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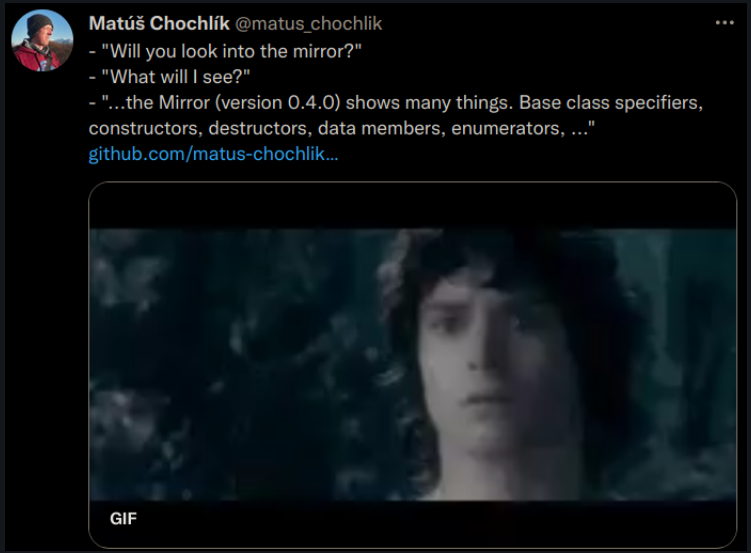


https://github.com/matus-chochlik/mirror

Metaobject

- A *meta-level* representation of a *base-level* entity
  - namespace, type, function, constructor, destructor, variable, constant, expression, ...
- On the *meta-level*[1] all of the above are "reified"
  - can be stored in variables, used as function arguments and return values,
  - provide the ability to write reflection algorithm libraries,
  - working at compile-time.
- We say a metaobject "reflects" the *base-level* entity

[1] unlike the base-level (namespaces, constructors, etc)

Metaobject – continued

- Provides access to *metadata* describing the reflected *base-level* entity
  - type of a variable,
  - data members of a `struct`,
  - constructors or member functions of a `class`,
  - base classes of a `class`,
  - return type of a function,
  - parameters of a function,
  - enumerators in an `enum` type,
  - name of a namespace, type, function, data member, parameter, etc.
  - address of a variable, data member or member function,
  - specifiers like `virtual`, `constexpr`, `static`, `noexcept`, `public`, `protected`, `private`, etc.
  - source location[2],
  - ...

[2] except for built-ins

Metaobject – continued

In a program a *metaobject* is a compile-time constant value of a type satisfying the following concept:

```
template <typename X>
concept metaobject = not-really-important-here;
```

Can be used to constrain function arguments:

```
void foo(metaobject auto m) { /*...*/ }
```

or more generally in a `requires` clause,

```
void bar(auto m)
  requires(metaobject<decltype(m)> &&
           something_else(m)) {
    /*...*/
}
```

Reflection

- The process of obtaining metadata or metaobjects which provide metadata indirectly
- Done through a dedicated operator or language expression
- For example

```
const auto meta_int = mirror[3](int);

static_assert(metaobject<decltype(meta_int)>);
```

[3] the reflection expression

Splicing

- The reverse of reflection
- Getting back to the base-level entity reflected by a metaobject
- As in...
  - getting a type or a template,
  - getting the value of a constant,
  - getting the pointer or reference to a variable,
  - getting the pointer to a function or a member function,
  - invoking a function, constructor or operator,
  - etc.
- ...through an operation on a metaobject reflecting that *base-level* entity
- "Splicing" can also mean emitting a snippet of code involving base-level entities, reflected by metaobjects

Reflection API

- Set of (compile-time) functions operating on *metaobjects*
- Several groups
  - metaobject classification functions,
  - primitive metadata extraction,
  - metaobject sequence operations,
  - general-purpose algorithms,
  - predicates, comparators, transformation functions,
  - syntax sugar, placeholder expressions,
  - ...
- Are `consteval` (or `constexpr`)[4]
- `noexcept` is also implied

[4] assumed, but omitted from examples in here to save space on slides

Reflection API – design goals

- The general API design stuff
- Concise and clear syntax, functional-style
- Support for as many use-cases as possible
- Provide functions handling recurring patterns and use-cases
- Support composition of function calls into bigger custom algorithms
- Proper ADL[5]; should not require excessive name qualification
- Be similar to the STL and other commonly-used libraries[6], where it makes sense.

[5] argument-dependent lookup

[6] Boost, ...

Hello, reflection! – the obligatory first example

```
struct hello {};

int main() {
  hello world;

  std::cout << get_name(mirror(hello))
            << ", "
            << get_name(mirror(world))
            << "!" << std::endl;

    return 0;
}
```

```
"hello, world!"
```

Reflection API – metaobject classification functions

- Indicate *what* does a metaobject reflect
- Return `bool` value
- `auto reflects_object(metaobject auto m) -> bool;`
- `auto reflects_{object_sequence, named, alias, typed, scope, scope_member, enumerator, record_member, base, namespace, global_scope, type, enum, record, class, lambda, constant, variable, lambda_capture, function_parameter, callable, function, member_function, special_member_function, constructor, destructor, operator, conversion_operator, expression, parenthesized_expression, function_call_expression}(metaobject auto m) -> bool;`
- Typically used in `requires` clauses or in `if constexpr`

Reflection API – metadata retrieval functions

- Return individual "atomic" pieces of metadata
- Some are applicable to all metaobjects
  - `get_source_line`, `get_source_column`, `reflect_same`, ...
- Some only work on metaobjects reflecting specific *base-level* entities
  - where they make sense,
  - `get_name`, `get_type`, `get_scope`, `get_enumerators`, ...

Reflection API – metadata retrieval functions

- Return one of these things:
  - boolean values (`is_static`),
  - integer values (`get_source_line`),
  - other constant values[7] (`get_constant`),
  - pointers or references[8] (`get_pointer`),
  - strings[9] (`get_source_file_name`, `get_name`),
  - types[10] (`get_reflected_type`),
  - other metaobjects (`get_scope`, `get_data_members`).

[7] like enumerators
[8] to values, data member, functions
[9] string views actually
[10] more precisely `type_identity`

Reflection API – somewhere in logging...

```
auto get_display_name(metaobject auto mo) -> string_view
  requires(reflects_named(mo));
```

```
void log_who_did_this(
  metaobject auto mo,
  ostream& log) {
  if constexpr(reflects_global_scope(mo)) {
    log << "it was the global scope!"
  } else if constexpr(reflects_named(mo)) {
    log << "it was " << get_display_name(mo);
  } else {
    log << "how the [:^#%@:]! should I know?"
  }
  log << " "
      << "(" << get_source_file_name(mo)
      << ":" << get_source_line(mo)
      << "," << get_source_column(mo)
      << ")";
}
```

Metadata getters – source location

```
auto get_source_file_name(metaobject auto)
  -> string_view;
```

```
auto get_source_line(metaobject auto)
  -> unsigned long;
```

```
auto get_source_column(metaobject auto)
  -> unsigned long;
```

Metadata getters – names

```
auto get_name(metaobject auto mo) -> string_view
  requires(reflects_named(mo));
```

"basic_string"

```
auto get_display_name(metaobject auto mo) -> string_view
  requires(reflects_named(mo));
```

"string"

```
auto get_full_name(metaobject auto mo) -> string;
```

"std::basic_string<char, ...>"

Metadata getters – specifiers

```
auto is_constexpr(metaobject auto mo) -> bool
  requires(reflects_variable(mo) ||
           reflects_callable(mo));
```

```
auto is_noexcept(metaobject auto mo) -> bool
  requires(reflects_callable(mo));
```

```
auto is_explicit(metaobject auto mo) -> bool
  requires(reflects_constructor(mo) ||
           reflects_conversion_operator(mo));
```

```
auto is_static(metaobject auto mo) -> bool
  requires(reflects_variable(mo) ||
           reflects_member_function(mo));
```

```
auto is_virtual(metaobject auto mo) -> bool
  requires(reflects_base(mo) ||
           reflects_destructor(mo)) ||
           reflects_member_function(mo));
```

Metadata getters – miscelaneous

```
auto is_scoped_enum(metaobject auto mo) -> bool
  requires(reflects_type(mo));
```

```
auto uses_class_key(metaobject auto mo) -> bool
  requires(reflects_type(mo));
```

```
auto uses_default_copy_capture(metaobject auto mo) -> bool
  requires(reflects_lambda(mo));
```

```
auto is_explicitly_captured(metaobject auto mo) -> bool
  requires(reflects_lambda_capture(mo));
```

```
auto has_default_argument(metaobject auto mo) -> bool
  requires(reflects_function_parameter(mo));
```

Metadata getters – miscelaneous

```
auto has_lvalueref_qualifier(metaobject auto mo) -> bool
  requires(reflects_member_function(mo));
```

```
auto is_implicitly_declared(metaobject auto mo) -> bool
  requires(reflects_special_member_function(mo));
```

```
auto is_deleted(metaobject auto mo) -> bool
  requires(reflects_callable(mo));
```

```
auto is_defaulted(metaobject auto mo) -> bool
  requires(reflects_special_member_function(mo));
```

```
auto is_move_constructor(metaobject auto mo) -> bool
  requires(reflects_constructor(mo));
```

Metadata getters – constants and values

```
auto get_constant(metaobject auto mo) -> const auto
  requires(reflects_constant(mo));
```

```
auto get_value(metaobject auto mo) -> const auto&
  requires(reflects_variable(mo));
```

```
auto get_value(metaobject auto mo, auto& obj) -> const auto&
  requires(reflects_record_member(mo) &&
           reflects_variable(mo));
```

Metadata getters – references and pointers

```
auto get_reference(metaobject auto mo) -> auto&
  requires(reflects_variable(mo));
```

```
auto get_reference(metaobject auto mo, auto& obj) -> auto&
  requires(reflects_record_member(mo) &&
           reflects_variable(mo));
```

```
auto get_pointer(metaobject auto mo) -> auto*
  requires(reflects_variable(mo) ||
           reflects_function(mo));
```

```
auto get_pointer(metaobject auto mo, auto& obj) -> auto*
  requires(reflects_record_member(mo) &&
           reflects_variable(mo));
```

Metadata getters – invocation of callables

```
auto invoke(metaobject auto mo, auto&&... args)
  requires(reflects_member_function(mo) &&
           is_static(mo));
```

```
auto invoke(auto mo, auto& inst, auto&&... args)
  requires(reflects_member_function(mo) &&
           !is_static(mo));
```

```
auto invoke(metaobject auto mo, auto&&... args)
  requires(reflects_constructor(mo));
```

```
auto invoke_on(auto mo, auto& inst, auto&&... args)
  requires(reflects_member_function(mo));
```

Metadata getters – metaobjects

```
auto get_scope(metaobject auto mo)
  requires(reflects_scoped(mo));
```

```
auto get_type(metaobject auto mo)
  requires(reflects_typed(mo));
```

```
auto get_underlying_type(metaobject auto mo)
  requires(reflects_enum(mo));
```

```
auto get_aliased(metaobject auto mo)
  requires(reflects_alias(mo));
```

```
auto get_class(metaobject auto mo)
  requires(reflects_base(mo));
```

```
auto get_subexpression(metaobject auto mo)
  requires(reflects_parenthesized_expression(mo));
```

Metadata getters – *base-level* types

```
template <metaobject MO>
using get_reflected_type_t = unspecified;
```

```
auto get_reflected_type(metaobject auto mo)
  -> type_identity<unspecified>
  requires(reflects_type(mo));
```

```
template <typename T>
auto is_type(
  metaobject auto mo,
  type_identity<T> = {})
  -> bool requires(reflects_type(mo));
```

```
template <template <typename> class Trait>
auto has_type_trait(metaobject auto mo)
  -> bool requires(reflects_type(mo));
```

Metaobject sequences

- Are (special kind of) metaobjects themselves
- Represent collections of other metaobjects
- Returned by many metaobject operations
  - base classes,
  - data members,
  - member functions,
  - constructors, destructors,
  - enumerators,
  - ...
- Initially the metaobject elements of a sequence are not materialized
- Only “unpacked” if necessary to improve performance

Metaobject sequences – getting sequences

```
auto get_base_classes(metaobject auto mo)
  requires(reflects_class(mo));
```

```
auto get_captures(metaobject auto mo)
  requires(reflects_lambda(mo));
```

```
auto get_constructors(metaobject auto mo)
  requires(reflects_record(mo));
```

```
auto get_data_members(metaobject auto mo)
  requires(reflects_record(mo));
```

```
auto get_destructors(metaobject auto mo)
  requires(reflects_record(mo));
```

Metaobject sequences – getting sequences

```
auto get_enumerators(metaobject auto mo)
  requires(reflects_enum(mo));
```

```
auto get_member_functions(metaobject auto mo)
  requires(reflects_record(mo));
```

```
auto get_member_types(metaobject auto mo)
  requires(reflects_record(mo));
```

```
auto get_operators(metaobject auto mo)
  requires(reflects_record(mo));
```

```
auto get_parameters(metaobject auto mo)
  requires(reflects_callable(mo));
```

Metaobject sequences – basic operations

Is something a sequence?

```
auto is_object_sequence(metaobject auto mo) -> bool;
```

Is there anything in the sequence?

```
auto is_empty(metaobject auto mo) -> bool
  requires(is_object_sequence(mo));
```

How many elements are there?

```
auto get_size(metaobject auto mo) -> size_t
  requires(is_object_sequence(mo));
```

Get the I-th element

```
template <size_t I>
auto get_element(metaobject auto mo)
  requires(is_object_sequence(mo));
```

Concatenate

```
auto concat(metaobject auto... mo)
  requires((... && is_object_sequence(mo)));
```

Metaobject sequences – basic iteration

```
void for_each(metaobject auto mo, auto function)
  requires(is_object_sequence(mo));
```

```
for_each(
  get_enumerators(mirror(weekday)),
  [](metaobject auto mo) {
    cout << get_name(mo)
         << ": "
         << int(get_constant(mo))
         << endl;
  });
```

Placeholder expressions

- Placeholders
  - pre-defined constant objects – `_1`, `_2`, ...
- Placeholder expressions
  - Functions matching the metaobject operations in name taking, placeholders or other placeholder expressions as arguments
- Create objects (like lambdas) that can be called later
- Predicates, comparators, transformation functions
- Custom composite algorithms

Placeholder expressions – "huh?"

```
template <typename F>
struct placeholder_expr {
  auto operator()(auto... a) const;
  // ...
};
// CTAD guide + some specializations
```

```
constinit const placeholder_expr<...> _1{};
constinit const placeholder_expr<...> _2{};
```

```
template <typename X>
auto some_operation(placeholder_expr<X> e) {
  return placeholder_expr{[e](auto... a) {
    return some_operation(e(a...));
  }};
}
```

Placeholder expressions – predicates

```
reflects_named(_1);
reflects_destructor(_1);
is_static(_1);
is_pure_virtual(_1);
is_public(_1);
is_noexcept(_1);
is_constexpr(_1);
is_copy_constructor(_1);
has_rvalueref_qualifier(_1);
uses_class_key(_1);
is_type<int>(get_type(_1));
has_type_trait<std::is_floating_point>(_1);
```

Placeholder expressions – comparators

```
reflect_same(_1, _2);
get_name(_1) < get_name(_2);
get_sizeof(_1) == get_sizeof(_2);
get_size(get_name(_1)) > get_size(get_name(_2));
```

Placeholder expressions – transforms

```
get_type(_1);
get_scope(_1);
get_display_name(_1);
get_name(get_aliased(_1));
get_name(get_aliased(get_type(_1)));
get_size(get_enumerators(_1));
is_empty(get_data_members(_1));
get_size(get_name(get_scope(get_type(_1))));
get_type(get_element<0>(get_operators(_1)));
get_name(get_element<1>(get_parameters(_1)));
```

Algorithms

- Implement small, specific, but non-trivial functionality
- On top of the primitive metaobject operations
- Can be easily combined in many ways into bigger, custom algorithms
- Can form and inter-operate with placeholder expressions
- Promote code re-usability
- Mostly operate on metaobject sequences
- Splicing can be done in the function objects passed to the algorithms

Algorithms – transform

Takes a sequence, returns new sequence containing metaobjects that are the result of applying a transformation `function`

```
auto transform(auto mo, auto function)
  requires(is_object_sequence(mo));
```

```
auto get_parameter_types = transform(
    get_parameters(_1),
    get_type(_1));

auto get_base_class_types = transform(
    get_base_classes(_1),
    get_class(_1));
```

Algorithms – filter, remove-if

Takes a sequence, returns new sequence containing only metaobjects satisfying a predicate

```
auto filter(auto mo, auto predicate)
  requires(is_object_sequence(mo));
```

Takes a sequence, returns new sequence containing only metaobjects *not* satisfying a predicate

```
auto remove_if(auto mo, auto predicate)
  requires(is_object_sequence(mo));
```

```
auto get_virtual_functions =
  filter(get_member_functions(_1), is_virtual(_1));

auto get_nonstatic_members =
  remove_if(get_data_members(_1), is_static(_1));
```

Algorithms – count-if

Takes a sequence, returns the count of metaobjects satisfying a predicate

```
auto count_if(auto mo, auto predicate)
  requires(is_object_sequence(mo));
```

```
auto count_public_bases =
  count_if(
    get_base_classes(_1),
    is_public(_1));

auto count_integer_members =
  count_if(
    get_data_members(_1),
    has_type_trait<is_integral>(get_type(_1)));
```

Algorithms – find-if, find-if-not

Takes a sequence, returns the first metaobject satisfying a predicate

```
auto find_if(auto mo, auto predicate)
  requires(is_object_sequence(mo));
```

Takes a sequence, returns the first metaobject *not* satisfying a predicate

```
auto find_if_not(auto mo, auto predicate)
  requires(is_object_sequence(mo));
```

```
auto find_function_foo = find_if(
    get_member_functions(_1),
    [](auto mo) { return has_name(mo, "foo"); });

auto find_nonstatic_member = find_if_not(
    get_data_members(_1),
    is_static(_1));
```

Algorithms – find-ranking

Takes a sequence, applies a query function returning a value on each metaobject. Returns the metaobject for which the value is *largest* according to a compare function[11].

```
auto find_ranking(
  auto mo, auto query, auto compare)
  requires(is_object_sequence(mo));

auto find_ranking(auto mo, auto query)
  requires(is_object_sequence(mo));
```

```
auto find_largest_data_member =
  find_ranking(
    get_data_members(_1),
    get_sizeof(get_type(_1)));
```

[11] if unspecified then less-than is used

Algorithms – get-top-value

Takes a sequence, applies a query function returning a value on each metaobject. Returns the *value* which is *largest* according to a compare function[12].

```
auto get_top_value(
  auto mo, auto query, auto compare)
  requires(is_object_sequence(mo));

auto get_top_value(auto mo, auto query)
  requires(is_object_sequence(mo));
```

```
    auto get_max_arity =
      get_top_value(
        get_member_functions(_1),
        get_size(get_parameters(_1)));
```

[12] if unspecified then less-than is used

Algorithms – choose

Takes a sequence, finds the first metaobject for which a `condition` is satisfied. If found, returns the result of a `transform` function on that metaobject, otherwise returns the `fallback` value.

```
auto choose(
  auto fallback,
  auto mo
  auto condition,
  auto transform) -> decltype(fallback)
  requires(is_object_sequence(mo));
```

Algorithms – the gist...

- There are more such algorithms
  - `fold`
  - `join`
  - `is_sorted`
  - `all_of`, `any_of`, `none_of`
  - `...`
- Named algorithms convey meaning of code better
- Typically require less typing than writing for-loops
- They may hide some compiler magic
  - `filter`, `transform`,
  - `...`

Composition

- The super-power of named algorithms
- Together with the primitive operations and the placeholder expressions, the basic algorithms can be *combined* into bigger, custom algorithms in-place
- Some examples follow...

Are enumerators consecutive?

```
enum class digits {
    zero = 0,
    one,
    two,
    three,
    four,
    five,
    six,
    seven,
    eight,
    nine
};
```

```
enum class po2s {
    one = 1,
    two = 2,
    four = 4,
    eight = 8,
    sixteen = 16,
    thirty_two = 32
};
```

Are enumerators consecutive?

```
auto are_consecutive = is_sorted(
  get_enumerators(_1),
  [](metaobject auto l, metaobject auto r) {
      return int(get_constant(l)) ==
             int(get_constant(r)) - 1;
  });
```

```
cout << are_consecutive(mirror(digits))<< endl;
cout << are_consecutive(mirror(po2s)) << endl;
```

Output:

```
1
0
```

Find enumerator with longest name

```
void print_enum(metaobject auto mo) {
  auto find_enum_with_longest_name =
    find_ranking(
      get_enumerators(_1),
      get_size(get_name(_1)));

  auto me = find_enum_with_longest_name(mo);

  cout << get_name(me)
       << ", length: "
       << get_name(me).size()
       << ", value: "
       << int(get_constant(me))
       << endl;
}
```

Find enumerator with longest name

```
enum class weekday : int {
    monday = 1,
    tuesday,
    wednesday,
    thursday,
    friday,
    saturday,
    sunday
};
```

```
enum class month : int {
    january = 1,
    february,
    march,
    april,
    may,
    june,
    july,
    august,
    september,
    october,
    november,
    december
};
```

```
print_enum(mirror(weekday));
print_enum(mirror(month));
```

Output:

```
wednesday, length: 9, value: 3
september, length: 9, value: 9
```

Does a class have overloaded functions?

```
const auto has_overloaded_functions =
  any_of(
    group_by(
      get_member_functions(_1),
      get_name(_1)),
    [](auto ms) {
      return get_size(ms) > 1Z;
    });
```

Does a class have overloaded functions?

```
struct foo {
  int plus(int x) { return x; }

  int plus(int x, int y) {
    return x + y;
  }
  int plus(int x, int y, int z) {
    return x + y + z;
  }
  int minus(int x) {
    return -x;
  }
  int minus(int x, int y) {
    return x - y;
  }
};
```

```
struct bar {
  int a() {
    return 0;
  }
  int b() {
    return 1;
  }
  int c() {
    return 2;
  }
};
```

```
cout << boolalpha << has_overloaded_functions(mirror(foo))<< endl;
cout << boolalpha << has_overloaded_functions(mirror(bar))<< endl;
```

Output:

```
true
false
```

Does a structure have some padding?

```
template <typename... T>
auto sum_sizeofs(type_list<T...>) -> bool {
    return (0Z + ... + sizeof(T));
}

template <typename T>
auto has_padding[13]() -> bool {
    return sizeof(T) >
           sum_sizeofs(extract_types[14](transform(
             filter(get_data_members(mirror(T)),
                    not_(is_static(_1))),
             get_type(_1))));
}
```

[13] is bigger than the sum of its parts?

[14] note that this operation involves splicing – getting base-level types from meta-types

Does a structure have some padding?

```cpp
struct S1 {
    int i;
    float f;
};
```

```cpp
struct S2 {
    char c;
    double d;
};
```

```cpp
template <typename T>
void print_has_padding() {
  cout << get_name(remove_all_aliases(mirror(T)))
       << ": " << (has_padding<T>() ? "has some" : "has no")
       << " padding\n";
}
```

```cpp
print_has_padding<S1>();
print_has_padding<S2>();
```

Output:

```
S1: has no padding
S2: has some padding
```

Are data members sorted by size?

```
struct foo {
    double d;
    int i;
    short s;
    char c;
};
```

```
struct bar {
    int i;
    float f;
    long l;
    bool b;
};
```

```
const auto are_sorted_by_size = is_sorted(
  get_data_members(_1),
  get_sizeof(_1) < get_sizeof(_2));
```

```
cout << boolalpha << are_sorted_by_size(mirror(foo))<< endl;
cout << boolalpha << are_sorted_by_size(mirror(bar))<< endl;
```

```
true
false
```

Hello again!

```
enum class greeting {
  hello, world, of, reflection
};
```

```
cout << join[15](
      get_enumerators[16](mirror[17](greeting)[18]),
      to_string(get_name[19](_1[20]))[21],
      string(" ")) << "!\n";
```

[15] algorithm
[16] metaobject sequence getter
[17] reflection operator
[18] reflection in action – returns a metaobject
[19] metadata (name) getter
[20] placeholder
[21] placeholder expression

Enumeration conversions – enum-to-string

```
template <typename E>
auto enum_to_string(E e) noexcept
  -> string_view {

  return choose(
    string_view{},
    get_enumerators(mirror(E)),
    has_value(_1, e),
    get_name(_1));
}
```

Enumeration conversions – string-to-enum

```
template <typename E>
auto string_to_enum(string_view s) noexcept
  -> optional<E> {

  return choose(
    optional<E>{},
    get_enumerators(mirror(E)),
    has_name(_1, s),
    get_value(_1));
}
```

Calculation of interface revision id

```
template <typename Intf>
struct versioned_interface {
public:
  static auto revision_id() noexcept -> hash_t {
    return fold(
      filter(
        get_member_functions(mirror(Intf)),
        is_virtual(_1)),
      get_hash(_1) ^ get_hash(get_type(_1)),
      [](auto... h) { return (... ^ h); });
  }
};
```

Calculation of interface revision id

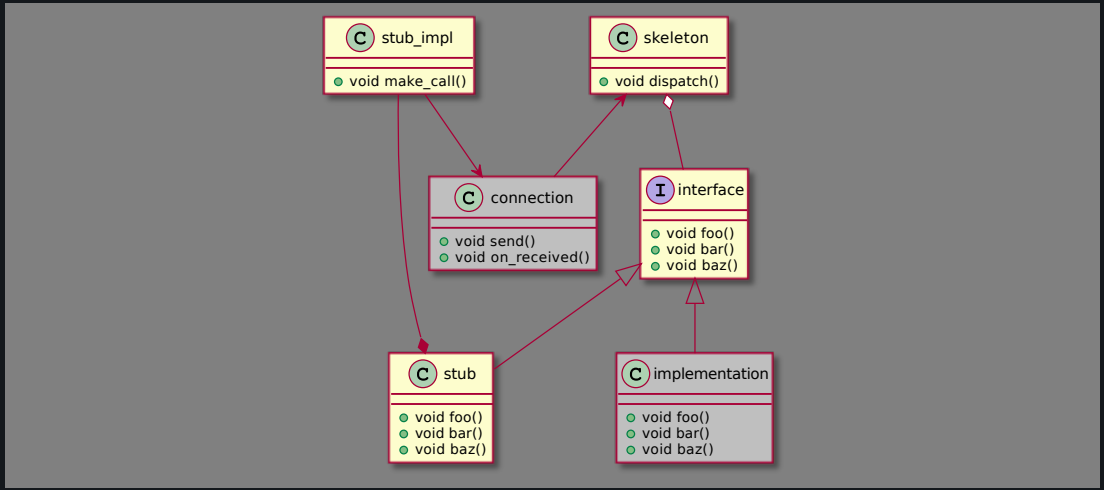
```
// initially
struct operations : versioned_interface<operations> {
  virtual void foo() = 0;
  virtual void bar(int) = 0;
  virtual auto baz(bool, bool) -> bool = 0;
};
cout << hex << operations::revision_id() << endl;
```

```
d423c43e4eabdc
```

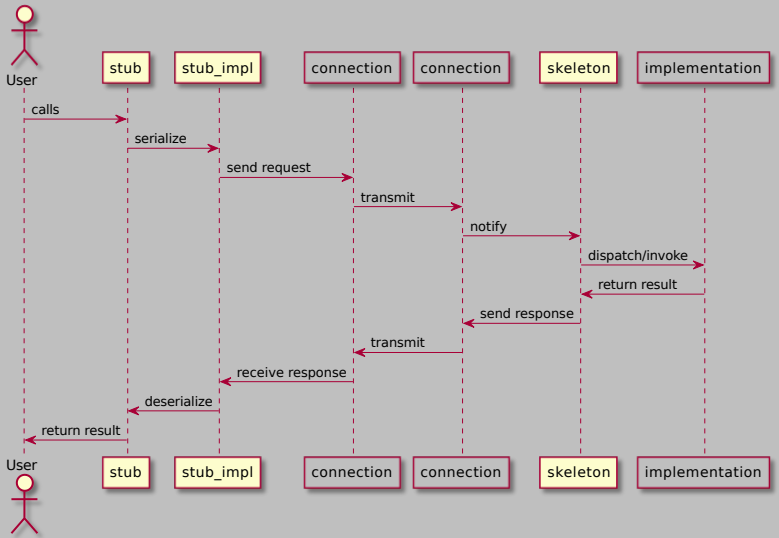
```
// later
struct operations : versioned_interface<operations> {
  virtual void foo() = 0;
  virtual void bar(long) = 0;
  virtual auto baz(bool, bool) -> int = 0;
};
cout << hex << operations::revision_id() << endl;
```

```
ef4203c133db7600
```

Remote procedure calls – class overview



Remote procedure calls – synchronous call sequence



RPC stubs/skeletons – the interface

```
struct calculator {
    virtual float add(float, float) = 0;
    virtual float subtract(float, float) = 0;
    virtual float multiply(float, float) = 0;
    virtual float divide(float, float) = 0;
    virtual float negate(float) = 0;
    virtual float invert(float) = 0;
};
```

RPC stubs/skeletons – the stub

```
class calculator_stub : public calculator {
private:
    rpc_stub_impl _impl;
public:
  float add(float l, float r) final {
    return _impl.make_call(
      mirror((calculator::add(l, r)))[22], l, r);
  }

  float subtract(float l, float r) final {
    return _impl.make_call(
      mirror((calculator::subtract(l, r))), l, r);
  }
  float multiply(float l, float r) final;
  float divide(float l, float r) final;
  float negate(float x) final;
  float invert(float x) final;
};
```

RPC stubs/skeletons – the generic stub implementation

```
class rpc_stub_impl {
  template <typename T>
  auto _deserialize(packet&, type_identity<T>) -> T;
public:
  auto make_call(metaobject auto mo, auto&... args)
    requires(reflects_function_call_expression(mo)) {
    packet request;
    _serialize(request, mo, args...);
    packet response{_send_and_receive(request)};

    return _deserialize(
      response,
      get_reflected_type(
        get_type(
          get_callable(
            get_subexpression(mo)))));
  }
};
```

RPC stubs/skeletons – the skeleton interface

```
struct rpc_skeleton {
  virtual void dispatch(
    packet& request,
    packet& response) = 0;
};
```

- Could be plugged-into a network connection
- Handles incoming data
- After call is finished the connection can send the response

RPC stubs/skeletons – the skeleton implementation[23]

```
template <typename Intf>
class rpc_skeleton_impl : public rpc_skeleton {
private:
  std::unique_ptr<Intf> _impl;
public:
  void dispatch(packet& request, packet& response) final {
    const auto method_id{_get_method_id(request)};

    for_each(get_member_functions(mirror(Intf)),
      [&](auto mf) {
        if(_get_method_id(mf) == method_id) {
          auto params = make_value_tuple(
            transform(get_parameters(mf), get_type(_1)));

          deserialize(params, request);
          auto result = apply(mf, *_impl, params);
          serialize(method_id, result, response);
        }
    });
  }
}
```

Scripting – is fun, hand-coding bindings, not so much

```
void add_to(chaiscript::ChaiScript& chai, auto mos)
  requires(is_object_sequence(mos));
```

```
void do_add_to(
chaiscript::ChaiScript& chai,
metaobject auto mo[24],
metaobject auto ms[25]) {
  if constexpr(reflects_object_sequence(mo)) {
    /* ... */
  } else if constexpr(reflects_base(mo)) {
    /* ... */
  } else {
    const string name{get_name(mo)};
    if constexpr(reflects_variable(mo)) {
    } else if constexpr(reflects_constructor(mo)) {
    } else if constexpr(reflects_function(mo)) {
    } else if constexpr(reflects_record(mo)) {
    }
  }
}
```

Scripting – handling sequences[26]

```
void do_add_to(
  chaiscript::ChaiScript& chai,
  metaobject auto mo,
  metaobject auto ms) {
    if constexpr(reflects_object_sequence(mo)) {
      for_each(mo, [&](auto me) {
        do_add_to(chai, me, ms);
      });
    } else if constexpr(reflects_base(mo)) {
      /* ... */
    } else {
      /* ... */
    }
}
```

[26] "That's easy!" – sir Robin of Camelot

Scripting – base classes

```
template <typename Base, typename Derived>
void add_base_class(
  chaiscript::ChaiScript& chai,
  type_identity<Base>,
  type_identity<Derived>) {
    chai.add(chaiscript::base_class<Base, Derived>());
}
```

```
void do_add_to(
  chaiscript::ChaiScript& chai,
  metaobject auto mo,
  metaobject auto ms) {
    if constexpr(reflects_object_sequence(mo)) {
    } else if constexpr(reflects_base(mo)) {
      add_base_class(
        chai,
        get_reflected_type(get_class(mo)),
        get_reflected_type(ms));
    } else {
      /* ... */
    }
}
```

Scripting – variables and data members

```
const string name{get_name(mo)};

if constexpr(reflects_variable(mo)) {
  if constexpr(reflects_record_member(mo)) {
    if constexpr(is_public(mo)) {
        chai.add(chaiscript::fun(
          get_pointer(mo)), name);
    }
  } else {
    chai.add(chaiscript::var(
        get_reference(mo)), name);
  }
}
```

Scripting – constructors

```
template <typename T, typename... P>
void add_constructor(
  chaiscript::ChaiScript& chai,
  type_identity<T>,
  type_list<P...>,
  const string& name) {
    chai.add(chaiscript::constructor<T(P...)>(), name);
}
```

```
const string name{get_name(mo)};

if constexpr(reflects_constructor(mo)) {
  if constexpr(is_public(mo)) {
      add_constructor(
        chai,
        get_reflected_type(get_scope(mo)),
        extract_types(transform(
          get_parameters(mo),
          get_type(_1))),
        name);
  }
}
```

Scripting – functions and operators

```
template <typename From, typename To>
void add_conversion(
  chaiscript::ChaiScript& chai,
  type_identity<From>,
  type_identity<To>) {
    chai.add(chaiscript::type_conversion<From, To>());
}
```

```
if constexpr(reflects_function(mo)) {
  if constexpr(reflects_record_member(mo) && is_public(mo)) {
      if constexpr(reflects_conversion_operator(mo)) {
        if constexpr(!is_deleted(mo)) {
            add_conversion(
              chai,
              get_reflected_type(get_scope(mo)),
              get_reflected_type(get_type(mo)));
        }
      } else {
        if constexpr(!is_deleted(mo)) {
          chai.add(chaiscript::fun(get_pointer(mo)), name);
        }
      }
  } else {
    chai.add(chaiscript::fun(get_pointer(mo)), name);
  }
}
```

Scripting – types and classes

```
template <typename T>
void add_type(
  chaiscript::ChaiScript& chai,
  type_identity<T>,
  const string& name) {
    chai.add(chaiscript::user_type<T>(), name);
}
```

```
const string name{get_name(mo)};

if constexpr(reflects_record(mo)) {
  add_type(chai,  get_reflected_type(mo), name);
  do_add_to(chai, get_base_classes(mo), mo);
  do_add_to(chai, get_member_types(mo), mo);
  do_add_to(chai, get_data_members(mo), mo);
  do_add_to(chai, get_constructors(mo), mo);
  do_add_to(chai, get_member_functions(mo), mo);
  do_add_to(chai, get_operators(mo), mo);
}
```

Scripting – Monty C++'s Flying Circus

```
class scene {
public:
  void person_says(
    const person&, string_view line);
  void person_relocates(
    person& p, string_view how);
  void event_happens(
    string_view what);
  void pause();
};
```

```
class person {
public:
  person(string name);

  auto name() const -> string_view;
  auto current_location() -> auto&;
  auto enter(location&);
  auto is_thrown_to(location&);
  void say(const string&);
};
```

```
class location {
public:
  location(string name, scene&);
  auto name() const -> string_view;
};
```

```
class king : public person {
public:
  king(string name);
};
```

```
class mysterious_force {
public:
  mysterious_force(location&);
  void throw_into_chasm(person&);
};
```

Scripting – set the scene...

```
scene at_the_bridge;
chaiscript::ChaiScript chai;

add_to(
  chai, make_sequence(
  mirror(mysterious_force),
  mirror(scene), mirror(location),
  mirror(person), mirror(king), mirror(at_the_bridge)));
```

```
chai[27](R"(
  var road = location("road leading to the bridge", at_the_bridge);
  var bridge = location("bridge of death", at_the_bridge);
  var chasm = location("chasm", at_the_bridge);

  var the_force = mysterious_force(chasm);

  var bridgekeeper = person("the Bridgekeeper");
  var king_arthur = king("king Arthur");
  var sir_lancelot = person("sir Lancelot");
  var sir_robin = person("sir Robin");
  var sir_galahad = person("sir Galahad");
  var sir_bedevere = person("sir Bedevere");
)");
```

[27] should have done this in Python!

Scripting – . . . and *action!*

```
chai(R"(
  bridgekeeper.enter(bridge);
  king_arthur.enter(road);
  sir_lancelot.enter(road);
  sir_robin.enter(road);
  sir_galahad.enter(road);
  sir_bedevere.enter(road);

  bridgekeeper.say(
    "Stop."
    "Who would cross the Bridge of Death "
    "must answer me these questions three, "
    "ere the other side he see.");
  sir_lancelot.say(
    "Ask me the questions, bridgekeeper. "
    "I am not afraid.");
  // ...
  the_force.throw_into_chasm(sir_robin);
  sir_robin.say("Auuuuuuuugh.");

  // ...
```

"Smart" concept definition – featuring CTRE!

```
template <typename T>
concept very_smart_integer[28] = ctre_match<
  "((signed|unsigned) )?"\
  "((long long|long|short)( int)?|int)"
>(get_name(remove_all_aliases(mirror(T))));

auto add(very_smart_integer auto l, very_smart_integer auto r) {
    return l + r;
}
```

```
cout << add(1U, 2U) << endl;
cout << add(short(3), short(4)) << endl;
cout << add(21, 21) << endl;
cout << add(400ULL, 20ULL) << endl;

cout << add(true, false) << endl; // NOPE!
```

[28] don't try this at home

Conclusions

- Reflection is *fun*
- Reflection is *useful*
- Reflection code can be readable
- Reflection code can be straightforward to write
- Reflection APIs can provide many non-trivial, reusable tools

There are so many use-cases – details in other talks

- Implementing the *factory* pattern
- Auto-registering with script language bindings
- Generating GUIs for visualization and data input
- Serialization and deserialization
- Implementing RPC/RMI stubs and skeletons
- Generating UML diagrams from code
- Generating DB system queries
- Fetching data from databases into C++ structures
- Generating `boost::spirit` parsers and formatters
- Parsing of configuration files
- Parsing of command-line arguments
- Mapping of URL arguments to function arguments
- ...

Where does all this come from?

- The *Mirror* library
  - primitive and sequence operations,
  - algorithms,
  - placeholder expressions,
  - examples and use-cases[29],
  - integration with other projects[30],
  - ...
- On top of the reflection TS implementation in `clang`
- There is much more than what fits into this talk
- See the reference (links below)

[29] including bigger ones

[30] CTRE, rapidjson, chaiscript, sqlite3, etc.

Links, shameless plugs, etc.

- *This presentation* – `https://matus-chochlik.github.io/mirror/latex/meeting_cpp.pdf`
- *The Mirror library repository* – `https://github.com/matus-chochlik/mirror`
- *The Mirror library reference (W.I.P.)* – `https://matus-chochlik.github.io/mirror/doxygen/`
- *Reflection TS in `clang`* – `https://github.com/matus-chochlik/llvm-project`
- *Reflection TS draft* – `https://cplusplus.github.io/reflection-ts/draft.pdf`

What's next for reflection?

- More splicing
- Code fragment splicing
- Splicing *identifiers* depending on metaobjects[31]
- Support for more use-cases

[31] maybe even with custom formatting

That's all folks...

Thanks for your attention.

Happy to answer any additional questions.

I lied – There is more

Additional API[32] – Operation name enums & generic functions

```
enum class trait {
  reflects_object,
  // ...
  reflects_expression,
  // ...
  is_call_operator_const,
  is_volatile,
  // ...
  is_public,
  is_static,
  is_virtual,
  // ...
  uses_default_copy_capture,
  // ...
};
```

```
template <trait T>
auto has_trait(
  metaobject auto) -> bool;
```

```
enum class operation {
  // ...
  get_name,
  get_type,
  // ...
  get_enumerators,
  // ...
};
```

```
template <operation O>
auto is_applicable(
  metaobject auto) -> bool;

template <operation O>
auto apply(metaobject auto);

template <operation O>
auto try_apply(metaobject auto)
    -> optional<...>;
```

[32] pseudocode

Additional API – Print all metaobject traits

```
void print_traits(metaobject auto mo) {
  const auto mes = get_enumerators(mirror(trait));
  const auto maxl =
    get_top_value(mes, get_size(get_name(_1)));

  cout << "traits of "
       << get_display_name(mo) << "\n";

  for_each(mes, [&](metaobject auto me) {
    cout << "  " << get_name(me)
         << ": "
         << string(maxl - get_name(me).size(), ' ')
         << boolalpha
         << has_trait<get_constant(me)>(mo)
         << "\n";
  });
  cout << endl;
}
```

Additional API – Print all metaobject traits

Output:

```
traits of std::string
reflects_object:                true
reflects_object_sequence:       false
reflects_named:                 true
reflects_alias:                 true
reflects_typed:                 false
reflects_scope:                 true
reflects_scope_member:          true
reflects_enumerator:            false
reflects_record_member:         false
reflects_base:                  false
reflects_namespace:             false
reflects_global_scope:          false
reflects_type:                  true
reflects_enum:                  false
reflects_record:                true
...
```

Parsing command-line arguments – into a structure

```
class program_arg {
public:
  auto next() -> program_arg;
  auto is_long_tag(...) -> bool;
  operator string_view();
};
```

```
class program_args {
public:
  program_args(int, const char**);
  auto begin();
  auto end();
};
```

```
template <typename T>
bool parse(
  T& opts,
  const program_args& args);
```

```
struct options {
  string message{"Hi world!"};
  milliseconds interval{500};
  int count{3};
};
```

```
int main(
  int argc,
  const char** argv) {
  const program_args
      args{argc, argv};
  options opts;
  if(parse(opts, args)) {
    // do something
    return 0;
  }
  return 1;
}
```

Auto-parsing command-line arguments – with reflection and splicing

```
template <typename T>
bool parse(T& opts, const program_args& args) {
  bool parsed = true;
  for(const auto& arg : args) {
    for_each(get_data_members(mirror(T)), [&](auto mdm) {
      if(arg.is_long_tag(get_name(mdm))) {
        if(const auto opt{from_string(
          arg.next(), get_reflected_type(get_type(mdm)))}
        ) {
          get_reference(mdm, opts) = opt.value();
        } else {
          std::cerr << "invalid value '" << arg.next()
                    << "' for option " << arg
                    << "!" << std::endl;
          parsed = false;
        }
      }
    });
  }
  return parsed;
}
```

MOAR “smart” concepts!

```
struct excellent {
    void foo() {}
    void bar() {}
    void baz() {}
};
```

```
template <typename T>
concept has_foo_and_such = any_of(
  get_member_functions(mirror(T)),
  ctre_match<"foo|bar|baz">(get_name(_1)));
```

```
void foonction(has_foo_and_such auto) {
    cout << "this is excellent!" << endl;
}
```

```
foonction(excellent{});
foonction(std::string{}); // ERROR
```

Min/max enumerator value

```cpp
auto min_enum = get_top_value(
  get_enumerators(_1),
  get_constant(_1),
  std::greater<>{});
```

```cpp
auto max_enum = get_top_value(
  get_enumerators(_1),
  get_constant(_1),
  std::less<>{});
```

```cpp
auto print_info = [&](auto me) {
  cout << get_name(me)
       << ":  min(" << enum_to_string(min_enum(me))
       << "), max(" << enum_to_string(max_enum(me))
       << ")" << std::endl;
};
```

Are enumerators bitfield bits?

```
const auto is_bitfield_enum =
  is_sorted(get_enumerators(_1), [](auto l, auto r) {
    if constexpr(has_type_trait<is_signed>(
      get_underlying_type(get_type(l)))) {
      return false;
    } else {
      auto to_underlying = [](auto e) {
        using U = underlying_type_t<decltype(e)>;
        return static_cast<U>(e);
      };
      return to_underlying(get_constant(l)) << 1U ==
             to_underlying(get_constant(r));
    }
  });
```

Have classes the same structure?

```
auto have_same_structure = [](
  metaobject auto ml,
  metaobject auto mr) {

  const auto structure_hash = fold(
      get_data_members(_1),
      get_hash(get_type(_1)),
      [](auto... h) {
        return (... ^ h);
      });

  return structure_hash(ml) ==
         structure_hash(mr);
};
```

Have classes the same structure?

```
struct foo {
  int i;
  float f;
  std::string s;
};
```

```
struct bar {
  int j;
  float e;
  std::string z;
};
```

```
struct baz {
  long l;
  double d;
  char c;
  bool b;
};
```

```
cout << boolalpha
     << have_same_structure(mirror(foo), mirror(bar))
     << endl;
cout << boolalpha
     << have_same_structure(mirror(foo), mirror(baz))
     << endl;
```

Output:

```
true
false
```