ... etc. ...
};
// to apply multiple metaclasses M1 and M2
class myclass {
    constexpr{ __apply(M1, M2); }           // placeholder for some other syntax
    // ... etc. ...
};
```

7 FAQs

7.1 Q: Will metaclasses create a major tooling need? A: No.

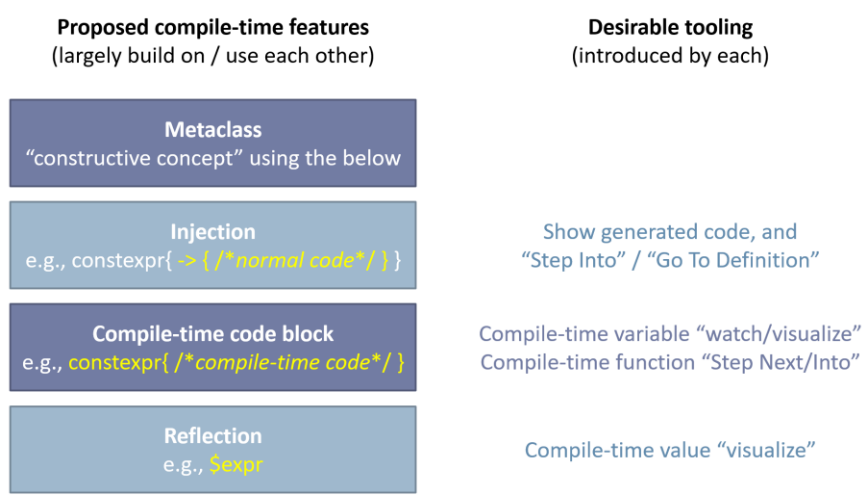
In short: The foundational features of reflection, compile-time code, and injection do create the major new tooling requirements. Metaclasses build upon those features (they are "just" a way to package up a group of reflections, compile-time codes, and injections and given that group a common name that can be reused), and can reuse the tooling we create for those features.



Every abstraction that C and C++ have ever added works without tooling, and also benefits from tooling (see right). In each case:

- *The feature is usable before tooling.* For example, absent other tool support, C++ programmers use `printf`-style debugging to see variable values, we figure out overload candidates by inspection to debug why we can't call an overloaded function, and we manually inspect and imagine specialization instantiations to figure out the outcome of a template metaprogram.
- *The feature, no matter how basic, benefits from tools to "look inside the abstraction."* For example, C++ debuggers now routinely offer watch windows to see variable values, and compilers routinely show overload candidates when we can't call an overloaded function. (TMP remains hard to write, read, and tool; so we should replace indirect TMP with direct compile-time `constexpr` code that's much easier to write, read, and tool… and then apply the tooling we have for ordinary code to that compile-time code.)

Metaclasses build on injection, which builds on compile-time code blocks, which uses reflection. The bottom three of those layers will benefit from tooling (see right). Importantly, note that metaclasses themselves do not add a major new tooling requirement. The three layers they depend on, and which we should adopt into C++ anyway in isolation, do – and once we have them, there is no primary new kind of tooling required by metaclasses.



As an example of tooling for metaclasses, when the user writes this source class:

```
value Point {
    int x;
    int y;
    Point(int, int);
};
```

and the metaclass program generates this class definition:

```
class Point {
private:
    int x = 0;
    int y = 0;
public:
    Point(int, int);
    Point() = default;
    Point(const Point&) = default;
    Point(Point&&) = default;
    Point& operator=(const Point&) = default;
    Point& operator=(Point&&) = default;
    auto operator<=>(const Point&) = default;
};
```

then how do we show (visualize, "see") the defined class?

Without any special tooling, this proposal provides the minimum guaranteed level of "`printf`-style debugging":

```
constexpr{ compiler.debug($Point); } // we can always print what's generated
```

Additionally, an IDE could for example offer a button beside to switch between viewing the source class (editable) and the defined class (noneditable), and additionally use the latter for its existing Step Into behavior.

> **Note** Any IDE that does this should immediately work better for existing C++17 code. For example, doing this enables Step Into for today's special member functions, which is already something most (>50%) C++ developers wish they had but most (>95%) do not have (source: poll of audiences, N ≈ 2,000).

If the source class is a template, such as

```
template<class T> customized_type MyClass { /*...*/ };
```

so that applying a metaclass could in general generate different things in each instantiation depending on the properties of type `T`, the IDE can still allow the same view-switching on at least each instantiation `MyClass<T>`. For example, for a given variable `var` whose type is an instantiation `MyClass<SpecificType>`, performing Step Into a call `var.func()` goes to the defined type for `MyClass<SpecificType>` which is concrete and unique.

7.2 Q: Will this encourage dialects and fragmentation, as with Lisp and Smalltalk? A: No.

Unlike Lisp and/or Smalltalk facilities, metaclasses cannot:

- redefine language facilities;
- redefine other people's types; or
- affect the global environment.

Metaclasses are just a convenient way to write your own type(s), with exactly the same capabilities C++ already has if you write exactly the equivalent type out longhand without the metaclass.

7.2.1 Problems in other languages

In Lisp and related languages, programmers can redefine other people's code and even global language facilities (e.g., the notorious `(defun defun () 3)` in Lisp, or `(define define () 3)` in Scheme). This is powerful, but undisciplined (causes arbitrary global effects up to and including breaking the language itself), fragile (Lisp makes it notoriously easy to write "write-only" code that is difficult to review, read, and maintain), and causes programs to be tightly coupled among their components and with their developer's environment (Lisp makes it notoriously easy to write code whose meaning depends on local customizations, is hard to share, and when shared is hard to compose with other code that came from an environment with competing assumptions).[4]

In Smalltalk and its variations, programs are easily dependent upon customizations in their "workspace" and/or their particular local environment. This integrated model had its strengths, such as enabling great support for edit-and-continue during debugging far before that feature was mainstream. However, it did so at the cost of tight coupling – a program became tied into its environment.

In both, these features led to major problems, some more so for one language than the other:

- **Fragmented local dialects.** Code has a specific meaning that depends on other locally installed code.
- **Nonportable code**: A library writer cannot in general extract a piece of code and reuse it in a different environment without potentially changing its meaning, unless it also ships the parts of the environment it depends upon for its meaning.
- **Noncomposable code**: When two library writers do successfully ship code, each of which depends on (and comes with) its own environmental settings, a program cannot in general combine both libraries in the same whole program if their environmental requirements are incompatible.
- **Unreviewable/unmaintainable "write-only" code.** A programmer can't confidently review or maintain a piece of code without knowing potentially the entire local environment. (This is not true of C++ code which uses only un-redefinable classes, functions, and overloading that all in turn only depend on other

[4] Various incarnations and offshoots of Lisp attempted to mitigate this problem in various ways without actually taking away the root cause: Common Lisp added the guarantee that all symbols in the package `COMMON-LISP` are protected and must not be redefined by user code otherwise you get undefined behavior; although this provides some protection for the standard facilities, it does not solve the general problem because it still permits one set of user code to redefine things in another set of user code. Also, implementations like SBCL attempted to further improve the problem by providing ways to "lock" packages so their contents cannot be accidentally redefined; however, even SBCL also provides ways to "unlock" them again.

entities they directly reference and that are in scope. The closest thing in C++ is implicit conversion operators which can appear to change the meaning of code, and even those do not change already-defined entities.)

None of these characteristics apply to metaclasses:

- **No mutable language: Metaclasses explicitly cannot change any language feature.** On the "input" side of a metaclass, we take only a single type's definition written using C++'s existing grammar (extended only to permit a metaclass as a more specialized name in the position of `class` or `struct`). That's it; it is an explicit goal to exclude creating a mutable language ("that way lies madness"), including that nothing in this proposal permits defining new operators, changing the meaning of language features, or making the C++ grammar extensible.
- **No mutable types: Metaclasses explicitly cannot change anyone else's types or code.** On the "output" side of a metaclass, we can compute and generate the actual definition of the given type, and possibly compute and generate related functions or types as part of our output. That's it; it is an explicit goal to exclude changing or redefining any other already-declared or -defined entities, including `std::` types and other people's types, which would violate the ODR.
- **Metaclasses's effects are local, not global.** They do not have global effect; applying a metaclass simply participates in reading a single type's declaration to generate its final definition.

Metaclasses are not like the customization/redefinition features in in Lisp and Smalltalk. Instead, metaclasses are actually like C++ classes and functions: user-defined entities. And they are handled the same way: put in namespaces (including popular ones into namespace `std::`), having a single well-known unchanging definition (ODR-preserving), referenced by normal name lookup (including allowing qualification), and shared as libraries.

7.2.2 Example

Here is a key motivating example:

```
interface Shape {
    string name() const;
    /*...*/
};
```

They key concern I have heard expressed is: Will this code have different meaning in different environments, because the meaning of `interface` could change?

The answer is: No, same as `string` in this same example. Both names select a unique entity found by name lookup.

What is perhaps initially misleading in this code example is that it uses the names `interface` and `string` unqualified. That's just a convenience for brevity, as usual. If both are defined in namespace `std`, then for the foregoing code that defines `Shape` to compile, it must write `using`:

```
using std::interface;
using std::string;

interface Shape {
    string name() const;
    /*...*/
};
```

or explicitly qualify:

```
std::interface Shape {
    std::string name() const;
    /*...*/
};
```

Metaclasses like `interface` are no different from classes like `string`. They are just entities managed using namespaces (`std` for common ones like `interface` and `string`) and found by name lookup.

But can't a company define their own `interface` and/or `string`? Yes, but that's strictly better than where we are today. Consider:

- **`string`:** Before there was a standard `string`, library vendors and companies and end users constantly rolled their own, often incompatibly; the best a company or end user could usually do was adopt a widely-used library string such as Rogue Wave's `RWString` in their own code, and write conversions as needed to work with the string types used by their other libraries. Now that there is a standard `string`, that repetition and fragmentation happens much less, even though library vendors (and sometimes companies, but almost never end users) occasionally do still need to write their own `string` because of specific requirements, and just put those classes in their own namespaces. End users just use `std::string`, or occasionally `OtherLibrary::string`. – And even if an end user happens to use a non-standard one, they are still far better off by reusing a third-party or internal company one rather than rolling their own string type by hand, and possibly incompatibly, every time.
- **`interface`:** Today without a standard `interface`, library vendors and companies and end users constantly rolled their own by convention, often incompatibly. Once we have a standard `interface`, that repetition and fragmentation will happen much less, even though library vendors (and sometimes companies, but almost never end users) occasionally will still need to write their own `Qt::interface` or `WinRT::interface` because of specific requirements, and can just put those metaclasses in their own namespaces. End users would just use `std::interface`, or occasionally `Qt::interface`. – And even if an end user happens to use a nonstandard one, they are immeasurably better off by reusing a third-party or internal company one rather than rolling their own interface style by hand, and possibly incompatibly, every time.

Just giving an entity a reusable name is a force for reuse, and convergence. The more widely known that name is, the more convergence; a name in the standard library is likely to help code to reuse the name and therefore converge a lot, but even a nonstandard name that is specific to a library or a company helps code reuse and therefore converge by avoiding reinvention and the resulting incompatibility.

Being able to give a metaclass a name, and share it as a library, will likely reduce fragmentation by discouraging people from rolling their own. We already write them by convention; we can only benefit from writing them as reusable composable code.

8 Revision history

R2 (pre-Jacksonville, 2018-02):

- Switched to function-style declaration syntax per SG7 direction in Albuquerque (old: `$class M` → new: `constexpr void M(meta::type target, const meta::type source)`).
- Simplified some examples, including deferred `ordered` et al. to a later revision of this paper that can show integrating the newly adopted `operator<=>`.

R2 (pre-Albuquerque, 2017-10):

- Expanded section 2.5, "Composition," to discuss composability.
- Added new sections 5, 6, and 7 in response to Toronto feedback and for discussion in Albuquerque.

R1 (post-Toronto, 2017-07):

- Minor tweaks from Toronto.

R0 (pre-Toronto, 2017-06): Initial revision.