Metaclasses

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Abstract

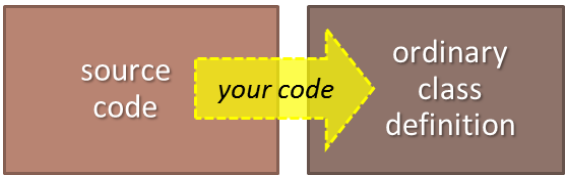
The only way to make a language more powerful (bigger), but also make its programs simpler, is by *abstraction*: adding well-chosen abstractions that let programmers replace manual code patterns with saying directly what they mean. There are two major categories:

> **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. Templates are a powerful parameterization of functions and classes, but do not enable authoring new encapsulated behavior.
>
> **(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, `$class` 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 includes a set of common metaclasses, and proposes that several are common enough to belong in `std::`. Each subsection of §3 is equivalent to a significant "language feature" that would otherwise require its own EWG paper and be wired into the language, but here can be expressed instead as just a (usually tiny) library that can go through LEWG. For example, this paper begins by demonstrating how to implement Java/C# `interface` as a 10-line C++ `std::` metaclass – with the same expressiveness, elegance, and efficiency of the built-in feature in such languages, where it is specified as ~20 pages of text.

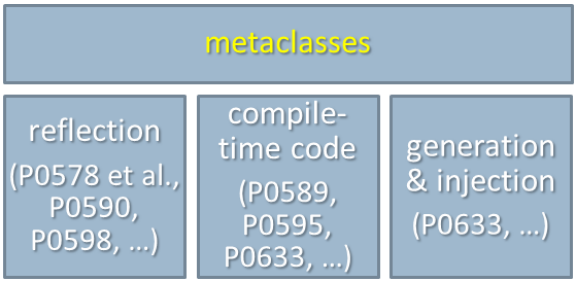
1 Overview

Metaclasses 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 – enabled 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`.



This paper builds on, and with, related work:

- C++ and published TS work, including concepts, constexpr, if constexpr.
- In-progress TS work: reflection (P0578 et al., P0590, P0598, …)
- In-progress proposals: compile-time programming (P0589, P0595, P0633, …)



This paper hopes to provide "what we want to be able to write" use cases for using features in the related work.

Primary goals:

- Expand C++'s abstraction vocabulary beyond `class`/`struct`/`union`/`enum` which are 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 "language extensions" 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++.

Primary intended benefits:

- For users: Don't have to wait for a new compiler. Can share some kinds of "new language features" as libraries. Can even add productivity features themselves.
- For standardization: More features as libraries ⇒ easier evolution. Testable code ⇒ higher quality proposals.
- 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.

Metaclasses are primarily for library writers; users would use them widely, but usually won't write their own.
A Clang-based prototype is available at *github.com/asutton/clang* (source) and *cppx.godbolt.org* (live compiler).

1.1 Design principles

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

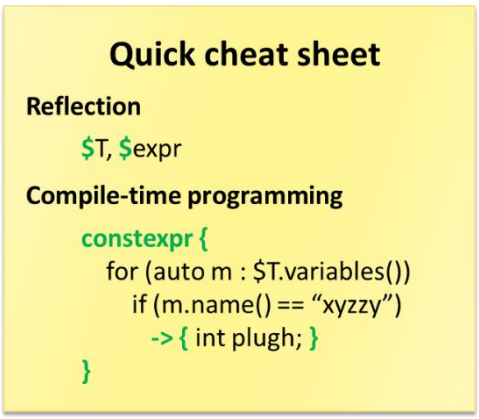
The primary design goal is conceptual integrity [Brooks 1975], which means that the design is coherent and reliably does what the user expects it to do. Conceptual integrity's major supporting principles are:

- **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 declare metaclasses, and instead lets programmers write metaclasses using 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 Synopsis of P0633-based compile-time programming

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; here is a "cheat sheet" synopsis of current draft syntax for the main features of those papers that will be used for this paper's examples, but the higher-level metaclass facility proposed herein is not affected by the syntactic details and the intent of this proposal is to build on whatever syntax ends up being adopted.



The strawman syntax for reflection is prefix `$`. For example:

```
$T                                  // reflect type T
$expr                               // reflect expression expr
```

The strawman syntax for a compile-time code block, which can appear at any scope, is a `constexpr { }` block. Within a `constexpr` block, `-> { }` injects code into the enclosing scope. For example:

```
constexpr {                         // execute this at compile time
    for (auto m : $T.variables())   // examine each member variable m in T
        if (m.name() == "xyzzy")    // if there is one with name "xyzzy"
            -> { int plugh; }       // then inject also an int named "plugh"
}
```

For further details, see P0633 and the other cited papers.

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

```
constexpr {
    if (count_if($T.functions(), [](auto f){ return f.name[0] == 'g'; }) < 1)
        compiler.error("at least " + to_string(min) +
                       " function names must start with 'g'");
}
```

1.3 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.

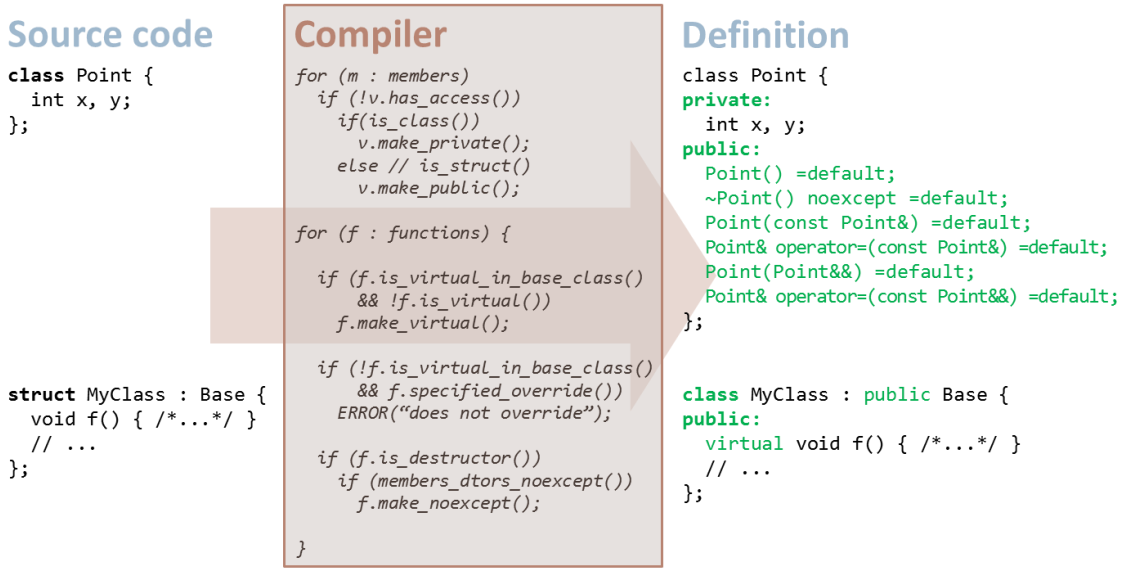
Thanks also to the following experts for their comments in discussions and/or on drafts of this paper: Louis Brandy, Chandler Carruth, Casey Carter, Matúš Chochlík, Lawrence Crowl, Pavel Curtis, Louis Dionne, Gabriel Dos Reis, Joe Duffy, Kenny Kerr, Nicolai Josuttis, Aaron Lahman, Scott Meyers, Axel 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.

2 Language: Metaclasses

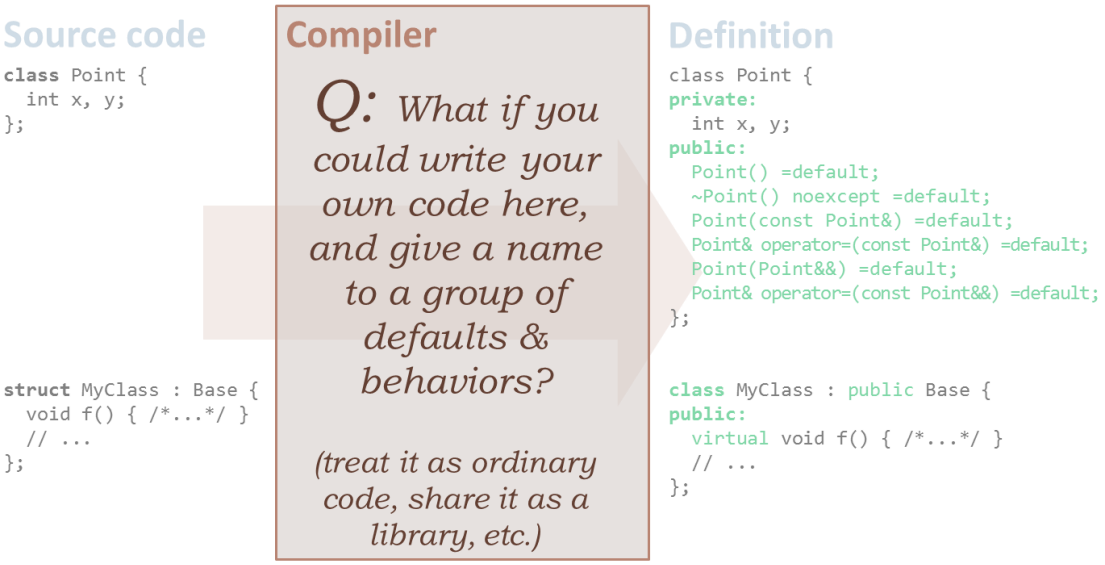
"Classes can represent almost all the concepts we need… Only if the library route is genuinely infeasible should the language extension route be followed." — B. Stroustrup (D&E, p. 181)

This paper relies on C++ classes' 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. This lets the programmer distinguish a subset or "category" of the set of all ordinary classes, identified by the metaclass name. It also elevates idiomatic conventions into the type system as compilable and testable code.

The primary goal of metaclasses is to make defining types more convenient and flexible, in a way that achieves other goals such as expressing more future "language" extensions as class libraries instead of hardwiring them into the core language.

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.

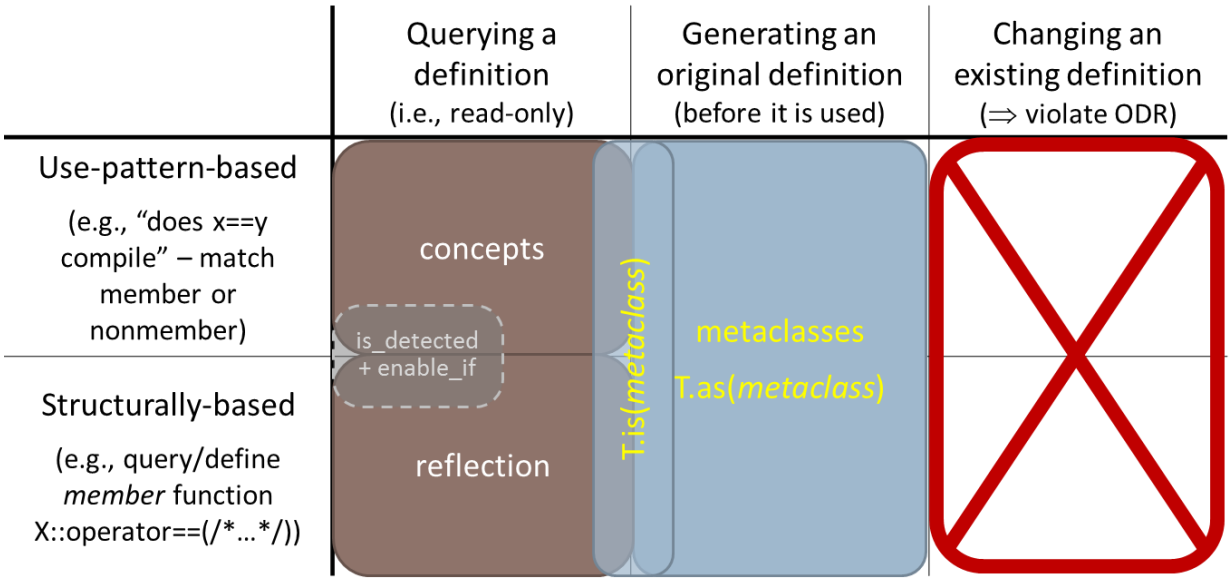


Figure 1: How the pieces fit

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

2.1 Overview: "Constructive" concepts

A metaclass is defined using `$class`, and can express constraints, defaults, and more using compile-time code. A metaclass is just code; it can be put in a namespace, and shared in a header or a module, in the same ways as other compile-time code we have today (in particular, templates). For example:

```
namespace std::experimental {
    $class interface {
        // 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 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 instantiating the metaclass by using it to define an ordinary class:

```
interface Shape {                       // Shape is-a interface

    int area() const;                   // metacode in $class interface runs on
    void scale_by(double factor);       // the contents in this protoclass body

};
```

Here:

- 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 ***protoclass***. It is passed as input to the metaclass `interface`. The contents are available via reflection; the functions can be reflected as `$interface.functions()`, the data members as `$interface.variables()`, etc.
- At the opening brace of `interface`, `Shape` is ***open*** and its definition can be used by code in the body of metaclass `interface`, for reflection and other purposes. While a class is open (and only then), reflection on itself returns non-`const` information that can be modified.
- At the closing brace of `interface`, metaclass finalization runs (see below), after which `Shape` is ***complete*** a normal fully defined class type. This is the point of definition of `Shape`. When a class is fully defined, reflection returns `const` information.

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

- **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.
- **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 functions:** Default declarations and implementations for functions 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."
- **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 of `$class`):

```
constexpr {
    for (auto o : $thisclass.variables())
        if (!f.has_access()) f.make_private();    // make data members private by default
    bool __has_declared_dtor = false;
    for (auto f : $thisclass.functions()) {
        if (!f.has_access()) f.make_public();     // make functions public by default
        __has_declared_dtor |= f.is_dtor();       // and find the destructor
    }
    if (!__has_declared_dtor)                     // if no dtor was declared, then
        -> { public: ~$thisclass.name$() { } }    // 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.

C++17 style	**This paper (proposed)**
Applying a reusable abstraction with custom **defaults** and **constraints** = Medium improvement	

`class IShape {`
`public:`
`  virtual int area() const =0;`
`  virtual void scale_by(double factor) =0;`
`  // ... etc.`
`  virtual ~IShape() noexcept { };`
`  // be careful not to write nonpublic/nonvirtual function`
`};  //  or copy/move function or data member; no enforcement`
	`interface IShape {`
	`  int area() const;`
	`  void scale_by(double factor);`
	`  // ... etc.`
	`};`
	
	`// see below in this table for the`
	`// definition of $class interface`

Applying a reusable abstraction that additionally has custom **generated functions** = Large improvement	

`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); }`
`};`
	`value Point {`
	`  int x = 0;`
	`  int y = 0;`
	`  // ... behavior functions ...`
	`};`

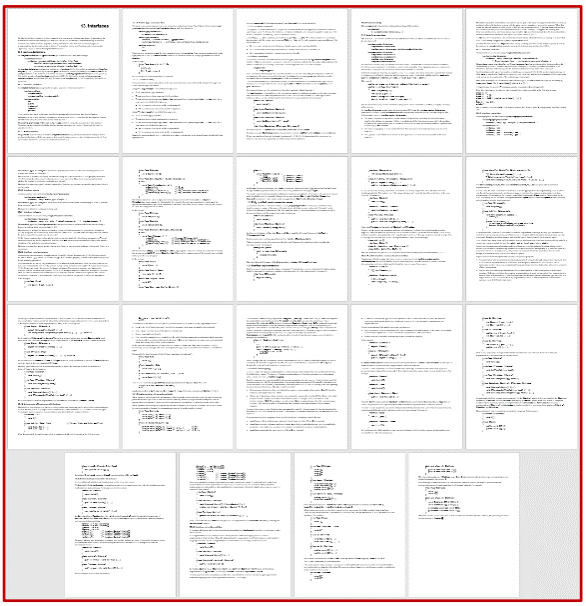
Applying a reusable abstraction with defaults, generated functions, and **custom semantics** = XL improvement

```
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>
literal_value pair {
    T1 first;
    T2 second;
};

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

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 IShape {
    int area();
    void scale_by(double factor);
}
```

```
// (Proposed) C++ library impl: ~10 lines of testable code
$class interface {
  ~interface() noexcept { }
  constexpr {
    compiler.require($interface.variables().empty(),
      "interfaces may not contain data");
    for (auto f : $interface.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();
    }
  }
};
```

```
// User code (proposed C++)
interface IShape {
    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 "literal_value") that can then be reused directly to just as simply define other similar types (e.g., `std::tuple`, users' own literal value types).

2.3 Example: `interface`

The previous page shows the code for an example, `$class 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.

`$interface.functions()` includes all functions in the current class `interface` is being applied to, including functions it inherited from any of its base classes. The `interface` metaclass:

- **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.

```
interface drawable {              // this is an interface
    int draw(widget w);           // 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(widget w);           // 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 Declarations

The contents of a metaclass consist of:

- Declarations of members to appear the completed class, using ordinary class scope declaration syntax.
- Compile-time code to reflect, and modify protoclass members in-place or compute new declarations.

At metaclass scope, a member declaration can appear unadorned using all ordinary syntax. If in a `constexpr` block, it can be injected into the metaclass scope using `-> { }`.

Alternatively, a part of the declaration can be provided by compatible `meta::` values. For example, in a function declaration, the function name can be provided by any compile-time `meta::` value that has a `.name`, or a `meta::string`, and the parameter list can be provided by any compile-time `meta::` value that has `.parameters`:

```
$class x {
    // for each function, create a no-op overload with an extra “int” parameter
    constexpr {
        for (auto f : $x.functions())
          -> { void (f$)( f$, int ) { } }
    }
};
```

2.5 Composition

Because metaclasses are just code, they can be combined and refactored like regular code.

In particular, we can define additional metaclasses in terms of existing ones using inheritance-like extension syntax (note that there is no need, and no support, for declaring access-specifiers). Here is an example from §3.5:

```
$class value : basic_value, ordered {  // a value is-an ordered basic_value
    // ... with additional defaults/constraints/generation/etc. ...
};
```

As with base class constructors, each metaclass is executed in left-to-right depth-first order. If the composed metaclasses conflict (e.g., one requires all data members to be private, and the other all public), the result will not be usable because any attempt to use it will cause errors.

A metaclass can also compose concepts, with the semantics that the resulting class is required to satisfy the concept. For example, given a concept `Regular`, we can add it to the requirements list:

```
$class value : ordered, basic_value, Regular {     // include a Concept
    // etc.
};
```

and behaves as a convenience shorthand for:

```
$class value : ordered, basic_value {
    // etc.                        // run metaprogram first: defaults/generation/…
    requires Regular<value>;       // then put this at the end, when we have
};                                 // the complete generated type
```

Here is a second example, returning to `interface`: Let's say we decided that `interface` could be refactored to extract just the first line, the "pure virtual destructor" requirement, and have it be a separately reusable meta-class. We could write the following equivalently to the previous definition of `interface`:

```
$class has_pure_virtual_dtor {
    // generated function: now moved into its own metaclass
    ~name$() noexcept = 0;
};

$class interface : has_pure_virtual_dtor {
    // 8<---no mention of a destructor, now we get it from has_pure_virtual_dtor
    // ...
    // ... remaining unfactored default/constraint logic as before
    // ...
};
```

2.6 `.is` and `.as`

2.6.1 `.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` iff:

- 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 defined in §3.6:

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

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

```
class IShape1 {                    // written by hand as in C++17
public:
    virtual void draw() = 0;
    virtual ~IShape1() noexcept = 0;
};

interface IShape2 {                // same written using a metaclass
    void draw();
};
```

Both types `.is(interface)`:

```
static_assert ($IShape1.is(interface));
static_assert ($IShape2.is(interface));
```

This applies transitively to base metaclasses. For example, if `interface` had been refactored as shown in §2.5 to be written in terms of a `has_pure_virtual_dtor` "base" metaclass, the following would also hold:

```
static_assert ($IShape1.is(has_pure_virtual_dtor));
static_assert ($IShape2.is(has_pure_virtual_dtor));
```

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

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

2.6.2 `.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. To express that, use `$T.as(M)`, which generates a type that is identical to `T` but is additionally defined using the named metaclass `M`. Here is an example using a metaclass `ordered` (see §3.4):

```
struct legacy_point { int x; int y; }; // in C++17 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 fall out naturally from `.as` …

2.6.3 Bonus: 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:

```
$class new_type { };                   // no-op metaclass
```

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

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

Common motivating cases are 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);
```

2.7 Concepts + metaclasses

Concepts and metaclasses are complementary. The key is that metaclasses are "constructive concepts" in that they go beyond concepts to define new types, but metaclass implementations *use* both concepts and reflection:

- Metaclasses use concepts to ask "can class `T` be used this way" via use-pattern constraints.
- Metaclasses use reflection-based computation 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>)                      // if T is Copyable, then
            -> { requires Copyable<vector>; } // 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, including by default, and there is a virtual destructor and no data or copying. The definition is as we saw earlier.

```
$class interface {
    /* see §2.3 */
};
```

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

```
interface drawable {
    void draw(canvas& c);              // defaults to pure virtual
    // int x;                          // would be error, no data allowed
    // drawable(const drawable& from); // would be error, no copying allowed
};
```

In this interface, `draw` is 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.

```
$class base_class {
    constexpr {
        for (auto f : $base_class.functions()) {
            if (f.is_dtor() && !(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");
            if (f.is_copy() || f.is_move())
                compiler.error("base classes may not copy or move;"
                               " consider a virtual clone() instead");
        }

        for (auto b : $base_class.base_classes())
            if (b.is(interface) && !b.has_access()) f.make_public();

        if (!$base_class.variables().empty())
            compiler.error("pure base classes may not contain data");
    }
};
```

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

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

class rectangle : public shape {
    override void draw(canvas& c) { /*...*/ }
};
```

3.3 final

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

```
$class final {
    final.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.

This section is written in terms of C++17 and does not depend on my parallel paper P0515 *Consistent Comparison*. However, P0515 makes comparisons much better, and if that paper is adopted then this section is easily updated to refer to the features added by that paper including `<=>` three-

way comparison and all five comparison categories. Nearly all of P0515 can be implemented as a library in this way, except only the automatic generation of comparison functions for fundamental types and for existing class types defined without metaclasses.

This section illustrates how opting in to default comparisons is easy and efficient using metaclasses, by demonstrating a single comparison category (total ordering) implemented as a library with full opt-in semantics.

An `ordered` type is a `class` that requires operators `<`, `>`, `<=`, `>=`, `==`, and `!=`. If the functions are not user-written, lexicographical memberwise implementations are generated by default.

```
$class ordered {
    constexpr {
        if (! requires(ordered a) { a == a; }) -> {
            friend bool operator == (const ordered& a, const ordered& b) {
                constexpr {
                    for (auto o : ordered.variables())          // for each member
                       -> { if (!(a.o.name$ == b.(o.name)$)) return false; }
                }
               return true;
            }
        }

        if (! requires(ordered a) { a < a; }) -> {
        friend bool operator <  (const ordered& a, const ordered& b) {
                for (auto o : ordered.variables()) -> {          // for each member
                    if (a.o.name$ < b.(o.name)$) return true;    // (disclaimer: inefficient; P0515
                    if (b.(o.name$) < a.o.name$) return false;   // with 3-way comparison is better)
                }
                return false;
            }
        }

        if (! requires(ordered a) { a != a; })
            -> { friend bool operator != (const ordered& a, const ordered& b) { return !(a == b); } }
        if (! requires(ordered a) { a > a; })
            -> { friend bool operator >  (const ordered& a, const ordered& b) { return   b <  a ; } }
        if (! requires(ordered a) { a <= a; })
            -> { friend bool operator <= (const ordered& a, const ordered& b) { return !(b <  a); } }
        if (! requires(ordered a) { a >= a; })
            -> { friend bool operator >= (const ordered& a, const ordered& b) { return !(a <  b); } }
    }
};
```

Note This example shows how using concepts is convenient in metaclasses, especially when we just care whether a given operation (here comparison) is provided already at all, regardless of the manner in which it's provided (as a member, nonmember friend, etc.). So this code just writes:

```
if (! requires(ordered a) { a == a; })
```

Alternatively, we could also have written the following (assuming `constexpr` range-based `find_if`), but it's more tedious and less general:

```
        if (find_if($ordered.functions(),
                    [](auto x){ return x.name == “operator==”; })
            != ordered.functions().end())
```

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
```

However, most code will not use `ordered` directly because it’s an intermediate metaclass. Which brings us to **`value`**, an important workhorse…

3.5 `value` types (regular types)

A `value` is a `class` that is a totally ordered 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:

```
$class basic_value {
    constexpr {
        if (find_if(value.functions(), [](auto x){ return x.is_default_ctor(); }) != value.functions().end())
            -> { basic_value() = default; }

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

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

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

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

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

A `value` is a totally ordered regular type:

```
$class value : ordered, basic_value { };
```

Note If P0515 is accepted, we would naturally expand this to provide other convenient opt-ins here, and because "total ordering" and "equality comparable" are the most commonly used and the default to be encouraged, they get the nice names:

```
$class weakly_ordered_value    : weakly_ordered    , basic_value { };
$class partially_ordered_value : partially_ordered , basic_value { };
$class equal_value             : equal             , basic_value { };
$class weakly_equal_value      : weakly_equal      , basic_value { };
```

Example:

```
value Point { int x; int y; };   // note: that's it, convenient and fully opt-in

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});
```

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 objects and functions, no virtual functions, no user-defined constructors (i.e., no invariants) or assignment or destructors, and the most powerful comparison supported by all of its members (including none if there is no common comparison category).

Notes Up to this point, we've seen (a) applying defaults, (b) enforcing requirements, (c) combining metaclasses. Now we'll look at reflecting on members, evaluating whether they meet a metaclass, and selectively combining metaclasses.

The full 5-way comparison category computation below assumes we've gone ahead with P0515, so they're stronger than the simple extract shown in §3.3.

```
$class plain_struct : basic_value {
    constexpr {
        for (auto f : plain_struct.functions()) {
            compiler.require(f.is_public() || !f.is_virtual())
                            "a plain_struct function must be public and nonvirtual");

            compiler.require(!(f.is_ctor() || f.is_dtor() || f.is_copy() || f.is_move())
                              || f.has_default_body())
                            "a plain_struct can't have a user-defined "
```

```
                        "constructor, destructor, or copy/move");
        }

        bool all_ordered           = true,    // to compute common comparability
             all_weakly_ordered    = true,
             all_partially_ordered = true,
             all_equal             = true,
             all_weakly_equal      = true;

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

            all_ordered           &= o.type.is(ordered);
            all_weakly_ordered    &= o.type.is(weakly_ordered);
            all_partially_ordered &= o.type.is(partially_ordered);
            all_equal             &= o.type.is(equal);
            all_weakly_equal      &= o.type.is(weakly_equal);
        }

        if (all_ordered)              // generate greatest common comparability
            plain_struct = plain_struct.as(ordered);
        else if (all_equal)
            plain_struct = plain_struct.as(equal);
        else if (all_weakly_ordered)
            plain_struct = plain_struct.as(weakly_ordered);
        else if (all_weakly_equal)
            plain_struct = plain_struct.as(weakly_equal);
        else if (all_partially_ordered)
            plain_struct = plain_struct.as(partially_ordered);
    }
};
```

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 group_o_stuff {
    int i;                        // implicitly public
    string s;
};

group_o_stuff 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.

```
$class copyable_pointer : value {
    T& operator* () const;        // require * and -> operators
    T* operator->() const;
```

```
};
```

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

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

copyable_pointer 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' type, and otherwise has only `public $` member variables of its enumerators' type, all of which are naturally scoped because they are members of a type.

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. Now, we'll generate an additional data member.

```
$class basic_enum : value {
    constexpr {
        compiler.require(basic_enum.variables().size() > 0,
                         "an enum cannot be empty");

        if ($basic_enum.variables().front().type().is_auto())
             -> { using U = int; } // underlying type
        else -> { using U = $basic_enum.variables().front().type(); }

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

Note A very 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 need to be careful not to violate C++'s zero-overhead principle; we must not impose 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 always generating string names for the members

of a `basic_enum`, would be a baby step down the slippery slope toward always-on or 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
string to_string(E e) {
    switch (value) {
        constexpr {
            for (const auto o : $E.variables())
                if (!o.default_value.empty())
                    -> { case o.default_value()$: return E::(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.

```
$class enum_class : basic_enum {
    constexpr {
        U next_value = 0;
        for (auto o : $enum_class.variables()) {
            if (!o.has_default_value())
                o.set_default_value(next_value);
            next_value = o.get_default_value()++;
        }
    }
};
```

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.

```
$class flag_enum : basic_enum {
    flag_enum  operator&  (const flag_enum& that) { return value & that.value; }
    flag_enum& operator&= (const flag_enum& that) { value &= that.value; return *this; }
    flag_enum  operator|  (const flag_enum& that) { return value | that.value; }
    flag_enum& operator|= (const flag_enum& that) { value |= that.value; return *this; }
    flag_enum  operator^  (const flag_enum& that) { return value ^ that.value; }
    flag_enum& operator^= (const flag_enum& that) { value ^= that.value; return *this; }

    flag_enum()              { value  = none; } // default initialization
    explicit operator bool() { value != none; } // test against no-flags-set

    constexpr {
        compiler.require(objects.size() <= 8*sizeof(U),
                         "there are " + objects.size() + " enumerators but only room for " +
                         to_string(8*sizeof(U)) + " bits in value type " + $U.name());

        compiler.require(!numeric_limits<U>.is_signed,
                         "a flag_enum value type must be unsigned");

        U next_value = 1;                       // generate powers-of-two values
        for (auto o : $flag_enum.variables()) {
            compiler.require(!o.has_default_value(),
                "flag_enum enumerator values are generated and cannot be specified explicitly");
            o.set_default_value(next_value);
            next_value *= 2;
        }
    }

    U none = 0;                                 // add name for no-flags-set value
};
```

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);        // comparison comes from 'value'
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 (April 2016) came out with Anthony Williams' 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 an object 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.

A `bitfield` metaclass 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:

```
$class bitfield : final, comparable_value {       // no derivation

    constexpr {
        auto objects = bitfield.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.empty() || o.T == $void,
            "unnamed bitfield members must have type void");

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

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

$bitfield.variables().clear();         // now replace the previous instance vars
byte data[ (size/CHAR_BITS) + 1 ];     // now allocate that much storage

bitfield() {                           // default ctor inits each non-pad member
    constexpr {
        for (const auto& o : objects)
            if (o.type != $void)
                -> { new (&data[0]) o.type.name$(); };
    }
}

~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 != $void)             // via its accessor
                -> { case o.num$: set_(o.name$)() = that.(o.name)$(); }
}

bool operator==(const bitfield& that) const {
    constexpr {                        // (we'll get != from 'comparable_value')
        for (auto o : objects)         // just compare each member
            -> { if (o.name$() != that.(o.name)$()) return false; }
        return true;
    }
}
```

```
};
```

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. Further, in C++11 we had to add the wart of a special "`:0`" syntax (added in C++11) 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 it: 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.

```
$class safe_union : final, comparable_value {     // no derivation
```

```
constexpr {
    auto objects = safe_union.variables();    // take a copy of the class's objects
    size_t size  = 1;                 // first, calculate the required size
    size_t align = 1;                 //   and alignment for the data buffer
    for (auto o : $safe_union.variables()) {
        size  = max(size,  sizeof (o.type));
        align = max(align, alignof(o.type));
        if (o.storage.has_default()) o.make_member();
        compiler.require(o.is_member(), "safe_union members must not be static");
        compiler.require(is_copy_constructible_v<o.type$>
                         && is_copy_assignable_v<o.type$>,
                        "safe_union members must be copy "
                        "constructible and copy assignable");
    }
    safe_union.variables().clear();    // now replace the previous instance vars
}
alignas(align) byte data[size]; //   with a data buffer
int active;                             //   and a discriminant
safe_union() { active = 0; }            // default constructor
void clear() {                          // cleanup goes here
    switch (active) {
        constexpr {
            for (const auto& o : objects)     // destroy the active object
                -> { case o.num$: 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
        }
    }

    constexpr {
    for (auto o : objects) -> {            // 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);
        }

    }
    }

    bool operator==(const safe_union& that) const {
                                           // (we'll get != from 'comparable_value')
        if (active != that.active)  // different active members => not equal
            return false;
        if (active == 0)                   // both empty => equal
            return true;
        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 things to the type members:

```
$class reopenable {
    constexpr {
        compiler.require($reopenable.member_variables().empty(),
                         "a reopenable type cannot have member variables");
        $reopenable.make_reopenable();
    }
};
```

A `namespace_class` is `reopenable`:

```
$class namespace_class : reopenable {
    constexpr {
        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:

C++17 style	Using a metaclass

`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`
`  }`
`}`
`}`
	`namespace_class boost {`
	`namespace_class math {`
	
	`  // public contents of boost::math`
	
	`private:`
	`  // implementation details of boost::math`
	`  // go here and can be called normally`
	`};`
	`};`

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.

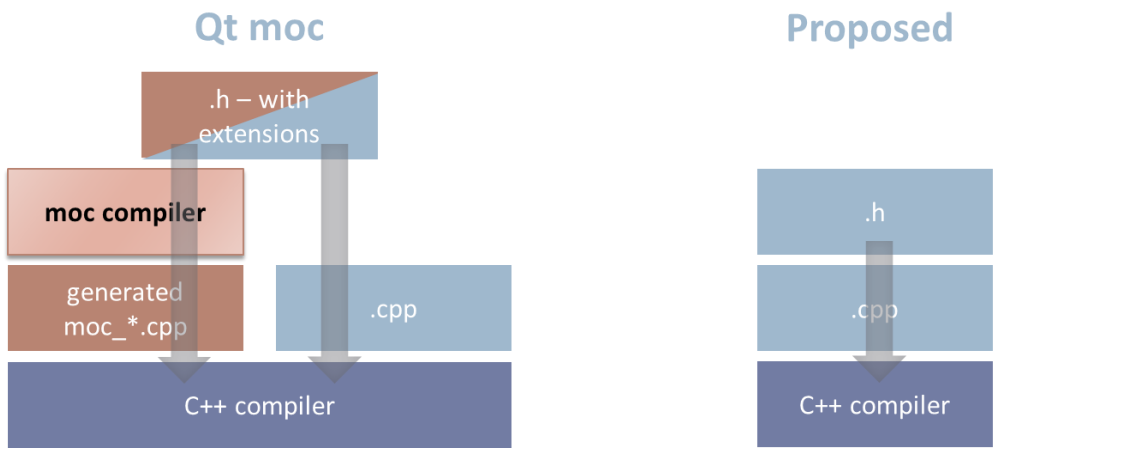


*Figure 2: Qt **extended** language + **side** compiler – build model vs. this proposal*

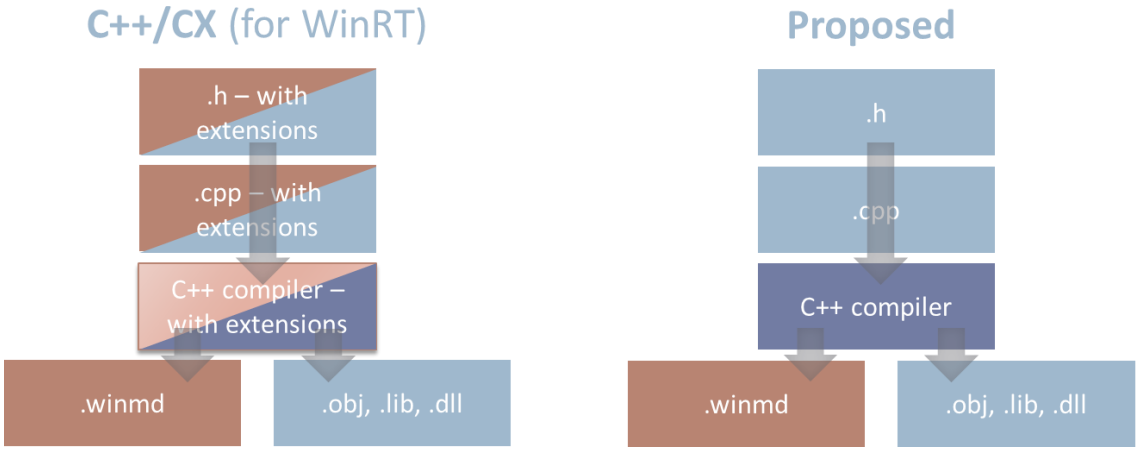


*Figure 3: C++/CX **extended** language + **extended** compiler – build model vs. this proposal*

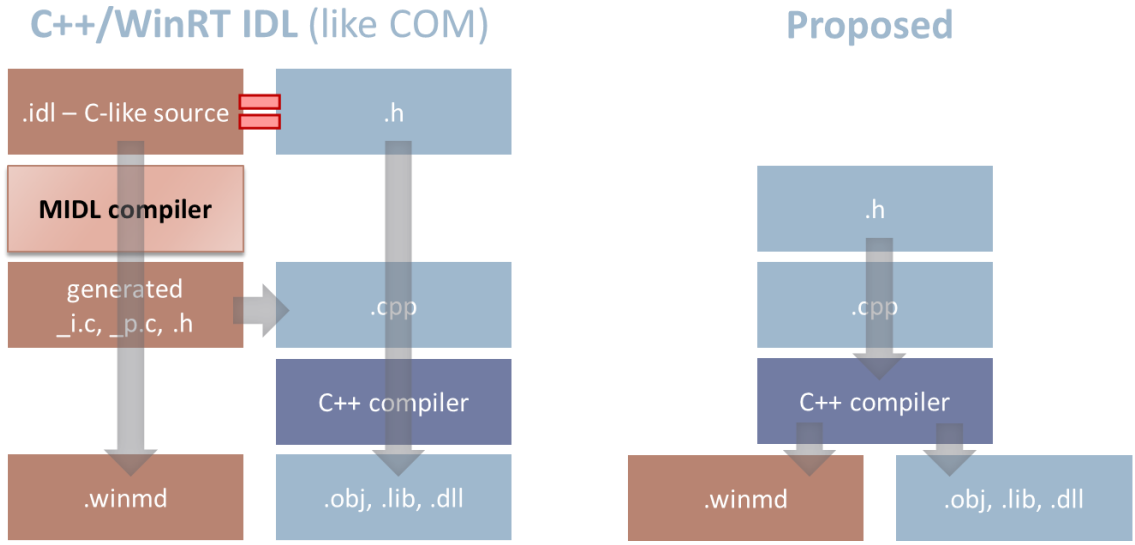


*Figure 4: C++/WinRT **side** language + **side** compiler – build model vs. this proposal*

4.1 Qt moc → metaclasses (sketch)

This section describes how Qt moc could be replaced by metaclasses.

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

`QClass` is a metaclass 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

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

```
template<class T>
$class property<T> {
    // ...
};
```

This metaclass implements the following requirements and defaults:

- Each function's name must begin with "get" or "set."
- `T` must be copyable.
- 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.