C++ now

Reflection is Good for (Code) Health

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2024

YOURS TRULY

- Quantitative research technology at Tower Research Capital
  - High frequency trading firm based out of NYC
- Develop low latency trading systems (C++)
  - Nanoseconds and microseconds
- Develop high throughput research systems (C++ and Python)
  - O(terabytes) data

- Program analysis and functional programming in a past life
- Love performance, software abstractions, and clean APIs

The boring part

This talk's contents are mine and mine alone

- Not my employer's :)

OVERVIEW

- What is reflection
- Reflection in other languages (Go, Python, Java)
- Reflection in C++ as per P2996
  - Syntax and examples
- Reflection libraries!
  - Python bindings
  - ABI hashing (boost::abi_hash?)
  - A duck-typed std::any (boost::virtual_any?)
- Alternatives ways to achieve “reflection”

Reflection?

In code.

Reflection?

Ability to write code in a language such that:

- Access information about other “code” in a programmatic form and operate on it

```
class MyClass {
   int a;
   int b;
};
for (auto member_info : gimme_class_members<MyClass>()) {
   std::cout << "member - " << member_info.name() << std::endl;
}
```

Reflection?

How is this different from metaprogramming / templates?

Reflection?

- Not much :)
- Operate on constexpr values instead of types
  - Syntactic difference, not semantic
- Compiler can provide richer “information” about code
  - Some of it is already there
  - A neat and consistent “bag” of features to expand in the future

Runtime Reflection

Ability to access information about other “code” at runtime

- Could be done in interpreted or compiled languages
  - But generally seen in interpreted languages

```
class MyClass:
    def __init__(self):
        self.x = 1
        self.y = 2
for member_name, member_value in MyClass().__dict__.items():
    print(f"{member_name}: {member_value}")
```

Compile Time Reflection / Static reflection

Ability to access information about other “code”:

- At compile time

```
class MyClass {
    int a;
    int b;
};
for (auto member_info : gimme_class_members<MyClass>()) {
    if (is_ptr(member_info)) { ... }
}
```

Examples from other languages

Venturing into some alien worlds

My favorite example: Python

At runtime your code can:

- Modify other code to do entirely different things when a method is called.
- Say you run some code and it can change what a method on your object actually does.
- Change what it means to access a field on an object.
- Add new methods or attributes to any object.

Fun with reflection - Python

```python
def modify_cls(cls):
    if not hasattr(cls, "copy"):
        return cls
    orig_copy = cls.copy
    def _wrapped_copy(obj):
        print("Calling wrapped copy")
        attrs = obj.__dict__.keys()
        print("Attributes: " +
              " ".join(attrs))
        result = orig_copy(obj)
        return result
    cls.copy = _wrapped_copy
```

```python
class MyClass:
    def __init__(self, x):
        self.x = x
    def copy(self):
        return MyClass(self.x)

>>> modify_cls(MyClass)
>>> MyClass(2).copy()
Calling wrapped copy
Attributes: x
<__main__.MyClass object at 0x7f1a9e6>
```

Golang

- Golang is a compiled but duck-typed language
  - Well, structurally typed, but close enough
- Relies heavily on interfaces
- Runtime reflection similar to python.
  - No special compile time constructs
  - Uses the `reflect` package’s methods to get “reflection values”.

Duck typing?

Duck.go

```go
type Vehicle interface {
   Start() string
}
type Car struct {
   Make  string
}
func (this Car) Start() {  // Car::Start(Car* this)
   return "Brrr"
}
type Truck struct {
   WheelCount int
}
func (this Truck) Start() {
   return "Brhhhhhhhhh"
}
```

```go
func (v Vehicle) SelfDrive() {
   fmt.Println(v.Start())
}

func main() {
   vehicles := []Vehicle{
      Car{"Toyota"},
      Truck{4},
   }
   for _, v := range vehicles {
      SelfDrive(v)
   }
}
```

Fun with reflection - Golang

```
type T struct {
	A int
	B string
}
t := T{23, "skidoo"}
s := reflect.ValueOf(&t).Elem()
typeOfT := s.Type()
for i := 0; i < s.NumField(); i++ {
	f := s.Field(i)
	fmt.Printf("%d: %s %s = %v\n", i, typeOfT.Field(i).Name, f.Type(), f.Interface())
}
// 0: A int = 23
// 1: B string = skidoo
```

*https://go.dev/blog/laws-of-reflection

Java

- Surprisingly, quite similar in feel to Python and Go.
- Reflection is “runtime”, in the sense that the object type saves type information accessible at program runtime.
- `java.lang.reflect`

Fun with reflection - Java

```
Class cls = Class.forName("method1");  // Surprising, lookup types with string!
Method methlist[] = cls.getDeclaredMethods();
for (int i = 0; i < methlist.length; i++) {
   Method m = methlist[i];
   System.out.println("name = " + m.getName());
   System.out.println("decl class = " + m.getDeclaringClass());
}
Class pvec[] = m.getParameterTypes();
for (int j = 0; j < pvec.length; j++)
   System.out.println("param #" + j + " " + pvec[j]);
```

*https://www.oracle.com/technical-resources/articles/java/javareflection.html

Scary?

Zero cost abstractions

- Prior examples had “reflection objects” at runtime.
- Despite the temptation, we must do compile time
  - No one likes the cost of RTTI
- We can lean on constexpr algorithms and metaprogramming!
  - Compile time programming is turing complete after all :)

A new hope!

P2996

We have a syntax and an implementation!

- P2996 is a promising paper gaining traction.
  - Wyatt Childers, Peter Dimov, Dan Katz, Barry Revzin, Andrew Sutton, Faisal Vali, Daveed Vandevoorde
- Two working implementations already!
  - Edison Design Group (EDG) compiler on Godbolt
  - Clang fork by Bloomberg on Godbolt and GitHub
  - Godbolt link for both: https://godbolt.org/z/cGK4Eo6K1

We have a syntax and an implementation!

- Good consensus on syntax and some semantics.
- Value based reflection is an interesting choice
    - We’ll talk about it soon :)
- Prior work: Reflection TS
    - David Sankel - Type based reflection

We have a reflection operator

unary operator ^

“Lifts” into reflection land

i.e. produces a reflection value

- function
- variable and friends
- non-static data member
- template
- constant expression
- namespace
- ...

```
auto magic_reflection_method(std::meta::info obj) {
 .. do something with “meta” info ..
}

auto result = magic_reflection_method(^MyType);
```

We have a std::meta::info

A formless type that describes all meta-information about a type / member / method / etc.

```
auto magic_reflection_method(std::meta::info obj) {
 .. do something with “meta” info ..
}

auto result = magic_reflection_method(^MyType);
```

We have a splice operator

```
[: r :] =>
  Takes a std::meta::info
    Constant expression
  Splices it back into your
    regular code
```

```
struct MyStruct {
    static int a;
    static int b;
};
template <typename T>
void get_member(std::meta::info elem) {
    std::cout << T::[:elem:] << std::endl;
}
std::cout
    << get_member<MyStruct>(^MyStruct::a)
    << std::endl;
```

We have a std::meta::define_class

We can create classes in thin air! (almost)

Need to declare it first, need to name all the members and their types.

```
struct S;
static_assert(is_type(define_class(^S, {
    data_member_spec(^int, {
      .name="i", .align=64
    }),
    data_member_spec(^int, {
      .name="j", .align=64
    }),
})));
```

We have a std::meta::define_class

Equivalent of....

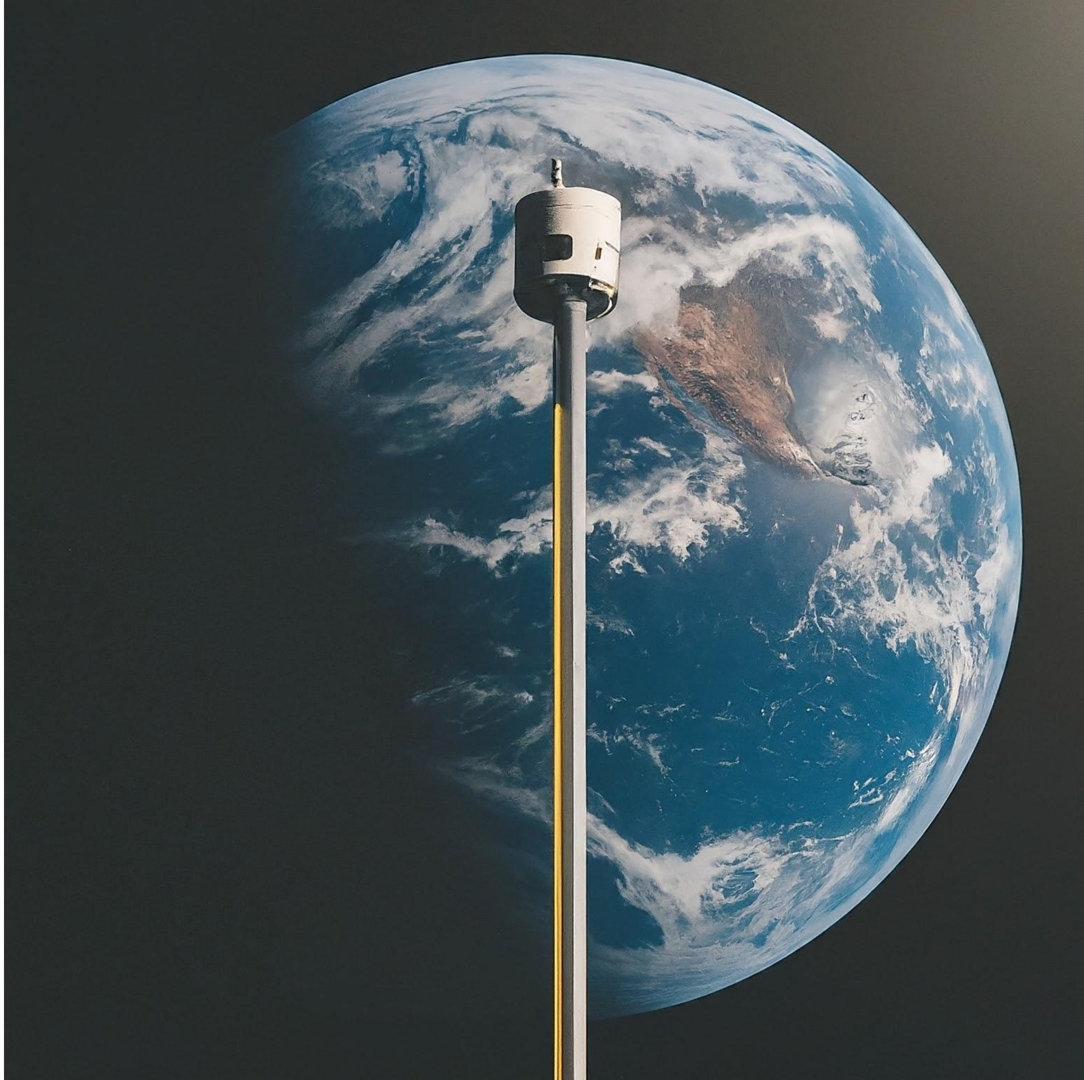
```
struct S;
struct S {
    alignas(64) int i;
    alignas(64) int j;
};
```

We have a lot of consteval methods to go with it

```
namespace std::meta {
  // [meta.reflection.names], reflection names and locations
  consteval string_view name_of(info r);
  consteval string_view qualified_name_of(info r);
  ...
  consteval bool is_function(info r);
  consteval bool is_variable(info r);
  consteval bool is_type(info r);
  // [meta.reflection.member.queries], reflection member queries
  template<class... Fs>
  consteval vector<info> members_of(info type, Fs... filters);
  ...
}
```

Elevator pitch

We really do need this in C++!



Enum to string

```
enum class MyEnum { VALUE_1, VALUE_2, MAX_VALUES };
template <typename EnumT> constexpr std::string enum_to_string(EnumT enum_value) {
   template for (constexpr auto e : std::meta::enumerators_of(^EnumT)) {
       if (enum_value == [:e:]) return std::string(std::meta::name_of(e));
   }
   return "<unnamed>";
}

template <typename EnumT> constexpr EnumT string_to_enum(std::string enum_str) {
  // some blackmagic
}
```

*copied from P2996

Easy cmdline parsing

```
struct MyOpts {
  std::string file_name = "input.txt";  // Option "--file_name <string>"
  int count = 1;                         // Option "--count <int>"
};

int main(int argc, char* argv[]) {
  MyOpts opts = parse_options<MyOpts>(
    std::vector<std::string_view>(argv + 1, argv + argc)
  );
}
```

*copied from P2996

Easy cmdline parsing

```
template <typename Opts> auto parse_options(ArgT args) -> Opts {
   Opts opts;
   template for (constexpr auto dm : nonstatic_data_members_of (^Opts)) {
       auto it = std::ranges::find_if(args, ... match string ...);
       auto iss = std::ispanstream(it[1]);
       if (iss >> opts.[:dm:]; !iss) {
           std::print(stderr, "Failed to parse option {}\n", *it);
           std::exit(EXIT_FAILURE);
       }
   }
   return opts;
}
```

*copied from P2996

Better cmdline parsing

```
struct Args : Clap {
   Option<std::string, {.use_short=true, .use_long=true}> name;
   Option<int, {.use_short=true, .use_long=true}> count = 1;
};

int main(int argc, char** argv) {
   auto opts = Args{}.parse(argc, argv);
   for (int i = 0; i < opts.count; ++i) {  // opts.count has type int
       std::print("Hello {}!", opts.name);   // opts.name has type std::string
   }
}
```

*copied from P2996

Operating on a class' layout

```
consteval auto get_layout() {
   constexpr auto members = nonstatic_data_members_of (^S);
   std::array<my_descriptor, members.size()> layout;
   for (int i = 0; i < members.size(); ++i) {
       layout[i] = {.offset = offset_of(members[i]), .size = size_of(members[i])};
   }
   return layout;
}
```

*copied from P2996

ARRAY OF STRUCTS TO STRUCT OF ARRAYS

```cpp
struct point {
   float x;
   float y;
};
using points = struct_of_arrays<point, 30>;
// equivalent to:
// struct points {
//   std::array<float, 30> x;
//   std::array<float, 30> y;
// };
```

*copied from P2996

Why this 'formless' std::meta::info?

Type vs Value based reflection

- Type based reflection is more intuitive
  - `std::meta::method` / `std::meta::variable` / `std::meta::class`
  - Can imagine writing template specializations etc
  - Maybe ranges and algorithms make life better with value based?

Type vs Value based reflection

- Type based reflection is more intuitive
  - `std::meta::method` / `std::meta::variable` / `std::meta::class`
  - Can imagine writing template specializations etc
  - Maybe ranges and algorithms make life better with value based?
- Slower to compile
  - Lot more types to handle for the compiler

Type vs Value based reflection - Compile times

```cpp
constexpr int f() {
    int i = 0;
    for (int k = 0; k < 10000; ++k)
        i += k;
    return i / 10000;
}
template <int N> struct S {
    static constexpr int sm = S<N - 1>::sm + f();
};
template <> struct S<0> {
    static constexpr int sm = 0;
};
constexpr int r = S<200>::sm;
```

```cpp
struct Int { int v; };
constexpr int f() {
    Int i = {0};
    for (Int k = {0}; k.v < 10000; ++k.v)
        i.v += k.v;
    return i.v / 10000;
}
template <int N> struct S {
    static constexpr int sm = S<N - 1>::sm + f();
};
template <> struct S<0> {
    static constexpr int sm = 0;
};
constexpr int r = S<200>::sm;
```

*copied from P1240R2

Type vs Value based reflection

- Type based reflection is more intuitive
  - `std::meta::method` / `std::meta::variable` / `std::meta::class`
  - Can imagine writing template specializations etc
  - Maybe ranges and algorithms make life better with value based?
- Slower to compile
  - Lot more types to handle for the compiler
- Makes language rigid by preventing future breakages
  - Major issue, downstream code can start depending on which type a specific reflection would be.
  - Sometimes might not be clear which type to classify a reflection into

Type vs Value based reflection

- We want users to write “duck typed” reflection code
  - They check if that reflection value has the feature they want from it
  - If so, you can use it in your desired context.
- Flexible because every usage would *ideally* be gated by a feature check
  - Easier to add feature checks compared to renaming meta classes
- Feature checks have better cross-interaction than inheritance

What do we know so far?

Language	Runtime or compile-time	Type or value based
Python	Runtime	?
Golang	?	?
Java	?	?
C++26 🤞	Compile-time	Value (std::meta::info)

Let's tabularize this

Language	Runtime or compile-time	Type or value based (loosely)
Python	Runtime	Value (with a sprinkle of Type)
Golang	Runtime	Value (with a sprinkle of Type)
Java	Runtime	Type
C++26 🤞	Compile Time	Value (std::meta::info)

How do we use this new superpower ?

No one likes chaos.

Libraries!

- Makes it easier to write general-purpose / boilerplate-reducing libraries
- Libraries would require fewer redundant inputs from the user
  - A CLI parsing library won’t need you to enumerate all objects in your struct each time.
  - Maybe it could take a spec to parse and return a struct to you storing that spec?

Libraries!

Python bindings, ABI hashing, A better std::any

Python bindings

A fan favorite, and one of the most common wishlist items

- We have a C++ class that we'd like to expose to Python
- Background:
  - You can run python and C++ code in the same process.
  - CPython is a C library and application.
  - Can run in the same process that is running your C++ code
  - We have to define how to "expose" C++ objects in python

```
struct Item {
   int id;
   PyObject* getPyValue() const;
};
struct Row {
   const auto& items() const { return items_; }
   auto nanotime() const { return nanotime_; }
};
class RowReader : public BinaryListener {
 public:
   RowReader(const std::string& filename)
       : reader_(filename);
   std::string getIdName(int id) const;
   const auto& getRows();
};
```

A fan favorite, and one of the most common wishlist items

- We don’t want to write *this*
- Most of the code is just repetition of what we already know
- Some of the things are non-obvious
  - Whether a function’s return type should be wrapped as a reference or a value copy
  - How to name a type in Python

```
BOOST_PYTHON_MODULE(binary_reader_bpy) {
   class_<Item>("Item", no_init)
       .def_readonly("id", &Item::id)
       .def("value", &Item::getPyValue);

   class_<Row, std::shared_ptr<Row>>("Row", no_init)
       .def("nanotime", &Row::nanotime)
       .def("items", &Row::items,
            return_internal_reference<>());

   class_<RowReader, boost::noncopyable>(
     "RowReader", init<std::string>(arg("filename"))
   )
       .def("getRows", &RowReader::getRows)
       .def("getIdName", &RowReader::getIdName);
}
```

Reflection makes it easy peasy

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Kind of...

Declare the type object

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Loop over the members and methods

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   template for (auto e : meta::members_of (^T)) {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Loop over the members and methods

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Probably don't want public members exposed

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Inform boost::python how to access the members??

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &MyStruct::a);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Inform boost::python how to access the members

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Inform boost::python about methods

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

It works :)

```
template <typename T> object make_python_type() {
   std::string cls_name{meta::name_of (^T)};
   auto type_obj = class_<T>(cls_name.c_str(), init<int, int>());
   [:expand(meta::members_of (^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) { return; }
       std::string name{meta::name_of(e)};
       if constexpr(meta::is_nonstatic_data_member(e))
           type_obj.def_readwrite(name.c_str(), &[:e:]);
       if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e)) {
           if constexpr(!std::is_reference_v<typename return_type<decltype(&[:e:])>::type>)
               type_obj.def(name.c_str(), &[:e:]);
       }
   };
   return type_obj;
}
```

Python bindings

- Can be done
- Still need to figure out how to customize things that can’t be defaulted properly
  - Return types with reference
  - Picking overloads for functions
- How to name types (and methods in case of overloads)
- Docstrings

CUSTOMIZING THE DEFAULT BEHAVIOR

- Defining template specializations!
- Not ideal, but has benefits
    - Can annotate even if you don’t have control on source code

```
constexpr auto customizations = {
   {^Row::items,
    return_value_policy::reference_internal},
   ...
};
```

*mentioned in P2911R0

USER DEFINED ATTRIBUTES

- Proposed in P1887, discussed in P2911
- Helpful in tagging information at the place of definition
- Requires control on the source code of the type

```
class Row {
public:
    [[return_policy("reference_internal")]]
    const auto& items() { ... }
};
```

*mentioned in P2911R0

USER DEFINED ATTRIBUTES

- One of my favorite features from Golang
- Annotating at the point of definition
  - Has its place, as opposed to annotating at the time of use

```go
type User struct {
   Name string `json:"name" required:"true"`
}
user := User{"John"}
field, ok := reflect.TypeOf(user).Elem().FieldByName("Name")
fmt.Println(field.Tag, field.Tag.Get("required"))
// json:"name" required:"true" true
```

*https://www.makeuseof.com/reflection-in-go/

Summary

- Default behavior can be done easily
- Customizations are trickier / not DRY
- User defined attributes might help!
    - In serialization / deserialization / CLI parsing too!

ABI hashing

Why and how

Setting the stage - Why is a type's hash useful?

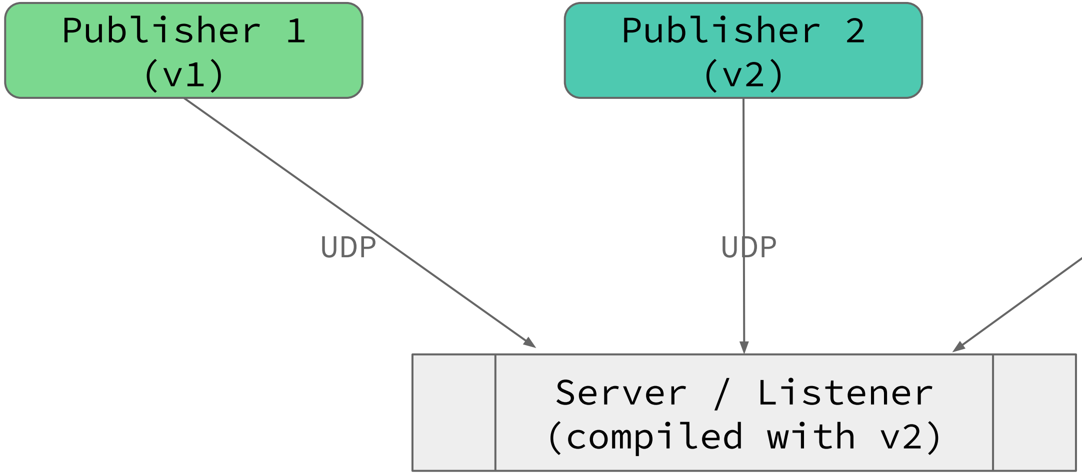
- Say you had a unique hash for a type's memory layout.
  - What would you do?
- Example message sent between two modules communicating.

SchemaType	Rest of your data

- We'd like to minimize the space we're using to describe the data's schema in a given message.
- Ideally good to keep the comparison fast as well.

Setting the stage - Why is a type's hash useful?

- Say you had a unique hash for a type's memory layout.
  - What would you do?



Setting the stage - Why is a type's hash useful?

- Say you had a unique hash for a type’s memory layout.
  - What would you do?
- Why not compare the “type” in text form?
  - Situations where speed is important
    - Cannot compare full type layouts each time for speed
    - Handshakes can help
  - Situations where size is important
    - Messages written to disk or sent over the network

Setting the stage - Why is a type's hash useful?

- Say you had a unique hash for a type's memory layout.
  - What would you do?
- Send this over UDP for handshake-less connections
  - Connections with handshakes can use a full description of the layout
    - That's hard enough already without protobuf etc.
  - Sending over a hash is reasonably size-efficient

Setting the stage - Why is a type's hash useful?

- Say you had a unique hash for a type's memory layout.
  - What would you do?
- Use it to safely type-cast across module boundaries
  - Multiple python modules?
  - Different .so files talking to each other with non-trivial types at the ABI boundary.

Setting the Stage - Why is a type's hash useful?

- Say you had a unique hash for a type's memory layout.
  - What would you do?

libcreator.so

```cpp
struct MyCls {
   int x;
   virtual int foo() = 0;
};
shared_ptr<MyCls> create() {
  return make_shared<Impl>(22);
}

class_<MyCls, shared_ptr<MyCls>>(
 "MyClsPy", no_init
);
```

```python
obj = creator.create()
# type(obj) == creator.MyClsPy

usermodule.use(obj)
# ERROR!
# usePy expects
#   usermodule.MyClsPy
```

libusermodule.so

```cpp
struct MyCls {
   int x;
   virtual int foo() = 0;
};
int use(shared_ptr<MyCls> obj) {
   return obj->foo() + obj->x;
}

class_<MyCls, shared_ptr<MyCls>>(
 "MyClsPy", no_init
);
```

Issues with a simple version field

- Doesn't handle quirks that humans may miss (eg: attributes)
- Easy to forget to change version
  - Especially when transitive dependencies are changed
- Can't do it generically in a library, user has to handle

```
struct BaseT {
 int a;
} __attribute__((packed));

struct MyMessage : public BaseT {
 int b;
};
```

Okay how do we hash a type's layout?

Reflection!!

Reflection to iterate a type's layout

- Is a decent test of the capabilities of reflection as proposed in P2996.
- Requires recursively computing the hash of types of member variables of a class. Avoid cycles!
- Requires a constexpr hashing function.
- Requires full visibility into the class' internals
  - Sounds scary actually, we can now write code that can know about private members of a class

Reflection to iterate a type's layout

- Also, requires some level of configurability

```
struct ABIHashingConfig {
    static constexpr int MINIMUM_SUPPORTED_VERSION = 0;  // To allow future rollover
    static constexpr int MAXIMUM_SUPPORTED_VERSION = 0;  // To gracefully error out
    uint8_t version : 4 = 0;
    bool include_nsdm_names : 1 = true;
    bool include_indirections : 1 = false;  // Only relevant in intra-process
} __attribute__((packed));
```

ABI hashing - The test case

```
struct Order { int side = 1; size_t quantity = 0; };
template <typename T> struct MyList {
   T* start = nullptr;
   T* end = nullptr;
   bool valid : 1 = false;
};
template <typename T> struct MyList2 : public MyList<T> {};
struct OrderBook {
   MyList2<Order> buy_orders;
   MyList2<Order> sell_orders;
};
```

ABI hashing - The API

```
template <typename T, std::meta::abi::ABIHashingConfig config>
consteval size_t get_abi_hash();

// ...or...

consteval size_t get_abi_hash(std::meta::info R,
                              std::meta::abi::ABIHashingConfig config);
```

ABI hashing - Recurse over base classes

```
consteval size_t _get_abi_hash_impl(
        std::meta::info R,
        meta::abi::ABIHashingConfig config = meta::abi::ABIHashingConfig{}) {
    size_t hash = 0;
    for (auto e : bases_of(R)) {
        hash = hash_combine(hash, get_abi_hash(meta::type_of(e), config));
    };
```

ABI hashing - Looping over members - Ignoring pointers

```
for (auto e : nonstatic_data_members_of(R)) {
  auto elem_type = meta::type_of(e);
  auto is_indirect_ref = (meta::test_type (^std::is_pointer_v, elem_type) ||
                          meta::test_type (^std::is_reference_v, elem_type));
  if (!config.include_indirections && is_indirect_ref) {
     // Maybe even warn or throw, since no use-case.
     continue;
  }
```

ABI hashing - Looping over members - Members' layout

```
for (auto e : nonstatic_data_members_of(R)) {
   if (config.include_nsdm_names) {
       auto name = std::string(meta::name_of(e));
       hash = hash_combine(hash, HASH_STR(name.c_str()));
   }
   if (meta::is_bit_field(e)) {
       hash = hash_combine(hash, std::meta::offset_of(e),
                          std::meta::bit_offset_of(e), std::meta::bit_size_of(e));
   } else {
       hash = hash_combine(hash, std::meta::offset_of(e), std::meta::size_of(e));
   }
```

ABI hashing - Looping over members - type of the member?

```
for (auto e : nonstatic_data_members_of(R)) {
   if (meta::test_type (^std::is_class_v, elem_type)) {
       hash = hash_combine(hash, get_abi_hash(meta::type_of(e), config));
   } else {
       if (meta::test_type (^std::is_pointer_v, elem_type)) {
       } else if (meta::test_type (^std::is_reference_v, elem_type)) {
       } else {
           auto name = std::string(meta::name_of(meta::type_of(e)));
           hash = hash_combine(hash, HASH_STR(name.c_str()));
       }
   }
```

ABI hashing - Looping over members - type of the member?

```
for (auto e : nonstatic_data_members_of(R)) {
   if (meta::test_type (^std::is_class_v, elem_type)) {
   } else {
       if (meta::test_type (^std::is_pointer_v, elem_type)) {
           if (config.include_indirections) {
               hash = hash_combine(hash, HASH_STR("pointer"));
               constexpr auto ctype =
                   std::meta::substitute(^std::remove_pointer_t, {elem_type});
               hash = hash_combine(hash, get_abi_hash(ctype, config));
           }
```

ABI hashing - Finally, size

```
// Despite all members being the size, attributes like `packed` may change
// the size of the struct. Not everyone would be concerned with padding at
// the end though. Can consider making this optional via a config param.
if (std::meta::size_of(R) > 0) {
    hash = hash_combine(hash, std::meta::size_of(R));
}
```

ABI hashing - Avoiding cycles

```
consteval size_t get_abi_hash(std::meta::info R,
                              meta::abi::ABIHashingConfig config = meta::abi::ABIHashingConfig{},
                              std::vector<std::meta::info> active_types = {}) {
  auto it = std::ranges::find_if(active_types, [R](const auto& elem) { return elem == R; });
  if (it == active_types.end()) {
    active_types.push_back(R);
    return _get_abi_hash_impl(R, config, active_types);
  } else {
    // Cycle detected! Return the index since we must modify the hash still.
    return (it - active_types.begin());
  }
}
```

And just for fun, this might have looked like this with type based code

ABI hashing - Avoiding cycles

```
template <typename T, ABIHashingConfig config, typename... ActiveTypes>
consteval size_t get_abi_hash() {
    constexpr ssize_t type_index = mp11::mp_find<mp_list<ActiveTypes...>, T>();
    if constexpr(type_index != mp11::mp_size<mp_list<ActiveTypes...>>()) {
        return static_cast<size_t>(type_index);
    } else {
        return _get_abi_hash_impl<T, config, ActiveTypes...>();
    }
}
```

ABI hashing - So what do we have now

- A simple way to ensure compatibility of data layout across processes, without using protobuf etc
- A solution that solves 80% of the common set of requirements of users
  - Can a python binding library cast one type to the other safely?
  - Are these two networked binaries using the same data layout?
- Requires minimal to no work on the user’s ends
- Inflexible and hard to modify / handle unique situations

ABI hashing - Where do we go from here?

- Full ABI textual representation!
  - Or, an ABI for describing the ABI
- You could generate a “schema” file for your structs
  - Could be some JSON based schema
  - Could be a pre-existing schema like Apache Avro
  - This way we get a full ecosystem (with cross language support) for free.

A pythonic std::any

Hot take incoming

Boost::python had a dream

```
object f(object x, object y) {
    if (y == "foo")
        x.slice(3,7) = "bar";
    else
        x.attr("items") += y(3, x);
    return x;
}

// Duck typing and a completely untyped type!
```

https://www.boost.org/doc/libs/1_66_0/libs/python/doc/html/tutorial/tutorial/object.html

STD::ANY HAD A DREAM

```
// any type
std::any a = 1;
std::cout << a.type().name() << ": " << std::any_cast<int>(a) << '\n';
a = 3.14;
std::cout << a.type().name() << ": " << std::any_cast<double>(a) << '\n';
a = true;
std::cout << a.type().name() << ": " << std::any_cast<bool>(a) << '\n';

// No duck typing sadly, but we got the equivalent of std::variant<everything>
// Can’t do much though :)
```

https://en.cppreference.com/w/cpp/utility/any


BOOST::VIRTUAL_ANY
WITH DUCK TYPING
STD::ANY
BOOST::PYTHON
::OBJECT
imgflip.com

How would an ideal code look?

```
class MyDuck {
public:
   int x;
   MyDuck(int x) : x(x) {}
   std::string do_quack() const { return "quack"; }
};

auto a = make_virtual_any<int>(7);
std::cout << "Printing " << a << std::endl;

a = make_virtual_any<MyDuck>(MyDuck(3));
std::cout << "My obj " << a << " has .x == " << a.attr("x")
          << ", .do_quack() == " << a.attr("do_quack")() << std::endl;
```

We can do this!

Holding class : virtual_any

```
class virtual_any_interface;
class virtual_any {
   std::shared_ptr<virtual_any_interface> _impl;
  public:
   virtual_any(std::shared_ptr<virtual_any_interface> elem) : _impl(elem) {}
   virtual_any attr(const std::string& name);
   virtual_any operator()();
   friend std::ostream& operator<<(std::ostream& os, const virtual_any& self);
};

class virtual_any_interface {
  public:
   virtual virtual_any attr(const std::string& name) = 0;
   virtual virtual_any call() = 0;
   virtual std::ostream& stream(std::ostream& os) const = 0;
};
```

Virtual_any_interface

- virtual_any calls a virtual method on the held type
    - virtual_any_interface
- We implement virtual_any_interface for each type
    - Using reflection!
- Handle some special function operators natively
    - operator<<
    - operator()
    - operator+
    - Can handle more, but need to figure out how to handle variadic args

Implementation class : virtual_any_impl

```
template <typename T>
class virtual_any_impl : public virtual_any_interface {
   T _value;
   constexpr std::vector<std::pair<std::string, virtual_any>> get_attrs(); // All members and methods of T
  public:
   virtual_any_impl(T& value) : _value(std::forward<T>(value)) {}
   virtual virtual_any attr(const std::string& name) override;
   virtual virtual_any call() override; // .attr could've returned a std::function<virtual_any(void)>
   virtual std::ostream& stream(std::ostream& os) const override;
};
```

virtual_any_impl: Ignore special cases

```
template <typename T>
constexpr std::vector<std::pair<std::string, virtual_any>> virtual_any_impl<T>::get_attrs() {
   using T2 = std::remove_cvref_t<T>;
   if constexpr(!meta::test_type (^std::is_class_v, ^T)) {
       return {};
   } else if constexpr(std::is_same_v<T2, std::string> ||
                       std::is_same_v<T2, std::function<virtual_any(void)>>) {
       return {};
   } else {
       std::vector<std::pair<std::string, virtual_any>> attrs;
       // Actual logic
       return attrs;
   }
}
```

virtual_any_impl: Get all members and methods

```
template <typename T>
constexpr std::vector<std::pair<std::string, virtual_any>> virtual_any_impl<T>::get_attrs() {
   [:expand(meta::members_of(^T)):] >> [&]<auto e> {
       if constexpr(!meta::is_public(e)) return;
       else {
           auto name = std::string(std::meta::name_of(e));
           if constexpr(meta::is_nonstatic_data_member(e)) {
               attrs.push_back({name, make_virtual_any(_value.[:e:])});
           } else if constexpr(meta::is_function(e) && !meta::is_constructor(e) && !meta::is_destructor(e) &&
                               !meta::is_special_member(e)) {
               std::function<virtual_any(void)> l = [this]() { return make_virtual_any(_value.[:e:]()); };
               attrs.push_back({name, make_virtual_any(l)});
           }
       }
   };
}
```

virtual_any_impl: Implement the `attr` method

```
template <typename T>
virtual_any virtual_any_impl<T>::attr(const std::string& name) {
   auto attrs = get_attrs();
   if (attrs.size() == 0) {
       throw std::runtime_error("No attributes found");
   }
   for (const auto& [name2, e] : attrs) {
       if (name2 == name) {
           return e;
       }
   }
   std::stringstream ss;
   ss << "Attribute " << name << " not found in object of type " << std::meta::name_of(^T);
   throw std::runtime_error(ss.str());
}
```

virtual_any_impl: Implement other helper methods

```
template <typename T> virtual_any virtual_any_impl<T>::call() {
    if constexpr(std::is_same_v<T, std::function<virtual_any(void)>>) {
        return _value();
    } else {
        std::stringstream ss;
        ss << "Object of type " << std::meta::name_of(^T) << " is not callable";
        throw std::runtime_error(ss.str());
    }
}
template <typename T> std::ostream& virtual_any_impl<T>::stream(std::ostream& os) const {
    if constexpr(is_streamable<std::stringstream, T>::value) {
        os << _value;
    } else {
        os << "(non-streamable object of type " << std::meta::name_of(^T) << ")";
    }
    return os;
}
```

And there it is!

It works :)

```
int main() {
   auto a = make_virtual_any<int>(7);
   std::cout << "Printing " << a << std::endl;

   a = make_virtual_any<MyDuck>(MyDuck(3));
   std::cout << "My obj " << a << " has .x == " << a.attr("x") << std::endl;
   std::cout << "My obj " << a << " has .do_quack() == " << a.attr("do_quack")() << std::endl;
}

$ ./virtual_any/main.out
Printing 7
My obj MyDuck(3) has .x == 3
My obj MyDuck(3) has .do_quack() == quack quack quack
```

Discussion

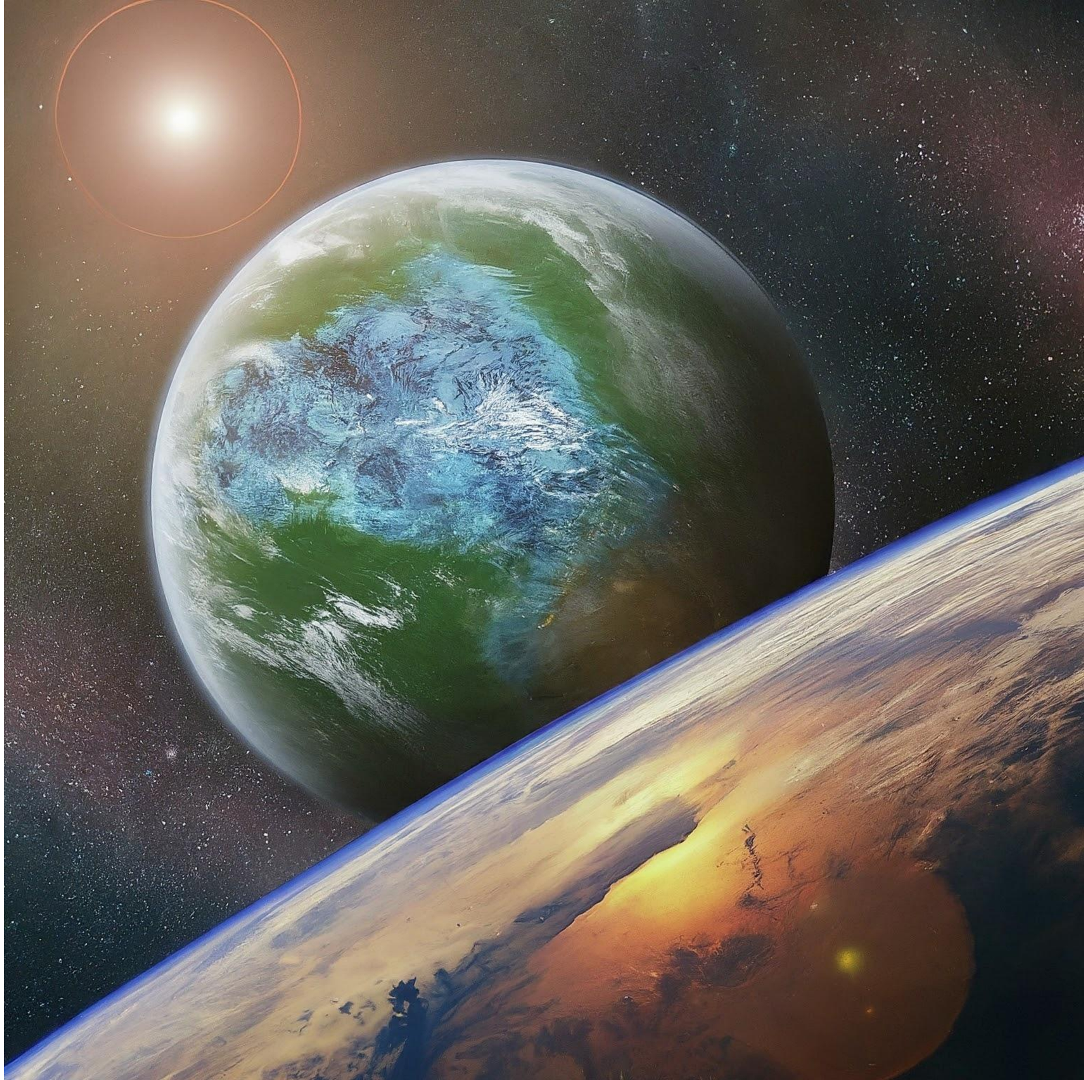
- Name is solid I know ;)
- Slow to run
  - Not the worst thing for writing script like code from time to time
  - Especially useful when dealing with containers and dictionaries and lists like in pythonic code
- Slow to compile
  - This one’s actually sad and hard to get around
  - Compilation can’t even be shared across compilation units
    - Unless... Language idioms

What do we get out of this?

- A fun new experiment with Reflection?
- Offers a clean duck-typed syntax, setup at compile time
  - Could start implementing better DSLs in C++?
- Removes need for complex ABI compatibility at module boundary
  - Sound familiar?

Alternatives to reflection

How did we survive
without this till now?



Human reflection

- Well, we’ve been writing boilerplate
  - Python bindings
  - Serialization / deserialization / CLI parsers
- Our code, and our libraries are worse off
- Compile-time reflection only makes for cleaner APIs
  - There’s no “new” semantic thing we can do now that we couldn’t do
  - We *can* do “new” syntactic things to avoid redundancy in code

Sourcegen!

- Protobuf
  - (in)famous library loved and hated by everyone at the same time
  - Lets you do some primitive “reflection-like” stuff
    - Enum <=> String
- Apache Avro
  - Sourcegen with a “handshake” / “header”
  - Better “reflection-like” API than protobuf

Sourcegen! ft. protobuf

```
enum VehicleType {
 UNDEFINED = 0;
 CAR = 1;
 TRUCK = 2;
 MOTORCYCLE = 3;
}

message Vehicle {
 string model = 1;
 VehicleType type = 2;
 repeated string features = 3;
}
```

```
enum VehicleType { UNDEFINED = 0, CAR, TRUCK, MOTORCYCLE };
bool VehicleType_IsValid(int value);
const ::google::protobuf::EnumDescriptor* VehicleType_descriptor();
inline const ::std::string& VehicleType_Name(VehicleType value);
inline bool VehicleType_Parse(const ::std::string& name, VehicleType* value);

class Vehicle {
public:
   const std::string& model() const;
   void set_model(const std::string& value); ...
   const ::google::protobuf::RepeatedPtrField<std::string>& features() const;
private:
   std::string model_;
   VehicleType type_;
   ::google::protobuf::RepeatedPtrField<std::string> features_;
};
```

Sourcegen! ft. Avro

```json
{
 "namespace": "example",
 "type": "record",
 "name": "Vehicle",
 "fields": [
   {"name":"model","type":"string"},
   {"name": "type",
    "type": {
      "type": "enum",
      "name": "VehicleType",
      "symbols": [...]
   }},
   {"name": "features",
    "type": {
      "type":"array","items":"string"
   }}
 ]
}
```

```cpp
struct Vehicle {
   std::string model;
   VehicleType type;
   std::vector<std::string> features;
   void serialize(std::ostream& out) const {
       auto schema = avro::compileJsonSchemaFromString(schemaJson);
       avro::EncoderPtr encoder = avro::binaryEncoder();
       encoder->init(out);
       avro::encode(*encoder, *this);
   }
   void deserialize(std::istream& in) {
       auto schema = avro::compileJsonSchemaFromString(schemaJson);
       avro::DecoderPtr decoder = avro::binaryDecoder();
       decoder->init(in);
       avro::decode(*decoder, *this);
   }
};
```

Sourcegen! ft. LLM

```
struct ConfigOptions {
    bool enable;
    int count;
    std::string mode;
};

int main() {
    boost::program_options po;
    po.add_options()
        ("enable", boost::program_options::value<bool>(), "enable")
        ("count", boost::program_options::value<int>(), "count")
        ("mode", boost::program_options::value<std::string>(), "mode");
}
```

Among others...

- Classdesc
  - Another form of sourcegen
- https://github.com/boost-ext/reflect
  - Template metaprogramming to its limits

[:FIN:]

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