Reflection – Metaobjects

value-based

Reflection uses constant values of a single built-in type:

```
info x = reflect(argument);
```

---

type-based

Reflection uses constant values of multiple types:

```
auto x = reflect(argument);
```

The actual (implementation-defined) type might be:

```
template <info X>
struct __metaobject {
  consteval operator info() const {
    return X;
  }
};
```

Reflection – APIs

value-based

Either purely `consteval` or template functions with non-type template parameters:

```
consteval auto foo(info mo);
```

```
template <info MO>
consteval auto bar();
```

---

type-based

`consteval` template functions taking metaobjects as function arguments:

```
consteval auto foo(metaobject auto mo);
consteval auto bar(metaobject auto mo);
```

```
template <typename T>
concept metaobject = unspecified;
```

Reflection – Implementation

value-based

Very fast to compile:

```
consteval auto foo(info mo);
```

Somewhat slower to compile:

```
template <info MO>
consteval auto bar();
```

---

type-based

Very fast to compile, but requires `consteval` conversion from `metaobject` to `info`:

```
consteval auto foo(info mo);
```

Slower to compile:

```
template <info MO>
consteval auto bar(__metaobject<MO> mo);
```

Reflection – Usage

value-based

Dual syntax:

```
use(foo(reflect(argument)));
```

or

```
use(bar<reflect(argument)>());
```

When to use which?

---

type-based

Uniform syntax:

```
use(foo(reflect(argument)));
```

and

```
use(bar(reflect(argument)));
```

Reflection – Containers

value-based

Vectors, etc. must be fixed to work in `consteval`

```
vector<info> x = members_of(...);
vector<info> y = bases_of(...);
```

Can be used with some STL algorithms, unless splicing is involved

---

type-based

Containers (sequences) are metaobjects themselves

```
auto x = get_data_members(...);
auto y = get_base_classes(...);
```

Have their own implementation of reflection-related algorithms, splicing is no problem

Reflection – Pros

value-based

- Faster to compile
- Uses less resources to compile

---

type-based

- Consistent and unified API
- More friendly to generic programming
- Plays better with ADL
- Better usability
- Easier to teach

Reflection – Cons

value-based

- Inconsistent API
- The `foo(...)` vs. `bar<...>()` syntax makes it less generic
- Rules when to use which, are sort of complicated and may look arbitrary
- More complicated to teach
- Issues with ADL on NTTPs

---

type-based

- Slower to compile
- Uses more resources to compile

Usability issues – the dual value-based API

```
// span<meta::info>, vector<meta::info>
auto mem = members_of(^T);
auto func = // some callable, example later
```

The following is possible only for a subset of possible reflection operations:

```
std::count_if¹(mem.begin(), mem.end(), func);
```

Specifically the `func` cannot use splicing, because `count_if` will call it as:

```
func(element);
```

and not as:

```
func<element>();
```

[1] or any other of countless possible algorithms

Usability issues – writing generic algorithms

Users[2] will want to write their own reusable algorithms, that take other functions[3] as their arguments:

```
consteval void my_reusable_algo(
  span<meta::info> s,
  function<bool(meta::info)> predicate,
  function<void(meta::info)> function) {
  for(auto e : s) {
    if(predicate(e) && something_else(e)) {
      function(e);
    }
  }
}
```

predicate, something_else and function *cannot* do splicing. . .

[2] and library authors
[3] predicates, transforms, etc.

Usability issues – supporting splicing

. . . to support splicing we'd have to:

```
template <auto s>
consteval void my_reusable_algo(
  auto predicate,
  auto function) {
  template for(auto e : s) {
    if(predicate<e>() && something_else<e>()) {
      function<e>();
    }
  }
}
```

making everything a template. But then this becomes slower to compile, partially defeating one of the main points of this API.

BTW, why so much focus on splicing? – some anecdotes. . .

- Out of these use-cases[4][5]
  - enum / string conversion,
  - serialization and deserialization,
  - parsing of command line arguments into a config structure,
  - RPC stubs and skeletons,
  - generic wrapper for a REST API,
  - automated registering with a scripting engine,
  - generating UML diagrams from code,
  - fetching and converting data from an SQL database,
  - generating SQL queries from the names in an “interface” class,
  - implementation of the factory pattern.
- All but one[6] required splicing
- Various forms of splicing are *very* common in use-cases

[4] all implemented here: `https://github.com/matus-chochlik/mirror`
[5] and there is a whole other presentation about the details
[6] UML generation

What are we trying to do?

Determine what is the actual overhead of this:

```
template <info X>
struct __metaobject {
  consteval operator info() const { return X; }
};
concept metaobject = unspecified;

consteval auto foo(info mo);
consteval auto bar(metaobject auto mo);
```

compared to this:

```
consteval auto foo(info mo);

template <info MO>
consteval auto bar();
```

in a real-life scenario.

The cost of reflection in a “large-ish” project?

- Let’s try `clang`
  - Estimate the number of “things” to reflect
  - Measure the overall compilation time
  - Measure the contribution of reflection
  - Compare purely value-based and typed metaobjects

How to materialize 100'000s of metaobjects?

Use a shell script...

```
L=100  # number of repeats
S=1000 # sampling step size
for l in $(seq 1 ${L})
do
  N=$((l * S))
  # factorize N into three integers
  D=...; E=...; F=...
```

...to generate a C++ source file...

```
  int main() {
    return bool(qux(make_index_sequence<${D}>{})) ? 0 : 1;
  }
```

..., compile and measure:

```
  time $(CXX) $(CXXFLAGS) -o /dev/null $<
done
```

The boilerplate – level 1

```
template <size_t ... K>
consteval auto qux(index_sequence<K...>) {
  return ( ... + baz(
    integral_constant<size_t, K>{},
    make_index_sequence<${E}>{}));
}
```

The boilerplate – level 2

```
template <size_t K, size_t ... J>
consteval auto baz(
  integral_constant<size_t, K>,
  index_sequence<J...>) {
  return ( ... + bar(
    integral_constant<size_t, K>{},
    integral_constant<size_t, J>{},
    make_index_sequence<${F}>{}));
}
```

The boilerplate – level 3

```
template <size_t K, size_t J, size_t ... I>
consteval auto bar(
  integral_constant<size_t, K>,
  integral_constant<size_t, J>,
  index_sequence<I...>) {
    // Simulate the metaobject "id" as:
    // MOID =
    //    K * $((N / D)) +
    //    J * $((N / (D * E))) +
    //    I;
    return /* Do something with MOID... */
}
```

The baseline

Just sum the *MOID* values at compile-time

```
template <size_t K, size_t J, size_t ... I>
consteval auto bar(
  integral_constant<size_t, K>,
  integral_constant<size_t, J>,
  index_sequence<I...>) {
    return (... +
      K * $((N / D)) +
      J * $((N / (D * E))) +
      I);
}
```

Measure how long does this take to compile and subtract from “real” measurements.

Type-based metaobject & template function

```
template <size_t M>
struct wrapper {
  consteval operator size_t() const {
    return M;
  }
};

template <size_t M>
consteval size_t foo(wrapper<M> w) {
  return w;
}
```

```
return ( ... + foo(wrapper<MOID>{}));
```

Type-based metaobject & consteval function

```
template <size_t M>
struct wrapper {
  consteval operator size_t() const {
    return M;
  }
};

consteval size_t foo(size_t m) {
  return m;
}
```

```
return ( ... + foo(wrapper<MOID>{}));
```

Value-based metaobject & template function

```
template <size_t M>
consteval size_t foo() {
  return M;
}
```

```
return ( ... + foo<MOID>());
```

Value-based metaobject & consteval function

```
consteval size_t foo(size_t m) {
  return m;
}
```

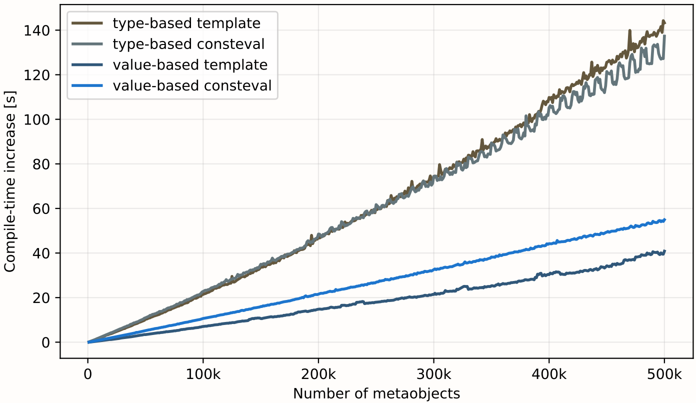
```
return ( ... + foo(MOID));
```

Test hardware

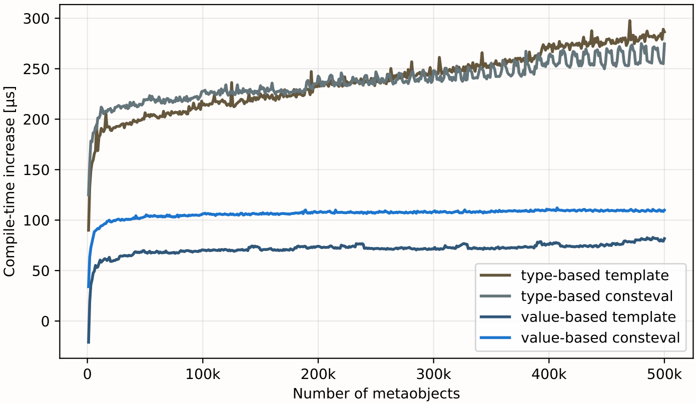
- Old desktop[7]:
  - i5-2400U @ 3.10GHz (4 cores)
  - 24GB RAM
- Corporate dev laptop[8]:
  - i7-1185G7 @ 3.0GHz (8 cores)
  - 32GB RAM
- Mid-range gaming laptop[9]:
  - AMD Ryzen7 4800HS (16 cores)
  - 16GB RAM
- RPi 4B[10]
  - ARM v7l
  - 4GB RAM

[7] 2010
[8] 2021
[9] 2019
[10] timeless

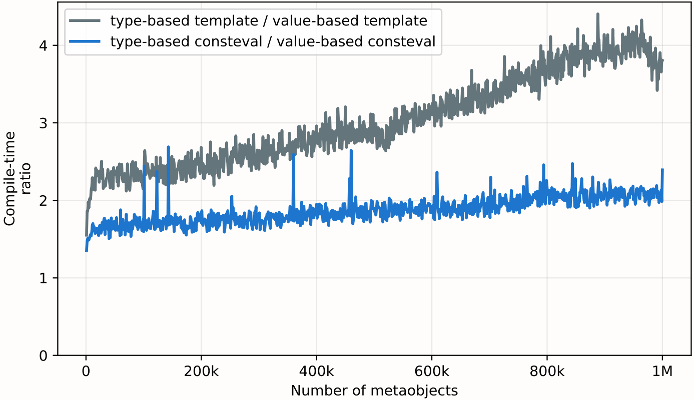
i5-2400 – compile time increase per N metaobjects



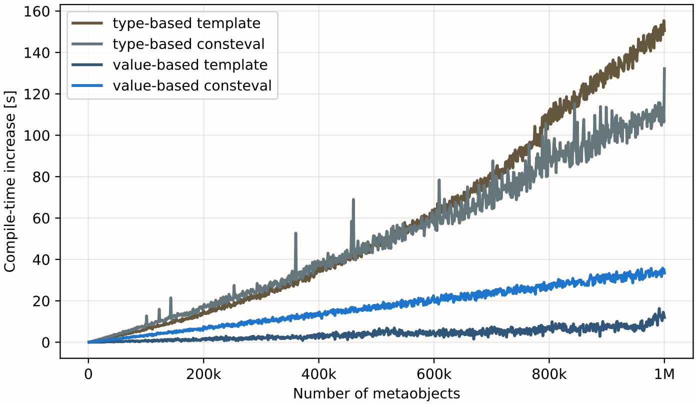
i5-2400 – compile time increase per 1 metaobject



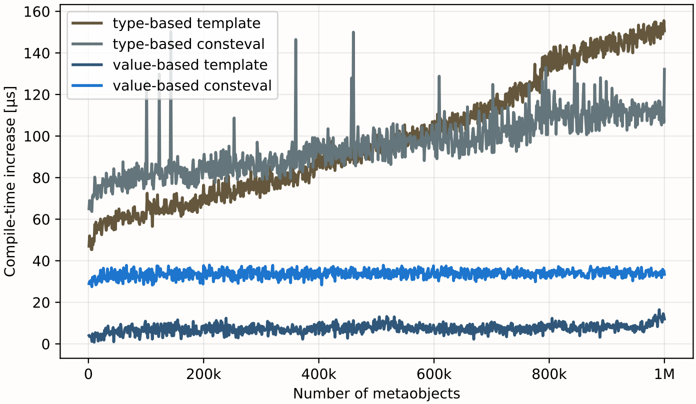
i5-2400 – How much faster is value-based vs. type-based



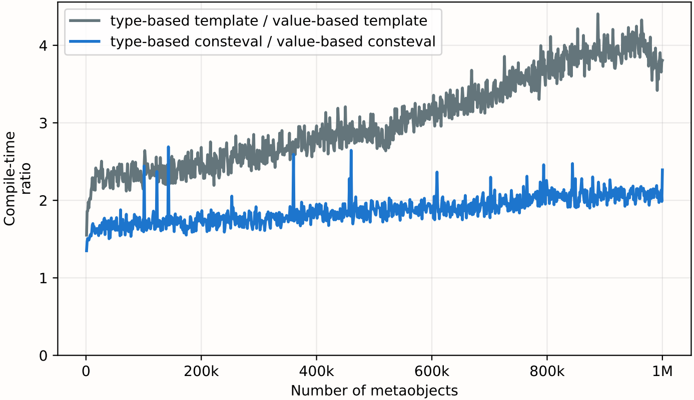
i7-1185 – compile time increase per N metaobjects



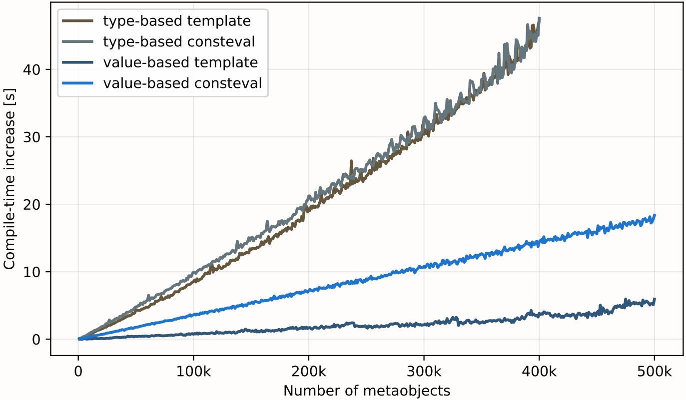
i7-1185 – compile time increase per 1 metaobject



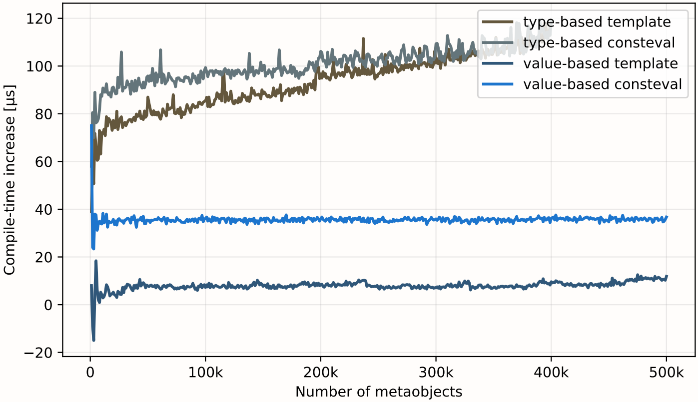
i7-1185 – How much faster is value-based vs. type-based



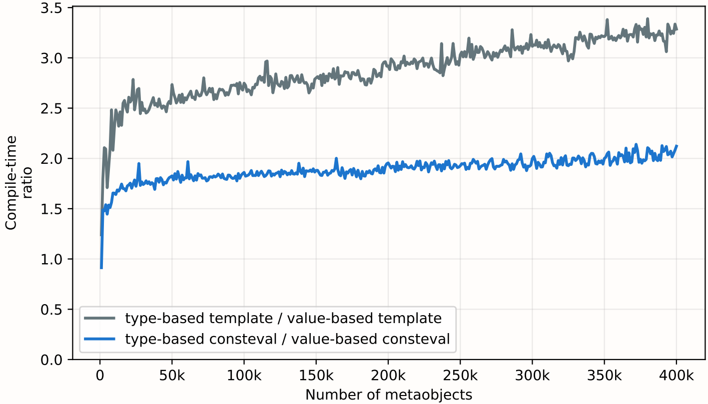
Ryzen7-4800HS – compile time increase per N metaobjects



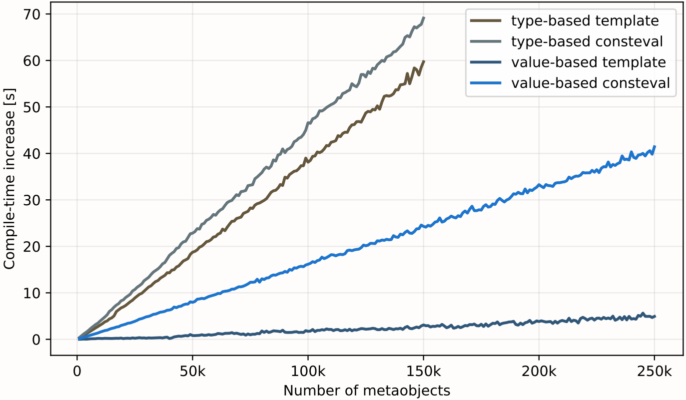
Ryzen7-4800HS – compile time increase per 1 metaobject



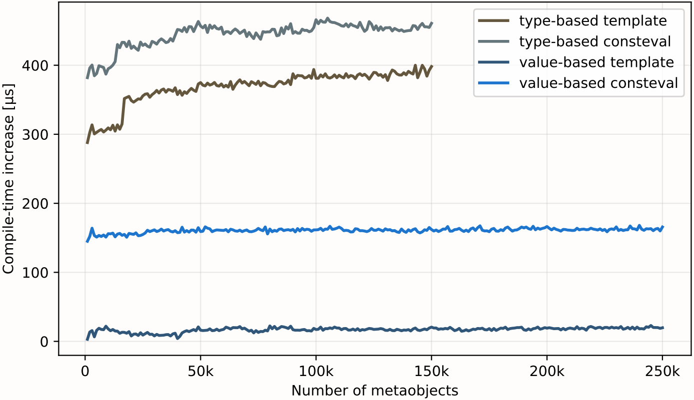
Ryzen7-4800HS – How much faster is value-based vs. type-based



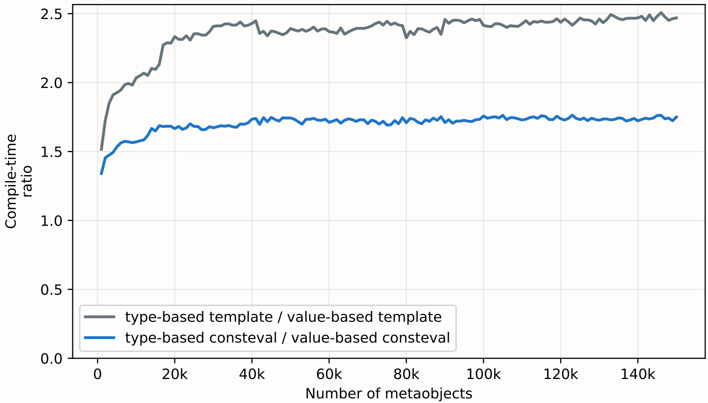
ARMv7 – compile time increase per N metaobjects



ARMv7 – compile time increase per 1 metaobject



ARMv7 – How much faster is value-based vs. type-based



What about executable sizes?

- This is boring. . .
- When the reflection-related functions are `consteval`, the executable size stays the same regardless of the representation of metaobjects or their count
- The test source code shown above always compiles into an executable roughly 16kB in size

But, what if – we tried something different. . .

- Instead of that template gizmo instantiating metaobjects in one place in the source
- Just generate a lot of source code with many separate metaobject operations
- As in. . .

Type-based metaobject & template function

```
template <size_t M>
struct wrapper {
  consteval operator size_t() { return M; }
};
template <size_t M>
consteval size_t foo(wrapper<M> w) {
  return w;
}
```

```
consteval int bar() {
  return static_cast<int>(
    foo(wrapper<1Z>{})+
    foo(wrapper<2Z>{})+
    // ...
    foo(wrapper<NZ>{}));
}
```

Type-based metaobject & consteval function

```
template <size_t M>
struct wrapper {
  consteval operator size_t() { return M; }
};

consteval size_t foo(size_t m) {
  return m;
}
```

```
consteval int bar() {
  return static_cast<int>(
    foo(wrapper<1Z>{})+
    foo(wrapper<2Z>{})+
    // ...
    foo(wrapper<NZ>{}));
}
```

Value-based metaobject & template function

```
template <size_t M>
consteval size_t foo() {
  return M;
}
```

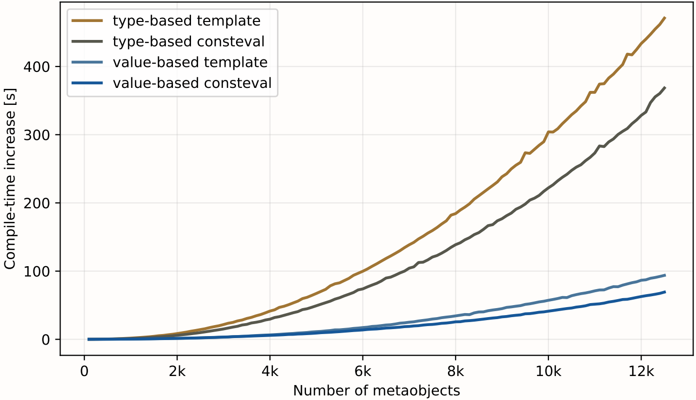
```
consteval int bar() {
  return static_cast<int>(
    foo<1Z>()+
    foo<2Z>()+
    // ...
    foo<NZ>());
}
```

Value-based metaobject & consteval function

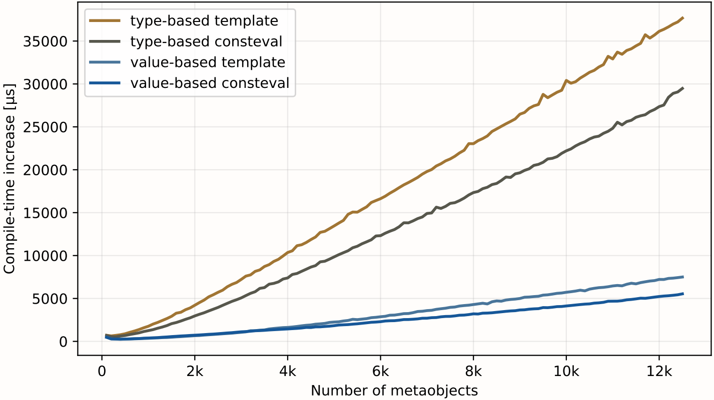
```
consteval size_t foo(size_t m) {
  return m;
}
```

```
consteval int bar() {
  return static_cast<int>(
    foo(1Z)+
    foo(2Z)+
    // ...
    foo(NZ));
}
```

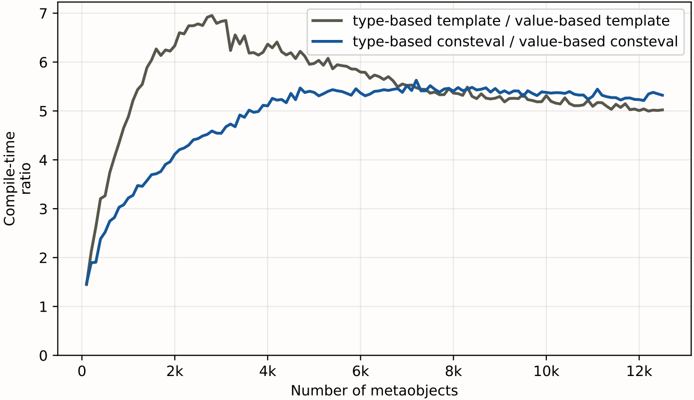
i5-2400 – compile time increase per N metaobjects



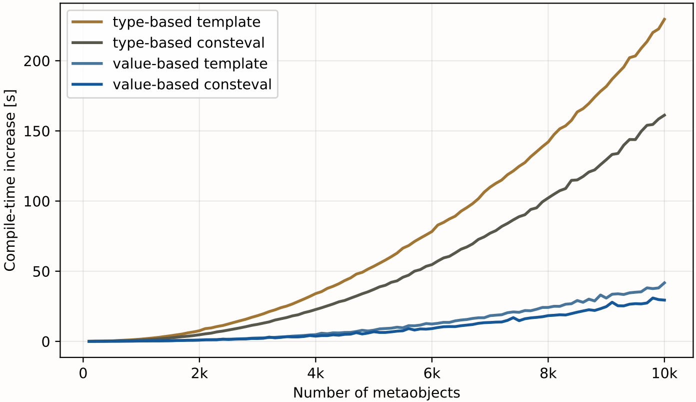
i5-2400 – compile time increase per 1 metaobject



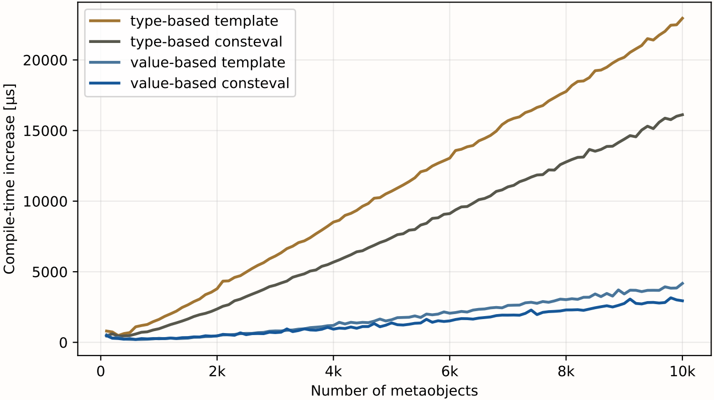
i5-2400 – How much faster is value-based vs. type-based



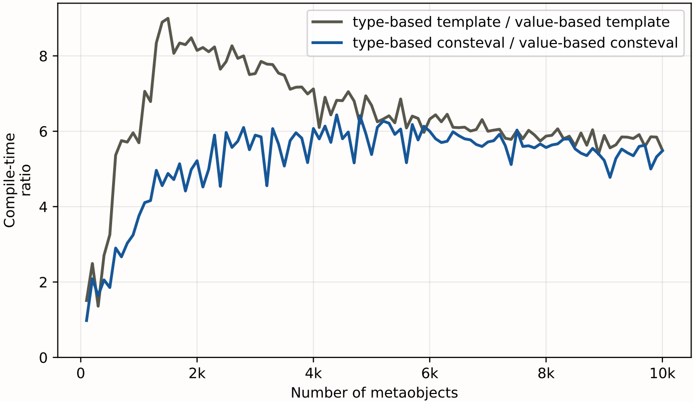
Ryzen7-4800HS – compile time increase per N metaobjects



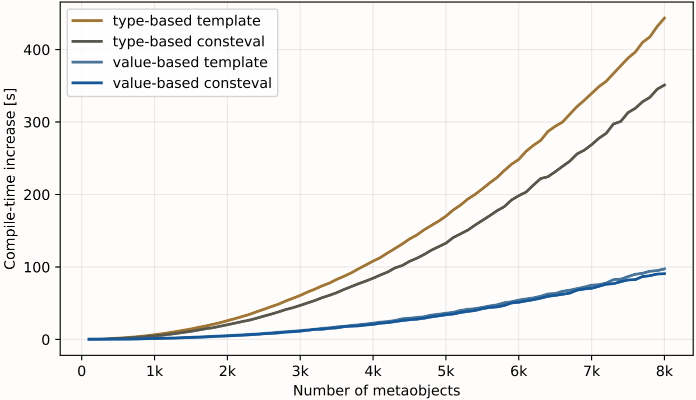
Ryzen7-4800HS – compile time increase per 1 metaobject



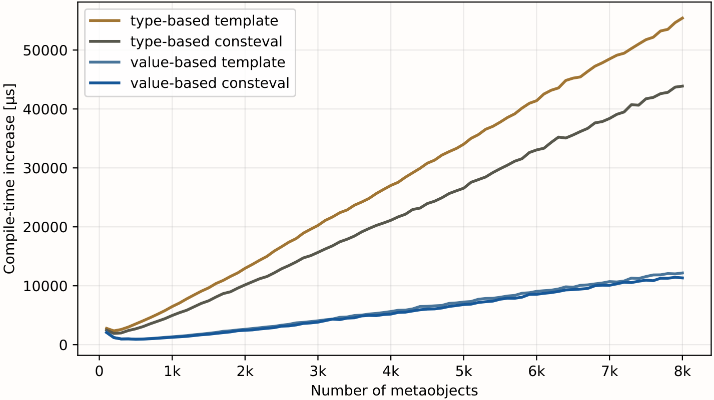
Ryzen7-4800HS – How much faster is value-based vs. type-based



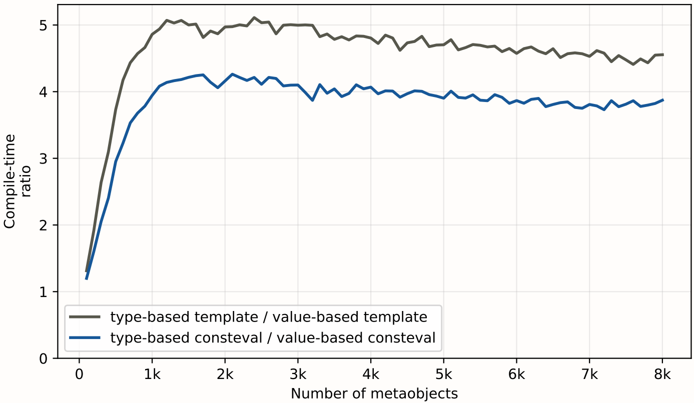
ARMv7 – compile time increase per N metaobjects



ARMv7 – compile time increase per 1 metaobject



ARMv7 – How much faster is value-based vs. type-based



Why the *huge* difference?

- Just some guesses...
  - In the second setup, each metaobject is an individually-parsed expression
  - Different than just multiple instantiations
  - Different source locations, etc.
- Even in the value-based cases the compile-times grow non-linearly
- This is *not* how you typically use reflection in real-life scenarios

Representing the reflection “operator”

- Above we have just used integer literals to represent metaobject “ids”
- What if we used a template function[11] to simulate the reflection expression
- What would be the effects on the compile-times?

[11] with NTTP

Representing the reflection "operator" – (cont.)

value-based

```
template <size_t I>
consteval auto reflect() {
    return I;
}
```

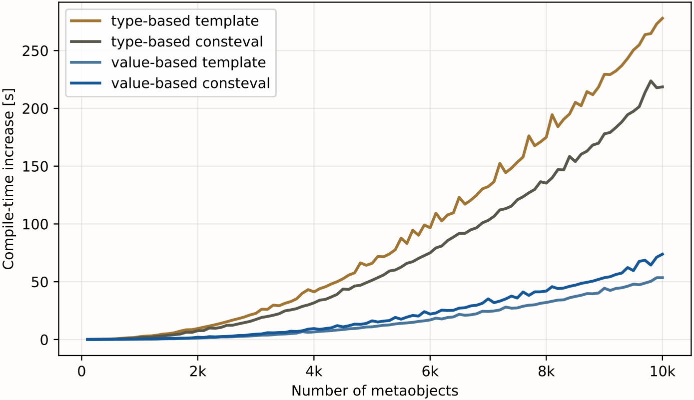
```
foo(reflect<NZ>());
// and
foo<reflect<NZ>()>();
```

type-based

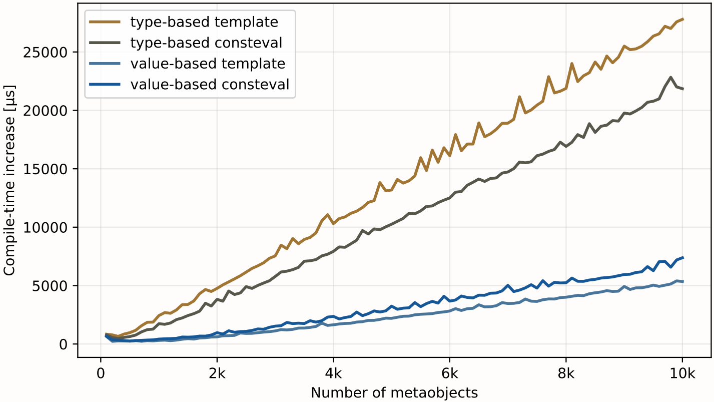
```
template <size_t I>
consteval wrapper<I> reflect() {
  return {};
}
```

```
foo(reflect<NZ>()));
```

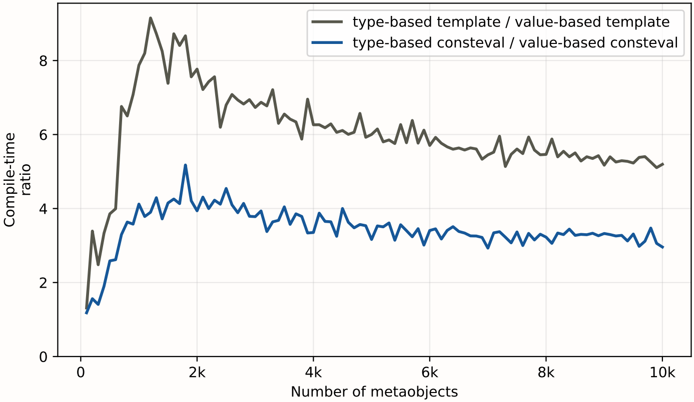
Ryzen7-4800HS – compile time increase per N metaobjects



Ryzen7-4800HS – compile time increase per 1 metaobject



Ryzen7-4800HS – How much faster is value-based vs. type-based



Estimating number of declarations in clang

Let's try *documented* declarations

Edit doxygen-cfg.in:

```
- GENERATE_XML    = NO
+ GENERATE_XML    = YES
```

Configure:

```
cmake \
  -DLLVM_ENABLE_DOXYGEN=On \
  ...
```

Generate Doxygen docs:

```
ninja doxygen-clang
```

Merge into a single XML file clang.xml:

```
xsltproc combine.xslt index.xml > clang.xml
```

Counting documented declarations in clang

Create count.xslt:

```
<?xml version="1.0" encoding="utf8"?>
<xsl:stylesheet version = '1.0'
 xmlns:xsl='http://www.w3.org/1999/XSL/Transform'>
  <xsl:template match="/">
    <xsl:value-of select="count(
      descendant::compounddef[12] |
      descendant::member[13] |
      descendant::value[14] |
      descendant::para[15] |
      descendant::param[16])
    "/>
  </xsl:template>
</xsl:stylesheet>
```

[12] structs, classes, enums, . . .

[13] data members, member functions, enumerators, . . .

[14] enumerator values, default arguments, . . .

[15] function/constructor/operator parameters, . . .

[16] template parameters, . . .

Counting documented declarations in `clang`

Calculate!

```
xsltproc \
    count.xslt \
    clang.xml
```

The result:

379091

- That's for version 15.0.0
- Around FEB-05-2022
- Round that up to 400'000, 500'000 or even 1'000'000
- Let's assume we want to reflect every single declaration

Clean build of clang

Edit toolchain.cmake:

```
set(LLVM_USE_LINKER lld)
set(CMAKE_EXE_LINKER_FLAGS -fuse-ld=${LLVM_USE_LINKER})
set(CMAKE_SHARED_LINKER_FLAGS -fuse-ld=${LLVM_USE_LINKER})
```

Configure:

```
cmake \
  -DLLVM_ENABLE_PROJECTS="clang;clang-tools-extra" \
  -DLLVM_ENABLE_RUNTIMES="libcxx;libcxxabi" \
  -DLLVM_TOOLCHAIN_FILE="toolchain.cmake" \
  ...
```

Build and measure elapsed time:

```
time ninja install install-cxx install-cxxabi
```

Clean build of `clang`

Results:

CPU:	i5-2400	i7-1185	Ryzen 7
real	122m25,943s	66m59,909s	34m45,899s
user	433m50,123s	510m55,382s	525m16,660s
sys	11m22,881s	12m52,287s	17m5,738s

Added, rounded and converted to seconds:

CPU:	i5-2400	i7-1185	Ryzen 7
real-time	7346s	4020s	2086s
cpu-time (user+sys)	27313s	31427s	32543s

Compared to build-time with 400’000 metaobjects

Compile-time of a typical `clang` build vs.
compile-time spent on materializing 400’000 metaobjects:

CPU:	i5-2400	i7-1185	Ryzen 7
clang:	27313s	31427s	32543s
type-based template	115.9s	48.8s	62.4s
	0.42%	0.16%	0.19%
type-based consteval	111.3s	53.4s	62.7
	0.41%	0.16%	0.19%
value-based template	36.3s	16.5s	19.0s
	0.13%	0.05%	0.06%
value-based consteval	50.3s	27.4s	29.6s
	0.18%	0.09%	0.09%

Conclusions

- The typical compile-time overhead of materializing a metaobject is on the order of tens or hundreds of microseconds
- The type-based metaobject representation is between 2x and 6x[17] slower to compile compared to the purely value-based representation

[17] in the worst "copy-paste" use-case

Conclusions – (cont.)

- Most typical reflection use-cases don't require reflecting every declaration in a project
- Even if reflecting almost everything, the overhead compared to total build time is a fraction of a percent even in the worst case
- For projects similar in complexity to `clang`, this results in 1-2 minutes added to several hours of compilation-time

Conclusions – (cont.)

- Some of the compile-time advantage of value-based API disappears, when splicing is involved
- In the value-based API splicing requires passing metaobject as non-type template arguments
- Splicing is quite common in various use-cases
- Combining reflection with template metaprogramming is common as well

The big question

Is the improvement in compile-time worth the decrease in usability of the value-based reflection API?