<epam>

Rethinking the Way We Do Templates in C++

(EVEN MORE)

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Plan for the talk

1. User experience
2. New toys in a toolbox
3. Wishful thinking
4. Performance

USER EXPERIENCE

Physical Units library in a nutshell

```
// simple numeric operations
static_assert(10q_km / 2 == 5q_km);
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static_assert(1q_km + 1q_m == 1001q_m);
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```

```
// unit conversions
static_assert(1q_h == 3600q_s);
static_assert(1q_km + 1q_m == 1001q_m);
```

```
// dimension conversions
static_assert(1q_km / 1q_s == 1000q_m_per_s);
static_assert(2q_km_per_h * 2q_h == 4q_km);
static_assert(2q_km / 2q_km_per_h == 1q_h);

static_assert(2q_m * 3q_m == 6q_m2);

static_assert(10q_km / 5q_km == 2);

static_assert(1000 / 1q_s == 1q_kHz);
```

Toy example

```
/* speed */ avg_speed(/* length */ distance, /* time */ duration)
{
  return distance / duration;
}
```

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/* speed */ avg_speed(/* length */ distance, /* time */ duration)
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```
const auto kmph = avg_speed(/* 220 km */, /* 2 hours */);
std::cout << /* kmph */ << " km/h\n";
```

```
const auto mph = avg_speed(/* 140 miles */, /* 2 hours */);
std::cout << /* mph */ << " mph\n";
```

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/* speed */ avg_speed(/* length */ distance, /* time */ duration)
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- **Compile-time safety** to make sure that the result is of a correct dimension

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- **Compile-time safety** to make sure that the result is of a correct dimension
- Support for **multiple units and unit prefixes**

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/* speed */ avg_speed(/* length */ distance, /* time */ duration)
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```

- **Compile-time safety** to make sure that the result is of a correct dimension
- Support for **multiple units and unit prefixes**
- **No runtime overhead**
  - no additional intermediate conversions
  - as fast as a custom code implemented with **`double`**s

Developer's experience: Boost.Units

```
namespace bu = boost::units;

constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d,
                                                   bu::quantity<bu::si::time> t)
{
  return d / t;
}
```

Developer's experience: Boost.Units

```
namespace bu = boost::units;

constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d,
                                                   bu::quantity<bu::si::time> t)
{
  return d / t;
}
```

Thanks to template aliases developers have really comfortable environment to develop their code

User's experience: Compilation: Boost.Units

```
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
{ return d * t; }
```

User's experience: Compilation: Boost.Units

```
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
{ return d * t; }
```

GCC-8

```
error: could not convert ‘boost::units::operator*(const boost::units::quantity<Unit1, X>&,
const boost::units::quantity<Unit2, Y>&) [with Unit1 = boost::units::unit<boost::units::list<boost::units::dim
<boost::units::length_base_dimension, boost::units::static_rational<1> >, boost::units::dimensionless_type>,
boost::units::homogeneous_system<boost::units::list<boost::units::si::meter_base_unit,
boost::units::list<boost::units::scaled_base_unit<boost::units::cgs::gram_base_unit, boost::units::scale<10,
boost::units::static_rational<3> > >, boost::units::list<boost::units::si::second_base_unit,
boost::units::list<boost::units::si::ampere_base_unit, boost::units::list<boost::units::si::kelvin_base_unit,
boost::units::list<boost::units::si::mole_base_unit, boost::units::list<boost::units::si::candela_base_unit,
boost::units::list<boost::units::angle::radian_base_unit, boost::units::list<boost::units::angle::steradian_base_unit,
boost::units::dimensionless_type> > > > > > > > > >; Unit2 = boost::units::unit<boost::units::list<boost::units::dim
<boost::units::time_base_dimension, boost::units::static_rational<1> >, boost::units::dimensionless_type>,
boost::units::homogeneous_system<boost::units::list<boost::units::si::meter_base_unit,
boost::units::list<boost::units::scaled_base_unit<boost::units::cgs::gram_base_unit, boost::units::scale<10,
boost::units::static_rational<3> > >, boost::units::list<boost::units::si::second_base_unit, boost::units::list
<boost::units::si::ampere_base_unit, boost::units::list<boost::units::si::kelvin_base_unit, boost::units::list
<boost::units::si::mole_base_unit, boost::units::list<boost::units::si::candela_base_unit, boost::units::list
<boost::units::angle::radian_base_unit, boost::units::list<boost::units::angle::steradian_base_unit,
boost::units::dimensionless_type> > > > > > > > > >; X = double; Y = double; typename
boost::units::multiply_typeof_helper<boost::units::quantity<Unit1, X>, boost::units::quantity<Unit2, Y> >::type =
...
```

User's experience: Compilation: Boost.Units

```
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
{ return d * t; }
```

GCC-8 (CONTINUED)

```
...
boost::units::quantity<boost::units::unit<boost::units::list<boost::units::dim<boost::units::length_base_dimension,
boost::units::static_rational<1> >, boost::units::list<boost::units::dim<boost::units::time_base_dimension,
boost::units::static_rational<1> >, boost::units::dimensionless_type> >, boost::units::homogeneous_system
<boost::units::list<boost::units::si::meter_base_unit, boost::units::list<boost::units::scaled_base_unit
<boost::units::cgs::gram_base_unit, boost::units::scale<10, boost::units::static_rational<3> > >,
boost::units::list<boost::units::si::second_base_unit, boost::units::list<boost::units::si::ampere_base_unit,
boost::units::list<boost::units::si::kelvin_base_unit, boost::units::list<boost::units::si::mole_base_unit,
boost::units::list<boost::units::si::candela_base_unit, boost::units::list<boost::units::angle::radian_base_unit,
boost::units::list<boost::units::angle::steradian_base_unit, boost::units::dimensionless_type> > > > > > > > >,
void>, double>](t)' from 'quantity<unit<list<[...],list<dim<[...],static_rational<1>>,[...]>>,[...],[...]>,[...]>'
to 'quantity<unit<list<[...],list<dim<[...],static_rational<-1>>,[...]>>,[...],[...]>,[...]>'
     return d * t;
            ~~^~~
```

User's experience: Compilation: Boost.Units

```
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
{ return d * t; }
```

GCC-8 (CONTINUED)

```
...
boost::units::quantity<boost::units::unit<boost::units::list<boost::units::dim<boost::units::length_base_dimension,
boost::units::static_rational<1> >, boost::units::list<boost::units::dim<boost::units::time_base_dimension,
boost::units::static_rational<1> >, boost::units::dimensionless_type> >, boost::units::homogeneous_system
<boost::units::list<boost::units::si::meter_base_unit, boost::units::list<boost::units::scaled_base_unit
<boost::units::cgs::gram_base_unit, boost::units::scale<10, boost::units::static_rational<3> > >,
boost::units::list<boost::units::si::second_base_unit, boost::units::list<boost::units::si::ampere_base_unit,
boost::units::list<boost::units::si::kelvin_base_unit, boost::units::list<boost::units::si::mole_base_unit,
boost::units::list<boost::units::si::candela_base_unit, boost::units::list<boost::units::angle::radian_base_unit,
boost::units::list<boost::units::angle::steradian_base_unit, boost::units::dimensionless_type> > > > > > > > >,
void>, double>](t)' from 'quantity<unit<list<[...],list<dim<[...],static_rational<1>>,[...]>>,[...],[...]>,[...]>'
to 'quantity<unit<list<[...],list<dim<[...],static_rational<-1>>,[...]>>,[...],[...]>,[...]>'
     return d * t;
            ~~^~~
```

This is only the very first line of the LOOOONG error log...

User's experience: Compilation: Boost.Units

```
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
{ return d * t; }
```

CLANG-7

```
error: no viable conversion from returned value of type 'quantity<unit<list<[...], list<dim<[...],
static_rational<1, [...]>>, [...]>>, [...]>, [...]>' to function return type 'quantity<unit<list<[...], list<dim<[...],
static_rational<-1, [...]>>, [...]>>, [...]>, [...]>'
    return d * t;
           ^~~~
```

User's experience: Compilation: Boost.Units

```
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
{ return d * t; }
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```
error: no viable conversion from returned value of type 'quantity<unit<list<[...], list<dim<[...],
static_rational<1, [...]>>, [...]>>, [...]>, [...]>' to function return type 'quantity<unit<list<[...], list<dim<[...],
static_rational<-1, [...]>>, [...]>>, [...]>, [...]>'
    return d * t;
           ^~~~
```

Sometimes a shorter error message is not necessarily better ;-)

Developer's experience: NHolthaus Units

```
constexpr units::velocity::meters_per_second_t avg_speed(units::length::meter_t d,
                                                         units::time::second_t t)
{
  return d / t;
}
```

Again, nice developer's experience thanks to aliases

User's experience: Compilation: NHolthaus Units

```
constexpr units::velocity::meters_per_second_t avg_speed(units::length::meter_t d, units::time::second_t t)
{ return d * t; }
```

User's experience: Compilation: NHolthaus Units

```
constexpr units::velocity::meters_per_second_t avg_speed(units::length::meter_t d, units::time::second_t t)
{ return d * t; }
```

GCC-8

```
error: static assertion failed: Units are not compatible.
   static_assert(traits::is_convertible_unit<UnitFrom, UnitTo>::value, "Units are not compatible.");
                 ^~~~~~
```

User's experience: Compilation: NHolthaus Units

```
constexpr units::velocity::meters_per_second_t avg_speed(units::length::meter_t d, units::time::second_t t)
{ return d * t; }
```

GCC-8

```
error: static assertion failed: Units are not compatible.
   static_assert(traits::is_convertible_unit<UnitFrom, UnitTo>::value, "Units are not compatible.");
                 ^~~~~~
```

`static_assert` is often not the best solution

- does not influence the overload resolution process
- for some compilers does not provide enough context

User's experience: Compilation: NHolthaus Units

```
constexpr units::velocity::meters_per_second_t avg_speed(units::length::meter_t d, units::time::second_t t)
{ return d * t; }
```

CLANG-7

```
error: static_assert failed due to requirement 'traits::is_convertible_unit<unit<ratio<1, 1>, base_unit<ratio<1, 1>,
ratio<0, 1>, ratio<1, 1>, ratio<0, 1>, ratio<0, 1>, ratio<0, 1>, ratio<0, 1>, ratio<0, 1>, ratio<0, 1> >, ratio<0, 1>,
ratio<0, 1> >, unit<ratio<1, 1>, base_unit<ratio<1, 1>, ratio<0, 1>, ratio<-1, 1>, ratio<0, 1>, ratio<0, 1>, ratio<0, 1>,
ratio<0, 1>, ratio<0, 1>, ratio<0, 1> >, ratio<0, 1>, ratio<0, 1> > >::value' "Units are not compatible."
                static_assert(traits::is_convertible_unit<UnitFrom, UnitTo>::value, "Units are not compatible.");
                ^             ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

A need to modernize our toolbox

- In most template metaprogramming libraries *compile-time errors are rare*

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- It is expected that engineers working with a physical units library **will experience compile-time errors very often**
  - generating compile-time errors for invalid calculation is the *main reason to create such a library*

A need to modernize our toolbox

- In most template metaprogramming libraries *compile-time errors are rare*
- It is expected that engineers working with a physical units library **will experience compile-time errors very often**
  - generating compile-time errors for invalid calculation is the *main reason to create such a library*

In case of the physical units library we have to rethink the way we do template metaprogramming!

User's experience: Debugging: Boost.Units

```
35  template<typename LengthSystem, typename TimeSystem>
36  constexpr auto avg_speed(bu::quantity<bu::unit<bu::length_dimension, LengthSystem>> d,
37                           bu::quantity<bu::unit<bu::time_dimension, TimeSystem>> t)
38  {
39      return d / t;
40  }
41
```

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```
35  template<typename LengthSystem, typename TimeSystem>
36  constexpr auto avg_speed(bu::quantity<bu::unit<bu::length_dimension, LengthSystem>> d,
37                           bu::quantity<bu::unit<bu::time_dimension, TimeSystem>> t)
38  {
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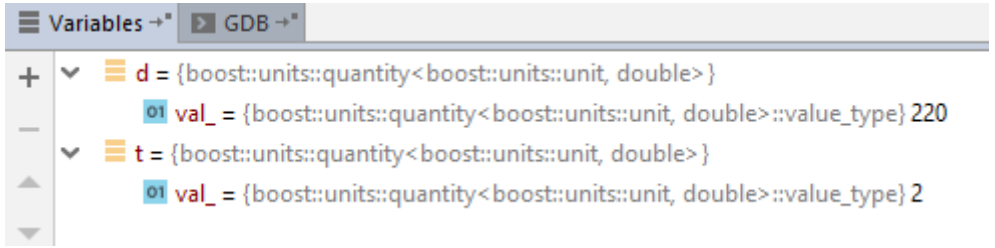

User's experience: Debugging: Boost.Units

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36  constexpr auto avg_speed(bu::quantity<bu::unit<bu::length_dimension, LengthSystem>> d,
37                           bu::quantity<bu::unit<bu::time_dimension, TimeSystem>> t)
38  {
39      return d / t;
40  }
41
```

```
Breakpoint 1, avg_speed<boost::units::heterogeneous_system<boost::units::heterogeneous_system_impl
<boost::units::list<boost::units::heterogeneous_system_dim<boost::units::si::meter_base_unit, boost::units::static_rational<1> >,
boost::units::dimensionless_type>, boost::units::list<boost::units::dim<boost::units::length_base_dimension,
boost::units::static_rational<1> >, boost::units::dimensionless_type>, boost::units::list<boost::units::scale_list_dim
<boost::units::scale<10, boost::units::static_rational<3> > >, boost::units::dimensionless_type> > >,
boost::units::heterogeneous_system<boost::units::heterogeneous_system_impl<boost::units::list
<boost::units::heterogeneous_system_dim<boost::units::scaled_base_unit<boost::units::si::second_base_unit,
boost::units::scale<60, boost::units::static_rational<2> > >, boost::units::static_rational<1> >,
boost::units::dimensionless_type>, boost::units::list<boost::units::dim<boost::units::time_base_dimension,
boost::units::static_rational<1> >, boost::units::dimensionless_type>, boost::units::dimensionless_type> > > (d=..., t=...) at
velocity_2.cpp:39
39          return d / t;
```

User's experience: Debugging: Boost.Units

```
35  template<typename LengthSystem, typename TimeSystem>
36  constexpr auto avg_speed(bu::quantity<bu::unit<bu::length_dimension, LengthSystem>> d,
37                           bu::quantity<bu::unit<bu::time_dimension, TimeSystem>> t)
38  {
39      return d / t;
40  }
41
```

```
(gdb) ptype d
type = class boost::units::quantity<boost::units::unit<boost::units::list<boost::units::dim<boost::units::length_base_dimension,
boost::units::static_rational<1, 1> >, boost::units::dimensionless_type>, boost::units::heterogeneous_system
<boost::units::heterogeneous_system_impl<boost::units::list<boost::units::heterogeneous_system_dim
<boost::units::si::meter_base_unit, boost::units::static_rational<1, 1> >, boost::units::dimensionless_type>,
boost::units::list<boost::units::dim<boost::units::length_base_dimension, boost::units::static_rational<1, 1> >,
boost::units::dimensionless_type>, boost::units::list<boost::units::scale_list_dim<boost::units::scale<10, static_rational<3>>>,
boost::units::dimensionless_type> > >, void>, double> [with Unit = boost::units::unit<boost::units::list<boost::units::dim
<boost::units::length_base_dimension, boost::units::static_rational<1, 1> >, boost::units::dimensionless_type>,
boost::units::heterogeneous_system<boost::units::heterogeneous_system_impl<boost::units::list
<boost::units::heterogeneous_system_dim<boost::units::si::meter_base_unit, boost::units::static_rational<1, 1> >,
boost::units::dimensionless_type>, boost::units::list<boost::units::dim<boost::units::length_base_dimension,
boost::units::static_rational<1, 1> >, boost::units::dimensionless_type>, boost::units::list<boost::units::scale_list_dim
<boost::units::scale<10, static_rational<3> > >, boost::units::dimensionless_type> > >, void>, Y = double] {
...
```

Type aliases are great for developers but not for end users

- **Developers** cannot live without aliases as they hugely *simplify code development and its maintenance*

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It is a pity that we still do not have **strong typedefs** in the C++ language :-(

Inheritance as a workaround

```
struct dim_speed : derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>> {};
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- **Similarly** to strong typedefs
  - *strong types* that do not vanish during compilation process
  - member and non-member functions of a base class *taking the base class type as an argument* will still *work with a child class type* provided instead (i.e. **op==**)

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- **Alternatively** to strong typedefs
  - do not automatically inherit *constructors and assignment operators*
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Inheritance as a workaround

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struct dim_speed : derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>> {};
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  - *strong types* that do not vanish during compilation process
  - member and non-member functions of a base class *taking the base class type as an argument* will still *work with a child class type* provided instead (i.e. **op==**)
- **Alternatively** to strong typedefs
  - do not automatically inherit *constructors and assignment operators*
  - member functions of a base class *returning the base class type* will still *return the same base type for a child class instance*

A good fit for simple empty types like **`derived_dimension`** and **`scaled_unit`**

Type substitution problem

```
Speed auto v = 10q_m / 2q_s;
```

Type substitution problem

```
Speed auto v = 10q_m / 2q_s;
```

```
template<typename D1, typename U1, typename Rep1, typename D2, typename U2, typename Rep2>
[[nodiscard]] constexpr Quantity auto operator/(const quantity<D1, U1, Rep1>& lhs,
                                                const quantity<D2, U2, Rep2>& rhs);
```

Type substitution problem

```
Speed auto v = 10q_m / 2q_s;
```

```
template<typename D1, typename U1, typename Rep1, typename D2, typename U2, typename Rep2>
[[nodiscard]] constexpr Quantity auto operator/(const quantity<D1, U1, Rep1>& lhs,
                                                const quantity<D2, U2, Rep2>& rhs);
```

How to form a **speed dimension child class** from division of **`length`** by **`time`**?

Downcasting facility (Version 1.0)

```cpp
template<typename T>
struct downcast_traits : std::type_identity<T> {};

template<typename T>
using downcast = downcast_traits<T>::type;
```

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```
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template<typename T>
using downcast = downcast_traits<T>::type;
```

```
struct dim_speed : derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>> {};
template<>
struct downcast_traits<derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>>> : std::type_identity<dim_speed> {};
```

Downcasting facility (Version 1.0)

```
template<typename T>
struct downcast_traits : std::type_identity<T> {};

template<typename T>
using downcast = downcast_traits<T>::type;
```

```
struct dim_speed : derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>> {};
template<>
struct downcast_traits<derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>>> : std::type_identity<dim_speed> {};
```

```
struct dim_area : derived_dimension<exp<dim_length, 2>> {};
template<>
struct downcast_traits<derived_dimension<exp<dim_length, 2>>> : std::type_identity<dim_area> {};
```

Downcasting facility (Version 1.0)

```
template<typename T>
struct downcast_traits : std::type_identity<T> {};

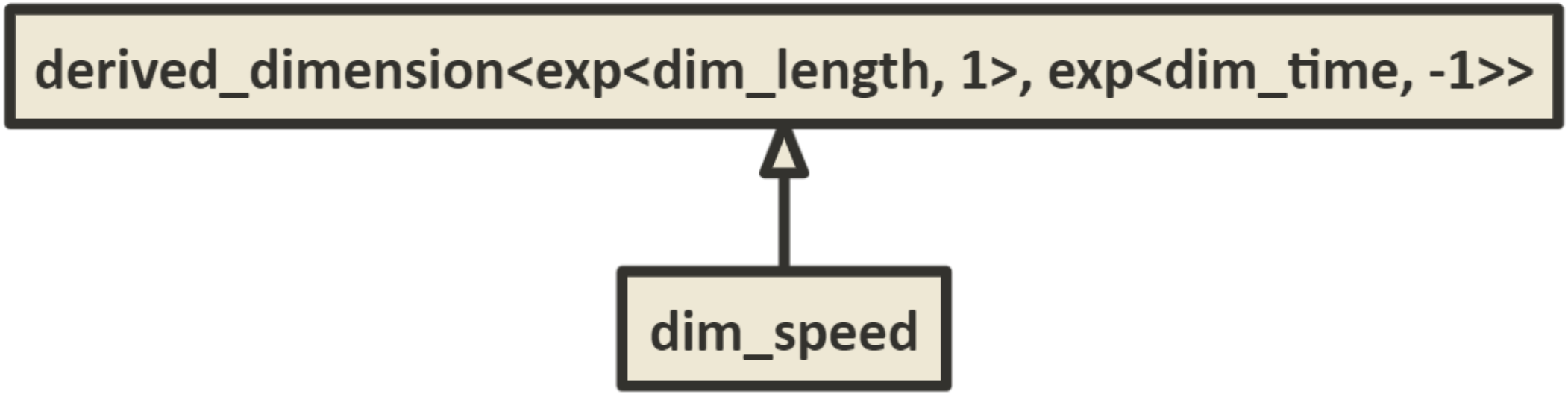
template<typename T>
using downcast = downcast_traits<T>::type;
```

```
struct dim_speed : derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>> {};
template<>
struct downcast_traits<derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>>> : std::type_identity<dim_speed> {};
```

```
struct dim_area : derived_dimension<exp<dim_length, 2>> {};
template<>
struct downcast_traits<derived_dimension<exp<dim_length, 2>>> : std::type_identity<dim_area> {};
```

`downcast_traits` specialization had to be provided for every derived dimension in the library

Downcasting facility (Version 2.0): Overview



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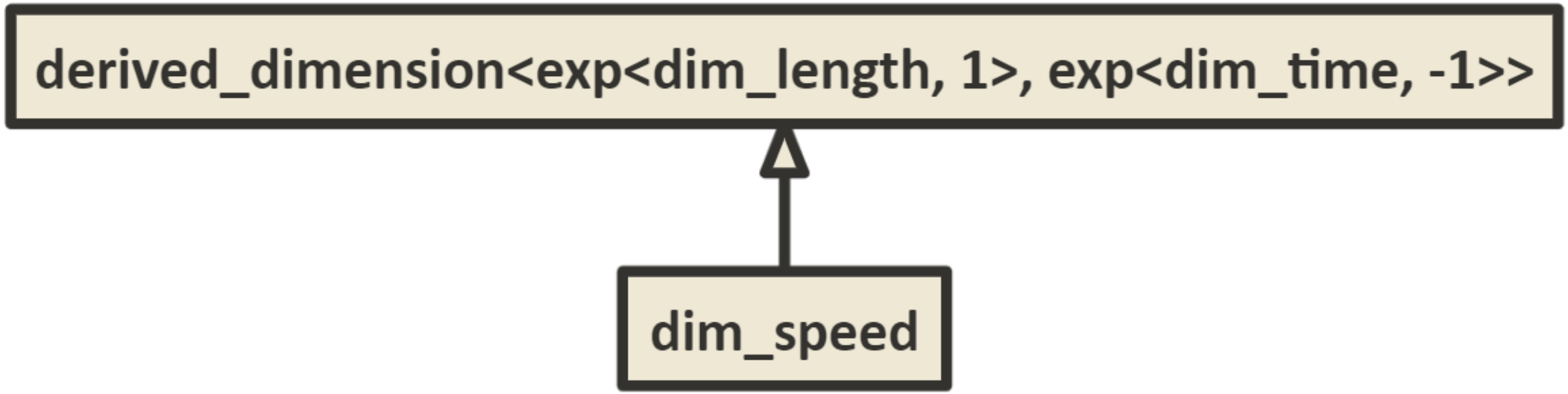
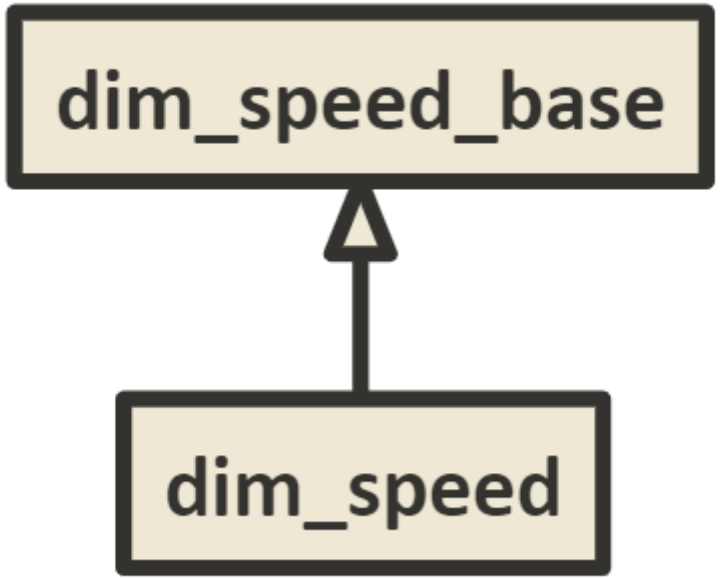


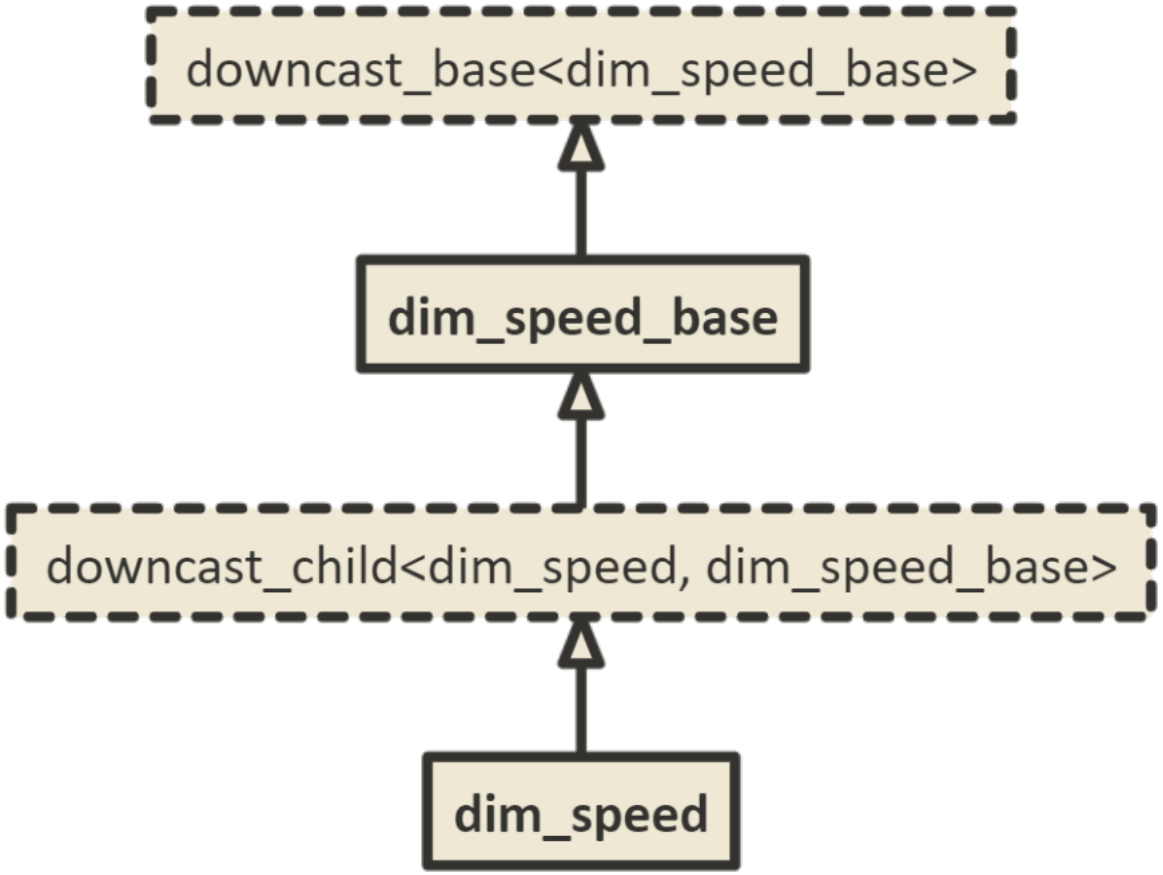
- For slideware let's assume

```
using dim_speed_base = derived_dimension<exp<dim_length, 1>, exp<dim_time, -1>>];
```

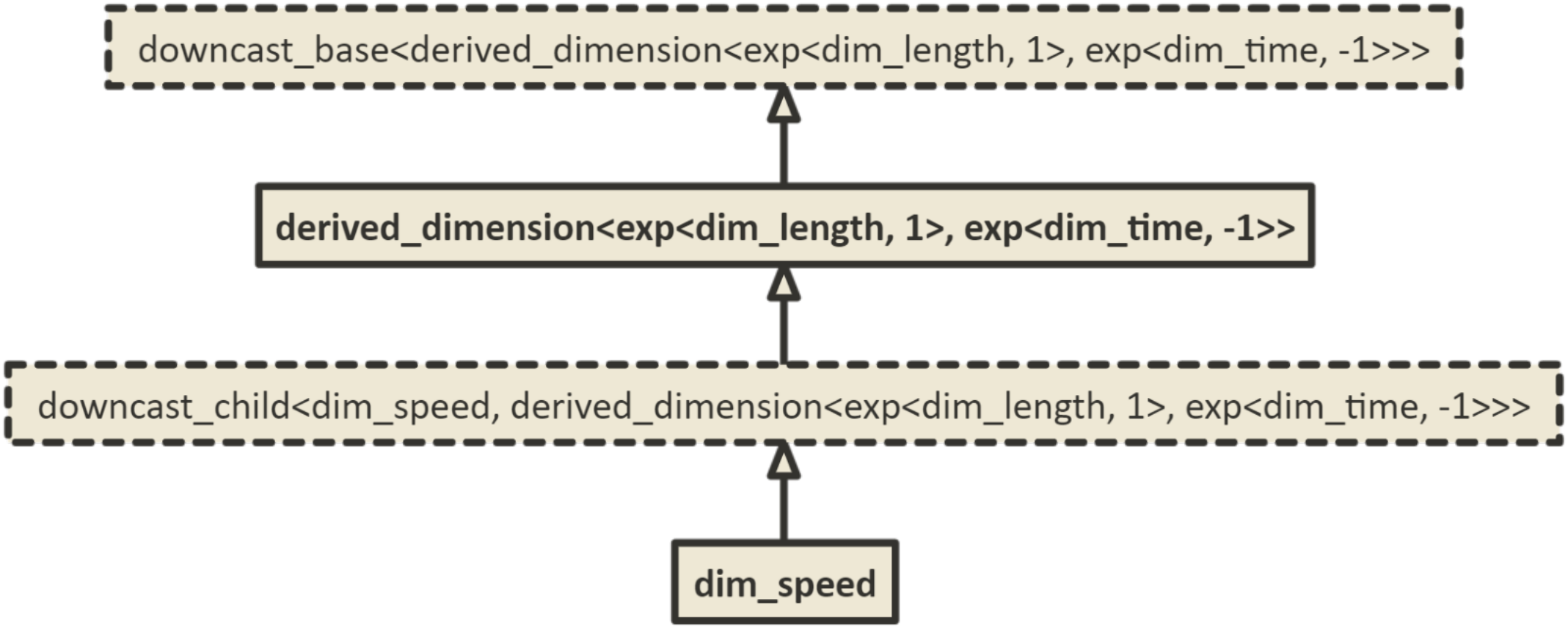
Downcasting facility (Version 2.0): Overview



Downcasting facility (Version 2.0): Overview



Downcasting facility (Version 2.0): Overview



Downcasting facility: Design

```
template<typename BaseType>
struct downcast_base {
  using downcast_base_type = BaseType;
  friend auto downcast_guide(downcast_base);  // declaration only (no implementation)
};
```

Downcasting facility: Design

```
template<typename BaseType>
struct downcast_base {
  using downcast_base_type = BaseType;
  friend auto downcast_guide(downcast_base);  // declaration only (no implementation)
};
```

```
template<typename T>
concept Downcastable =
    requires {
      typename T::downcast_base_type;
    } &&
    std::derived_from<T, downcast_base<typename T::downcast_base_type>>;
```

Downcasting facility: Design

```
template<typename BaseType>
struct downcast_base {
  using downcast_base_type = BaseType;
  friend auto downcast_guide(downcast_base);  // declaration only (no implementation)
};
```

```
template<typename T>
concept Downcastable =
    requires {
      typename T::downcast_base_type;
    } &&
    std::derived_from<T, downcast_base<typename T::downcast_base_type>>;
```

```
template<typename Target, Downcastable T>
struct downcast_child : T {
  friend auto downcast_guide(typename downcast_child::downcast_base) { return Target(); }
};
```

Downcasting facility: Design

```
template<Downcastable T>
using downcast = decltype(detail::downcast_impl<T>());
```

Downcasting facility: Design

```
namespace detail {









  template<typename T>
  constexpr auto downcast_impl()
  {
    if constexpr(has_downcast<T>)
      return decltype(downcast_guide(std::declval<downcast_base<T>>()))();
    else
      return T();
  }

}

template<Downcastable T>
using downcast = decltype(detail::downcast_impl<T>());
```

Downcasting facility: Design

```
namespace detail {

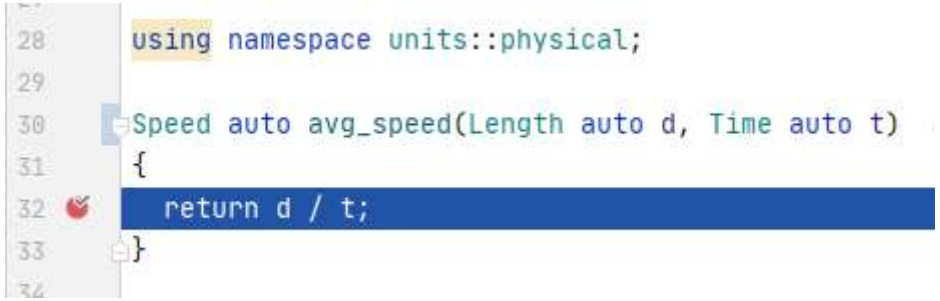
  template<typename T>
  concept has_downcast = requires {
    downcast_guide(std::declval<downcast_base<T>>());
  };

  template<typename T>
  constexpr auto downcast_impl()
  {
    if constexpr(has_downcast<T>)
      return decltype(downcast_guide(std::declval<downcast_base<T>>()))();
    else
      return T();
  }

}

template<Downcastable T>
using downcast = decltype(detail::downcast_impl<T>());
```

User experience: Debugging



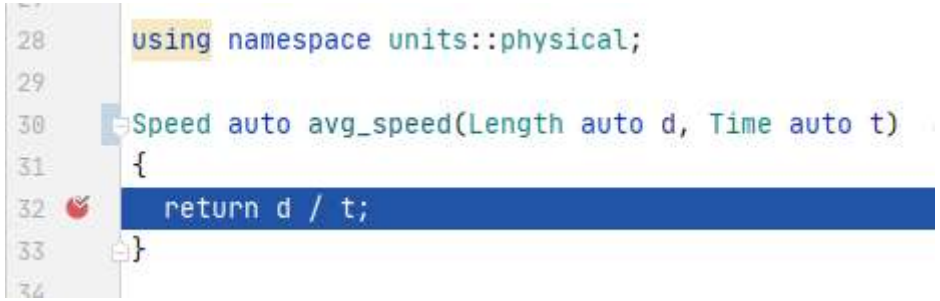
User experience: Debugging

```
28  using namespace units::physical;
29
30  Speed auto avg_speed(Length auto d, Time auto t)
31  {
32    return d / t;
33  }
```

Variables | GDB | Memory View

- d = {units::quantity<units::physical::si::dim_length, units::physical::si::kilometre, long>}
  - value_ = {long} 220
- t = {units::quantity<units::physical::si::dim_time, units::physical::si::hour, long>}
  - value_ = {long} 2

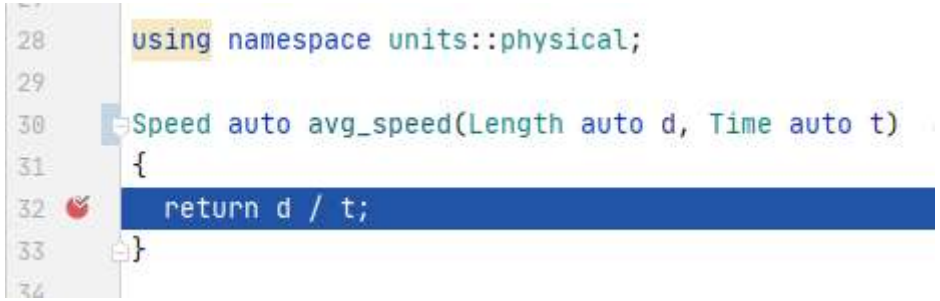
User experience: Debugging



```
28  using namespace units::physical;
29
30  Speed auto avg_speed(Length auto d, Time auto t)
31  {
32    return d / t;
33  }
```

```
Breakpoint 1, avg_speed<units::quantity<units::physical::si::dim_length, units::physical::si::kilometre, long>,
                        units::quantity<units::physical::si::dim_time, units::physical::si::hour, long> >
(d=..., t=...) at hello_units.cpp:32
32      return d / t;
```

User experience: Debugging



```
28  using namespace units::physical;
29
30  Speed auto avg_speed(Length auto d, Time auto t)
31  {
32    return d / t;
33  }
```

```
(gdb) ptype d
type = class units::quantity<units::physical::si::dim_length, units::physical::si::kilometre, long>
[with D = units::physical::si::dim_length, U = units::physical::si::kilometre, Rep = long] {
...
```

NEW TOYS IN A TOOLBOX

NTTP

Traditional implementation of `std::ratio`

```
template<intmax_t Num, intmax_t Den = 1>
struct ratio {
  static constexpr intmax_t num;
  static constexpr intmax_t den;

};
```

Traditional implementation of `std::ratio`

```
template<intmax_t Num, intmax_t Den = 1>
struct ratio {
  static constexpr intmax_t num = Num * static_sign<Den>::value / static_gcd<Num, Den>::value;
  static constexpr intmax_t den = static_abs<Den>::value / static_gcd<Num, Den>::value;
  using type = ratio<num, den>;
};
```

Traditional implementation of `std::ratio`

```
template<intmax_t Num, intmax_t Den = 1>
struct ratio {
  static constexpr intmax_t num = Num * static_sign<Den>::value / static_gcd<Num, Den>::value;
  static constexpr intmax_t den = static_abs<Den>::value / static_gcd<Num, Den>::value;
  using type = ratio<num, den>;
};
```

```
template<intmax_t Pn>
struct static_sign : integral_constant<intmax_t, (Pn < 0) ? -1 : 1> {};
```

Traditional implementation of `std::ratio`

```
template<intmax_t Num, intmax_t Den = 1>
struct ratio {
  static constexpr intmax_t num = Num * static_sign<Den>::value / static_gcd<Num, Den>::value;
  static constexpr intmax_t den = static_abs<Den>::value / static_gcd<Num, Den>::value;
  using type = ratio<num, den>;
};
```

```
template<intmax_t Pn>
struct static_sign : integral_constant<intmax_t, (Pn < 0) ? -1 : 1> {};
```

```
template<intmax_t Pn>
struct static_abs : integral_constant<intmax_t, Pn * static_sign<Pn>::value> {};
```

Traditional implementation of `std::ratio`

```
template<intmax_t Num, intmax_t Den = 1>
struct ratio {
  static constexpr intmax_t num = Num * static_sign<Den>::value / static_gcd<Num, Den>::value;
  static constexpr intmax_t den = static_abs<Den>::value / static_gcd<Num, Den>::value;
  using type = ratio<num, den>;
};
```

```
template<intmax_t Pn, intmax_t Qn>
struct static_gcd : static_gcd<Qn, (Pn % Qn)> {};

template<intmax_t Pn>
struct static_gcd<Pn, 0> : integral_constant<intmax_t, static_abs<Pn>::value> {};

template<intmax_t Qn>
struct static_gcd<0, Qn> : integral_constant<intmax_t, static_abs<Qn>::value> {};
```

Traditional implementation of `std::ratio_multiply`

```
namespace detail {

  template<typename R1, typename R2>
  struct ratio_multiply_impl {
  private:
    static constexpr intmax_t gcd1 = static_gcd<R1::num, R2::den>::value;
    static constexpr intmax_t gcd2 = static_gcd<R2::num, R1::den>::value;
  public:
    using type = ratio<safe_multiply<(R1::num / gcd1), (R2::num / gcd2)>::value,
                       safe_multiply<(R1::den / gcd2), (R2::den / gcd1)>::value>;
    static constexpr intmax_t num = type::num;
    static constexpr intmax_t den = type::den;
  };

}

template<typename R1, typename R2>
using ratio_multiply = detail::ratio_multiply_impl<R1, R2>::type;
```

constexpr-based implementation of ratio

```
template<typename T>
[[nodiscard]] constexpr T abs(T v) noexcept { return v < 0 ? -v : v; }
```

```
template<std::intmax_t Num, std::intmax_t Den = 1>
struct ratio {
  static constexpr std::intmax_t num = Num * (Den < 0 ? -1 : 1) / std::gcd(Num, Den);
  static constexpr std::intmax_t den = abs(Den) / std::gcd(Num, Den);
  using type = ratio<num, den>;
};
```

constexpr-based implementation of ratio

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template<typename T>
[[nodiscard]] constexpr T abs(T v) noexcept { return v < 0 ? -v : v; }
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```
template<std::intmax_t Num, std::intmax_t Den = 1>
struct ratio {
  static constexpr std::intmax_t num = Num * (Den < 0 ? -1 : 1) / std::gcd(Num, Den);
  static constexpr std::intmax_t den = abs(Den) / std::gcd(Num, Den);
  using type = ratio<num, den>;
};
```

- *Better code reuse* between run-time and compile-time programming
- *Less instantiations* of class templates

constexpr-based implementation of ratio_multiply

```
namespace detail {

  template<typename R1, typename R2>
  struct ratio_multiply_impl {
  private:
    static constexpr std::intmax_t gcd1 = std::gcd(R1::num, R2::den);
    static constexpr std::intmax_t gcd2 = std::gcd(R2::num, R1::den);
  public:
    using type = ratio<safe_multiply(R1::num / gcd1, R2::num / gcd2),
                       safe_multiply(R1::den / gcd2, R2::den / gcd1)>;
    static constexpr std::intmax_t num = type::num;
    static constexpr std::intmax_t den = type::den;
  };

}

template<Ratio R1, Ratio R2>
using ratio_multiply = detail::ratio_multiply_impl<R1, R2>::type;
```

Non-type template parameters (NTTP) (C++20)

One of the following (optionally cv-qualified) types

- a **structural type**
- a type that *contains a placeholder* (**auto**) type
- a placeholder for a *deduced class type* (CTAD)

Non-type template parameters (NTTP) (C++20)

One of the following (optionally cv-qualified) types

- a **structural type**
- a type that *contains a placeholder* (**auto**) type
- a placeholder for a *deduced class type* (CTAD)

Structural types

- a *scalar* type with a constant destruction
- an *lvalue reference* type
- a *literal class* where all base classes and non-static data members are public and non-mutable structural types

Non-type template parameters (NTTP) (C++20)

Two template *instantiations refer to the same* class, function, or variable if their corresponding NTTPs are **template argument equivalent**

NTTP: Template argument equivalent values (C++20)

- Integral types with the same values

NTTP: Template argument equivalent values (C++20)

- **Integral** types with the same values
- **Enumeration** type with the same values

NTTP: Template argument equivalent values (C++20)

- Integral types with the same values
- Enumeration type with the same values
- `std::nullptr_t`

NTTP: Template argument equivalent values (C++20)

- **Integral** types with the same values
- **Enumeration** type with the same values
- **`std::nullptr_t`**
- **Floating-point** type with identical values

NTTP: Template argument equivalent values (C++20)

- **Integral** types with the same values
- **Enumeration** type with the same values
- **`std::nullptr_t`**
- **Floating-point** type with identical values
- **Pointer type** with the same pointer value
- **Pointer-to-member** type referring to the same class member or both are **`nullptr`**
- **Reference** type referring to the same object or function

NTTP: Template argument equivalent values (C++20)

- **Integral** types with the same values
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- **Array** type with template argument equivalent elements

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- **Array** type with template argument equivalent elements
- **Class** type with *template argument equivalent* subobjects and reference members

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- **`std::nullptr_t`**
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- **Pointer-to-member** type referring to the same class member or both are **`nullptr`**
- **Reference** type referring to the same object or function
- **Array** type with template argument equivalent elements
- **Class** type with *template argument equivalent* subobjects and reference members
- **Union** type where either both have
  - *no active member*
  - the *same active member* and their active members are *template argument equivalent*

NTTP-based implementation of `ratio`

```
struct ratio {
  std::intmax_t num;
  std::intmax_t den;

  explicit constexpr ratio(std::intmax_t n, std::intmax_t d = 1) :
    num(n * (d < 0 ? -1 : 1) / std::gcd(n, d)),
    den(abs(d) / std::gcd(n, d))
  {
  }

  // ...
};
```

NTTP-based implementation of `ratio_multiply`

```
struct ratio {
  // ...
  [[nodiscard]] friend constexpr ratio operator*(const ratio& lhs, const ratio& rhs)
  {
    const std::intmax_t gcd1 = std::gcd(lhs.num, rhs.den);
    const std::intmax_t gcd2 = std::gcd(rhs.num, lhs.den);
    return ratio(safe_multiply(lhs.num / gcd1, rhs.num / gcd2),
                 safe_multiply(lhs.den / gcd2, rhs.den / gcd1));
  }









};
```

NTTP-based implementation of `ratio_multiply`

```
struct ratio {
  // ...
  [[nodiscard]] friend constexpr ratio operator*(const ratio& lhs, const ratio& rhs)
  {
    const std::intmax_t gcd1 = std::gcd(lhs.num, rhs.den);
    const std::intmax_t gcd2 = std::gcd(rhs.num, lhs.den);
    return ratio(safe_multiply(lhs.num / gcd1, rhs.num / gcd2),
                 safe_multiply(lhs.den / gcd2, rhs.den / gcd1));
  }

  [[nodiscard]] friend consteval ratio operator*(std::intmax_t n, const ratio& rhs)
  {
    return ratio(n) * rhs;
  }

  [[nodiscard]] friend consteval ratio operator*(const ratio& lhs, std::intmax_t n)
  {
    return lhs * ratio(n);
  }
};
```

NTTP in action

BEFORE

```
struct yard : derived_unit<yard, "yd", length, ratio<9’144, 10’000>> {};
struct foot : derived_unit<foot, "ft", length, ratio_multiply<ratio<1, 3>, yard::ratio>> {};
struct inch : derived_unit<inch, "in", length, ratio_multiply<ratio<1, 12>, foot::ratio>> {};
struct mile : derived_unit<mile, "mi", length, ratio_multiply<ratio<1’760>, yard::ratio>> {};
```

NTTP in action

BEFORE

```
struct yard : derived_unit<yard, "yd", length, ratio<9'144, 10'000>> {};
struct foot : derived_unit<foot, "ft", length, ratio_multiply<ratio<1, 3>, yard::ratio>> {};
struct inch : derived_unit<inch, "in", length, ratio_multiply<ratio<1, 12>, foot::ratio>> {};
struct mile : derived_unit<mile, "mi", length, ratio_multiply<ratio<1'760>, yard::ratio>> {};
```

AFTER

```
struct yard : derived_unit<yard, "yd", length, ratio(9'144, 10'000)> {};
struct foot : derived_unit<foot, "ft", length, yard::ratio / 3> {};
struct inch : derived_unit<inch, "in", length, foot::ratio / 12> {};
struct mile : derived_unit<mile, "mi", length, 1'760 * yard::ratio> {};
```

NTTP in action

BEFORE

```
struct yard : derived_unit<yard, "yd", length, ratio<9'144, 10'000>> {};
struct foot : derived_unit<foot, "ft", length, ratio_multiply<ratio<1, 3>, yard::ratio>> {};
struct inch : derived_unit<inch, "in", length, ratio_multiply<ratio<1, 12>, foot::ratio>> {};
struct mile : derived_unit<mile, "mi", length, ratio_multiply<ratio<1'760>, yard::ratio>> {};
```

AFTER

```
struct yard : derived_unit<yard, "yd", length, ratio(9'144, 10'000)> {};
struct foot : derived_unit<foot, "ft", length, yard::ratio / 3> {};
struct inch : derived_unit<inch, "in", length, foot::ratio / 12> {};
struct mile : derived_unit<mile, "mi", length, 1'760 * yard::ratio> {};
```

NTTP in action

BEFORE

```
static_assert(std::is_same_v<ratio_multiply<ratio<2>, ratio<3, 8>>::type, ratio<3, 4>::type>);
```

NTTP in action

BEFORE

```
static_assert(std::is_same_v<ratio_multiply<ratio<2>, ratio<3, 8>>::type, ratio<3, 4>::type>);
```

AFTER

```
static_assert(ratio(2) * ratio(3, 8) == ratio(3, 4));
```

NTTP in action

BEFORE

```
template<typename ExpList>
struct base_units_ratio;

template<typename E>
struct base_units_ratio<exp_list<E>> {
  using type = exp_ratio<E>::type;
};

template<typename E, typename... Es>
struct base_units_ratio<exp_list<E, Es...>> {
  using type = ratio_multiply<typename exp_ratio<E>::type, typename base_units_ratio<exp_list<Es...>>::type>;
};
```

NTTP in action

BEFORE

```
template<typename ExpList>
struct base_units_ratio;

template<typename E>
struct base_units_ratio<exp_list<E>> {
  using type = exp_ratio<E>::type;
};

template<typename E, typename... Es>
struct base_units_ratio<exp_list<E, Es...>> {
  using type = ratio_multiply<typename exp_ratio<E>::type, typename base_units_ratio<exp_list<Es...>>::type>;
};
```

AFTER

```
template<typename... Es>
constexpr ratio base_units_ratio(exp_list<Es...>)
{
  return (exp_ratio<Es>() * ...);
}
```

Class Types in Non-Type Template Parameters

Usage of class types as non-type template parameters (NTTP) might be *one of the most significant C++ improvements in template metaprogramming* during the last decade

Class Types in Non-Type Template Parameters

Usage of class types as non-type template parameters (NTTP) might be *one of the most significant C++ improvements in template metaprogramming* during the last decade

If a template parameter behaves like a value it probably should be an NTTP.

NEW TOYS IN A TOOLBOX

CONCEPTS

How do you feel about such an interface?

```
void* foo(void* t) { /* ... */ }
```

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```
void* foo(void* t) { /* ... */ }
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```
auto foo = [](auto&& t) { /* ... */ };
```

How do you feel about such an interface?

```
void* foo(void* t) { /* ... */ }
```

```
auto foo = [](auto&& t) { /* ... */ };
```

```
template<typename T> auto foo(T&& t) { /* ... */ }
```

How do you feel about such an interface?

```
void* foo(void* t) { /* ... */ }
```

```
auto foo = [](auto&& t) { /* ... */ };
```

```
auto foo(auto&& t) { /* ... */ }
```

How do you feel about such an interface?

```
void* foo(void* t) { /* ... */ }
```

```
auto foo = [](auto&& t) { /* ... */ };
```

```
auto foo(auto&& t) { /* ... */ }
```

```
template<typename T> class foo { /* ... */ };
```

How do you feel about such an interface?

```
void* foo(void* t) { /* ... */ }
```

```
auto foo = [](auto&& t) { /* ... */ };
```

```
auto foo(auto&& t) { /* ... */ }
```

```
template<typename T> class foo { /* ... */ };
```

Unconstrained template parameters are the **`void*`** of C++

Concepts

- Class/Function/Variable/Alias templates, and non-template functions (typically members of class templates) may be associated with a constraint

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- **Class**/**Function**/**Variable**/**Alias** templates, and **non-template functions** (typically members of class templates) may be **associated with a constraint**
- Constraint specifies **the requirements on template arguments**
  - can be used *to select the most appropriate function overloads and template specializations*

Concepts

- **Class**/**Function**/**Variable**/**Alias** templates, and **non-template functions** (typically members of class templates) may be **associated with a constraint**
- Constraint specifies **the requirements on template arguments**
  - can be used *to select the most appropriate function overloads and template specializations*
- *Named sets* of such requirements are called **concepts**

Concepts

- **Class**/**Function**/**Variable**/**Alias** templates, and **non-template functions** (typically members of class templates) may be **associated with a constraint**
- Constraint specifies **the requirements on template arguments**
  - can be used *to select the most appropriate function overloads and template specializations*
- *Named sets* of such requirements are called **concepts**
- **Concept**
  - is a *named predicate*
  - evaluated *at compile-time*
  - a *part of the interface of a template*

Concept categories

Concept categories

PREDICATES

```
template<class Derived, class Base>
concept derived_from =
  is_base_of_v<Base, Derived> &&
  is_convertible_v<const volatile Derived*, const volatile Base*>;
```

- Names ending with prepositions

Concept categories

CAPABILITIES

```
template<class T>
concept swappable =
  requires(T& a, T& b) {
    std::ranges::swap(a, b);
  };
```

- Single requirement concepts
- Named with adjectives **`-ible`** or **`-able`**

Concept categories

ABSTRACTIONS

```
template<class I>
concept bidirectional_iterator =
  std::ranges::forward_iterator<I> &&
  std::derived_from<ITER_CONCEPT(I), std::bidirectional_iterator_tag> &&
  requires(I i) {
    { --i } -> std::same_as<I&>;
    { i-- } -> std::same_as<I>;
  };
```

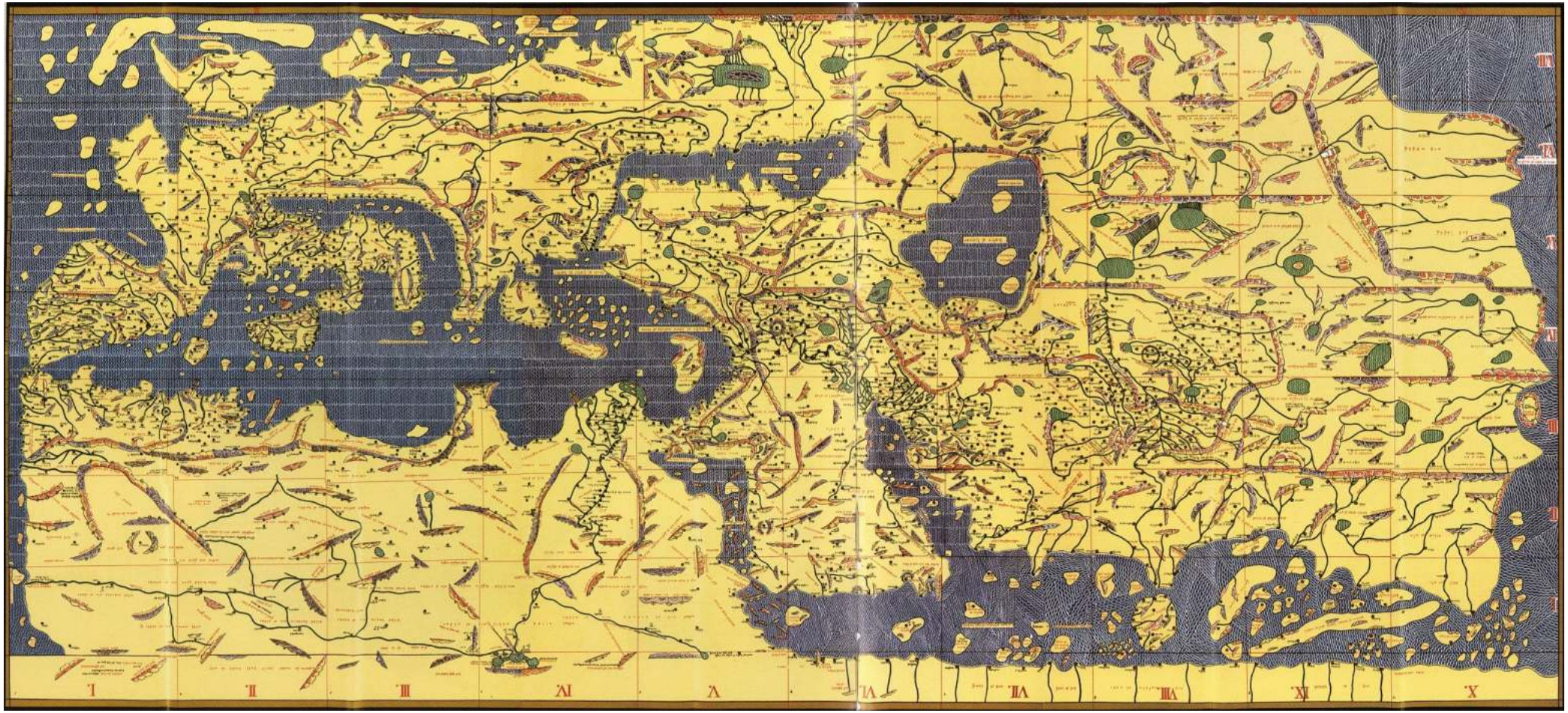
- High-level concepts
- Named using very generic nouns

Sicily's Medieval Map of the World

Sicily's Medieval Map of the World

Most of the experience we have with concepts comes from the range-v3 library (algorithms). Let's try to view it from another angle too...

Sicily's Medieval Map of the World (Upside down)



What about our `std::ratio_multiply`?

```
template<typename R1, typename R2>
using ratio_multiply = detail::ratio_multiply_impl<R1, R2>::type;
```

What about our `std::ratio_multiply`?

```
template<typename R1, typename R2>
using ratio_multiply = detail::ratio_multiply_impl<R1, R2>::type;
```

```
using type = std::ratio_multiply<std::string, std::milli>;
```

What about our `std::ratio_multiply`?

```
template<typename R1, typename R2>
using ratio_multiply = detail::ratio_multiply_impl<R1, R2>::type;
```

```
using type = std::ratio_multiply<std::string, std::milli>;
```

```
include/c++/9.2.0/ratio: In instantiation of 'struct std::__ratio_multiply<std::__cxx11::basic_string<char>,
std::ratio<1, 1000> >':
include/c++/9.2.0/ratio:311:11:   required by substitution of 'template<class _R1, class _R2> using ratio_multiply =
typename std::__ratio_multiply::type [with _R1 = std::__cxx11::basic_string<char>; _R2 = std::ratio<1, 1000>]'
<source>:4:57:   required from here
include/c++/9.2.0/ratio:294:35: error: 'num' is not a member of 'std::__cxx11::basic_string<char>'
  294 |         __safe_multiply<(_R1::num / __gcd1),
      |                          ~~~~~~~~~~^~~~~~~~
include/c++/9.2.0/ratio: In instantiation of 'const intmax_t std::__ratio_multiply<std::__cxx11::basic_string<char>,
std::ratio<1, 1000> >::__gcd1':
include/c++/9.2.0/ratio:294:35:   required from 'struct std::__ratio_multiply<std::__cxx11::basic_string<char>,
std::ratio<1, 1000> >'
include/c++/9.2.0/ratio:311:11:   required by substitution of 'template<class _R1, class _R2> using ratio_multiply =
typename std::__ratio_multiply::type [with _R1 = std::__cxx11::basic_string<char>; _R2 = std::ratio<1, 1000>]'
<source>:4:57:   required from here
include/c++/9.2.0/ratio:287:29: error: 'num' is not a member of
'std::__cxx11::basic_string<char>'
  287 |       static const intmax_t __gcd1 =
      |                             ^~~~~~
```

New concept category?

FAMILY OF INSTANTIATIONS

```
template<typename T>
concept Ratio = is_ratio<T>;
```

New concept category?

FAMILY OF INSTANTIATIONS

```
template<typename T>
inline constexpr bool is_ratio = false;

template<intmax_t Num, intmax_t Den>
inline constexpr bool is_ratio<ratio<Num, Den>> = true;

template<typename T>
concept Ratio = is_ratio<T>;
```

New concept category?

FAMILY OF INSTANTIATIONS

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inline constexpr bool is_ratio = false;

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- Named with an upper-case first letter of the class template to match

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template<typename T>
concept Ratio = is_ratio<T>;
```

- Named with an upper-case first letter of the class template to match

Well, that naming is not going to fly in the Committee ;-)

Concepts perception issue

> The experience of the authors and implementors of the Ranges TS is that **getting concept definitions and algorithm constraints right is hard**.
>
> *-- P0896 (The One Ranges Proposal)*

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- Above is often oversimplified as *"Defining concepts is hard, let's keep their number small"*

Concepts perception issue

> The experience of the authors and implementors of the Ranges TS is that **getting concept definitions and algorithm constraints right is hard**.
>
> *-- P0896 (The One Ranges Proposal)*

- Above is often oversimplified as *"Defining concepts is hard, let's keep their number small"*

Again, because this is what we explored so far...

The world is different and bigger than we initially imagined

Not all concepts have to be hard to define and prove correct

ANY INSTANTIATION OF A CLASS TEMPLATE

```
template<typename T>
inline constexpr bool is_ratio = false;

template<intmax_t Num, intmax_t Den>
inline constexpr bool is_ratio<ratio<Num, Den>> = true;
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Not all concepts have to be hard to define and prove correct

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```
template<typename T>
inline constexpr bool is_ratio = false;

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template<typename T>
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```
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inline constexpr bool is_ratio = false;

template<intmax_t Num, intmax_t Den>
inline constexpr bool is_ratio<ratio<Num, Den>> = true;
```

```
template<typename T>
concept Ratio = is_ratio<T>;
```

Is this concept easy to prove correct?

What about our `std::ratio_multiply`?

```
template<Ratio R1, Ratio R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

What about our `std::ratio_multiply`?

```
template<Ratio R1, Ratio R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
using type = ratio_multiply<std::string, std::milli>;
```

What about our `std::ratio_multiply`?

```
template<Ratio R1, Ratio R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
using type = ratio_multiply<std::string, std::milli>;
```

```
<source>:24:52: error: template constraint failure for 'template<class R1, class R2>  requires (Ratio<R1>) && (Ratio<R2>)
  using ratio_multiply = std::ratio_multiply<R1, R2>'
   24 | using type = ratio_multiply<std::string, std::milli>;
      |                                                    ^
<source>:24:52: note: constraints not satisfied
<source>:11:9:   required for the satisfaction of 'Ratio<std::__cxx11::basic_string<char, std::char_traits<char>,
  std::allocator<char> > >'
<source>:11:17: note: the expression 'is_ratio<T>' evaluated to 'false'
   11 | concept Ratio = is_ratio<T>;
      |                 ^~~~~~~~~~
```

Not all concepts have to be hard to define and prove correct

RATIO-LIKE TYPE

```
template<typename T>
concept Ratio = requires {
    T::num;
    T::den;
};
```

Not all concepts have to be hard to define and prove correct

RATIO-LIKE TYPE

```
template<typename T>
concept Ratio = requires {
    T::num;
    T::den;
};
```

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What about our `std::ratio_multiply`?

```
template<Ratio R1, Ratio R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
using type = ratio_multiply<std::string, std::milli>;
```

What about our `std::ratio_multiply`?

```
template<Ratio R1, Ratio R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
using type = ratio_multiply<std::string, std::milli>;
```

```
<source>:24:52: error: template constraint failure for 'template<class R1, class R2>  requires (Ratio<R1>) &&
  (Ratio<R2>) using ratio_multiply = std::ratio_multiply<R1, R2>'
   24 | using type = ratio_multiply<std::string, std::milli>;
      |                                                    ^
<source>:24:52: note: constraints not satisfied
<source>:14:9:   required for the satisfaction of 'Ratio<std::__cxx11::basic_string<char, std::char_traits<char>,
  std::allocator<char> > >'
<source>:14:17:   in requirements
<source>:15:8: note: the required expression 'T::num' is invalid
   15 |     T::num;
      |        ^~~
<source>:16:8: note: the required expression 'T::den' is invalid
   16 |     T::den;
      |        ^~~
```

Maybe we do not need named concepts here?

```
template<typename R1, typename R2>
  requires is_ratio<R1> && is_ratio<R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

Maybe we do not need named concepts here?

```
template<typename R1, typename R2>
  requires is_ratio<R1> && is_ratio<R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

But named concepts are really handy in this and many other cases...

Concepts example

```
template<typename T>
concept Speed = QuantityOf<T, dim_speed>;
```

```
constexpr price calc_fine(units::Speed auto speed);
```

Concepts example

```
template<typename T, typename D>
concept QuantityOf = Quantity<T> && Dimension<D> && equivalent_dim<typename T::dimension, D>;

template<typename T>
concept Speed = QuantityOf<T, dim_speed>;
```

```
constexpr price calc_fine(units::Speed auto speed);
```

Concepts example

```
template<typename T>
concept Quantity = is_instantiation_of<quantity>;

template<typename T, typename D>
concept QuantityOf = Quantity<T> && Dimension<D> && equivalent_dim<typename T::dimension, D>;

template<typename T>
concept Speed = QuantityOf<T, dim_speed>;
```

```
constexpr price calc_fine(units::Speed auto speed);
```

Concepts example

```
template<typename T>
concept Dimension = BaseDimension<T> || DerivedDimension<T>;

template<typename T>
concept Quantity = is_instantiation_of<quantity>;

template<typename T, typename D>
concept QuantityOf = Quantity<T> && Dimension<D> && equivalent_dim<typename T::dimension, D>;

template<typename T>
concept Speed = QuantityOf<T, dim_speed>;
```

```
constexpr price calc_fine(units::Speed auto speed);
```

Concepts example

```
template<typename T>
concept DerivedDimension = is_derived_from_instantiation_of<T, derived_dimension_base>;

template<typename T>
concept Dimension = BaseDimension<T> || DerivedDimension<T>;

template<typename T>
concept Quantity = is_instantiation_of<quantity>;

template<typename T, typename D>
concept QuantityOf = Quantity<T> && Dimension<D> && equivalent_dim<typename T::dimension, D>;

template<typename T>
concept Speed = QuantityOf<T, dim_speed>;
```

```
constexpr price calc_fine(units::Speed auto speed);
```

Concepts example

```
template<typename T>
concept BaseDimension = is_derived_from_base_dimension<T>;

template<typename T>
concept DerivedDimension = is_derived_from_instantiation_of<T, derived_dimension_base>;

template<typename T>
concept Dimension = BaseDimension<T> || DerivedDimension<T>;

template<typename T>
concept Quantity = is_instantiation_of<quantity>;

template<typename T, typename D>
concept QuantityOf = Quantity<T> && Dimension<D> && equivalent_dim<typename T::dimension, D>;

template<typename T>
concept Speed = QuantityOf<T, dim_speed>;
```

```
constexpr price calc_fine(units::Speed auto speed);
```

Not just a syntactic sugar

Not just a syntactic sugar

- Constraining *function template return types*

```
constexpr units::Speed auto avg_speed(units::Length auto d, units::Time auto t)
{
  return d / t;
}
```

Not just a syntactic sugar

- Constraining *function template return types*

```
constexpr units::Speed auto avg_speed(units::Length auto d, units::Time auto t)
{
  return d / t;
}
```

- Constraining the *deduced types* of user's variables

```
const units::Speed auto speed = avg_speed(220.km, 2.h);
```

Not just a syntactic sugar

- Constraining *function template return types*

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constexpr units::Speed auto avg_speed(units::Length auto d, units::Time auto t)
{
  return d / t;
}
```

- Constraining the *deduced types* of user's variables

```
const units::Speed auto speed = avg_speed(220.km, 2.h);
```

- Constraining *class template parameters* without introducing more parameters

```
template<Dimension D, ratio R>
  requires UnitRatio<R>
struct unit;
```

```
template<typename Q, direction D>
  requires Quantity<Q> || QuantityPoint<Q>
class vector;
```

What is the difference?

```cpp
template<typename T>
class wrapper {
  T data_;
public:
  template<typename U,
    typename = std::enable_if_t<std::is_integral_v<T>>>
  void foo(U u);

  // ...
};
```

```cpp
template<typename T>
class wrapper {
  T data_;
public:
  template<typename U>
    requires std::is_integral_v<T>
  void foo(U u);

  // ...
};
```

What is the difference?

```
template<typename T>
class wrapper {
  T data_;
public:
  template<typename U, typename Z = T,
    typename = std::enable_if_t<std::is_integral_v<Z>>>
  void foo(U u);

  // ...
};
```

```
template<typename T>
class wrapper {
  T data_;
public:
  template<typename U>
    requires std::is_integral_v<T>
  void foo(U u);

  // ...
};
```

SFINAE works only on current template parameters.
Concepts just work as expected.

What is the difference?

```
template<typename T>
class wrapper {
  T data_;
public:
  template<typename U, typename Z = T,
    typename = std::enable_if_t<std::is_integral_v<Z>>>
  void foo(U u);

  template<typename Z = T,
    typename = std::enable_if_t<std::is_integral_v<Z>>>
  void boo(Z t);

  // ...
};
```

```
template<typename T>
class wrapper {
  T data_;
public:
  template<typename U>
    requires std::is_integral_v<T>
  void foo(U u);

  void boo(T t)
    requires std::is_integral_v<T>;


  // ...
};
```

SFINAE works only on current template parameters.
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Benefits of using C++ Concepts

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1. Clearly state the design intent of the interface of a class/function template

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1. Clearly **state the design intent** of the interface of a class/function template
2. **Embedded in a template signature**
3. **Simplify and extend SFINAE**
   - *disabling specific overloads* for specific constraints (compared to **`std::enable_if`**)
   - constraints *based on dependent member types/functions existence* (compared to **`void_t`**)
   - *no dummy template parameters* allocated for SFINAE needs
   - constraining *function return types and deduced types of user's variables*

Benefits of using C++ Concepts

1. Clearly **state the design intent** of the interface of a class/function template
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3. **Simplify and extend SFINAE**
   - *disabling specific overloads* for specific constraints (compared to **`std::enable_if`**)
   - constraints *based on dependent member types/functions existence* (compared to **`void_t`**)
   - *no dummy template parameters* allocated for SFINAE needs
   - constraining *function return types and deduced types of user's variables*
4. Greatly **improve error messages**
   - raise *compilation error* about failed compile-time contract *before instantiating a template*
   - no more errors from *deeply nested implementation details of a function template*

And you know what? It is round ;-)

WISHFUL THINKING

Template Parameter Kinds

Templates are parameterized by *one* or *more* template parameters

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- **type** template parameters

```
template<typename Ptr> class smart_ptr { /* ... */ };
smart_ptr<int> ptr;
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- **type** template parameters

```
template<typename Ptr> class smart_ptr { /* ... */ };
smart_ptr<int> ptr;
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- **non-type** template parameters

```
template<typename T, size_t N> class array { /* ... */ };
array<int, 5> a;
```

Template Parameter Kinds

Templates are parameterized by *one* or *more* template parameters

- **type** template parameters

```
template<typename Ptr> class smart_ptr { /* ... */ };
smart_ptr<int> ptr;
```

- **non-type** template parameters

```
template<typename T, size_t N> class array { /* ... */ };
array<int, 5> a;
```

- **template** template parameters

```
template<typename T> class my_deleter {};
template<typename T, template<typename> typename Policy> class handle { /* ... */ };
handle<FILE, my_deleter> h;
```

Sometimes you do not want a named concept

```
template<typename T, template<typename> typename Trait>
concept Satisfies = Trait<T>::value;
```

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```
template<typename T, template<typename> typename Trait>
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```

```
template<typename T>
struct is_ratio : std::false_type {};

template<intmax_t N, intmax_t D>
struct is_ratio<std::ratio<N, D>> : std::true_type {};
```

```
template<Satisfies<is_ratio> R1, Satisfies<is_ratio> R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

Sometimes you do not want a named concept

```
template<typename T, template<typename> typename Trait>
concept Satisfies = Trait<T>::value;
```

```
template<typename T>
struct is_ratio : std::false_type {};

template<intmax_t N, intmax_t D>
struct is_ratio<std::ratio<N, D>> : std::true_type {};
```

```
template<Satisfies<is_ratio> R1, Satisfies<is_ratio> R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
template<typename T>
inline constexpr bool is_ratio = false;

template<intmax_t N, intmax_t D>
inline constexpr bool is_ratio<std::ratio<N, D>> = true;
```

- does not compile :-(

Sometimes you do not want a named concept

```
template<typename T, template<typename> typename Trait>
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template<typename T>
struct is_ratio : std::false_type {};

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struct is_ratio<std::ratio<N, D>> : std::true_type {};
```

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template<Satisfies<is_ratio> R1, Satisfies<is_ratio> R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

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template<typename T>
inline constexpr bool is_ratio = false;

template<intmax_t N, intmax_t D>
inline constexpr bool is_ratio<std::ratio<N, D>> = true;
```

- does not compile :-(

Template template parameter kind works only for class templates

Making variable templates a first class citizen (P2008)

CLASS TEMPLATES

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concept Satisfies = Trait<T>::value;
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template<typename T, template<typename> typename Trait>
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VARIABLE TEMPLATES

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template<typename T, template<typename> bool Trait>
concept Satisfies = Trait<T>;
```

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```
template<typename T, template<typename> typename Trait>
concept Satisfies = Trait<T>::value;
```

VARIABLE TEMPLATES

```
template<typename T, template<typename> bool Trait>
concept Satisfies = Trait<T>;
```

```
template<typename T, template<typename> auto Trait>
concept Satisfies = Trait<T>;
```

Making variable templates a first class citizen (P2008)

CLASS TEMPLATES

```
template<typename T, template<typename> typename Trait>
concept Satisfies = Trait<T>::value;
```

VARIABLE TEMPLATES

```
template<typename T, template<typename> bool Trait>
concept Satisfies = Trait<T>;
```

```
template<typename T, template<typename> auto Trait>
concept Satisfies = Trait<T>;
```

If you have ideas for other cool use cases of this feature PLEASE let me know.

Imagine a Universal Template Parameter Kind (P1985)

A template parameter **placeholder that can be replaced with any kind of a template parameter** (type, non-type, template)

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A template parameter **placeholder that can be replaced with any kind of a template parameter** (type, non-type, template)

EXAMPLE

```
template<template auto>
class X;
```

- takes any kind of template parameter

```
template<template auto...>
class Y;
```

- takes any number and any kind of template parameters

Concept to check for an instantiation of a class template

```
template<typename T, template<template auto...> typename Type>
inline constexpr bool is_instantiation_of = false;

template<template auto... Params, template<template auto...> typename Type>
inline constexpr bool is_instantiation_of<Type<Params...>, Type> = true;
```

Concept to check for an instantiation of a class template

```
template<typename T, template<template auto...> typename Type>
inline constexpr bool is_instantiation_of = false;

template<template auto... Params, template<template auto...> typename Type>
inline constexpr bool is_instantiation_of<Type<Params...>, Type> = true;
```

```
template<typename T, template<template auto...> typename Type>
concept instantiation_of = is_instantiation_of<T, Type>;
```

What about our `std::ratio_multiply`?

```
template<instantiation_of<std::ratio> R1, instantiation_of<std::ratio> R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
using type = ratio_multiply<std::string, std::milli>;
```

What about our `std::ratio_multiply`?

```
template<instantiation_of<std::ratio> R1, instantiation_of<std::ratio> R2>
using ratio_multiply = std::ratio_multiply<R1, R2>;
```

```
using type = ratio_multiply<std::string, std::milli>;
```

```
<source>:27:52: error: template constraint failure for 'template<class R1, class R2>  requires
   (instantiation_of<R1, std::ratio>) && (instantiation_of<R2, std::ratio>)
   using ratio_multiply = std::ratio_multiply<R1, R2>'
   27 | using type = ratio_multiply<std::string, std::milli>;
      |                                                    ^
<source>:27:52: note: constraints not satisfied
<source>:21:9:   required for the satisfaction of 'instantiation_of<std::__cxx11::basic_string<char, std::char_traits<char>,
   std::allocator<char> >, std::ratio>'
<source>:21:14: note: the expression 'is_instantiation_of<T, Type>' evaluated to 'false'
   21 | concept instantiation_of = is_instantiation_of<T, Type>;
      |                            ^~~~~~~~~~~~~~~~~~~
```

Which style do you prefer?

```
// C-like
unit named_coherent_derived_unit(void* dimension, void* symbol, void* prefix_type);
unit coherent_derived_unit(void* dimension);
unit named_scaled_derived_unit(void* dimension, void* symbol, void* ratio, void* prefix_type);
unit named_deduced_derived_unit(void* dimension, void* symbol, void* prefix_type, void* unit, ...);
unit deduced_derived_unit(void* dimension, void* unit, ...);
unit prefixed_derived_unit(void* prefix, void* unit);
```

Which style do you prefer?

```
// C-like
unit named_coherent_derived_unit(void* dimension, void* symbol, void* prefix_type);
unit coherent_derived_unit(void* dimension);
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unit named_deduced_derived_unit(void* dimension, void* symbol, void* prefix_type, void* unit, ...);
unit deduced_derived_unit(void* dimension, void* unit, ...);
unit prefixed_derived_unit(void* prefix, void* unit);
```

```
// strong types + C-like functions
unit named_coherent_derived_unit(dimension dim, string symbol, prefix_type pt);
unit coherent_derived_unit(dimension dim);
unit named_scaled_derived_unit(dimension dim, string symbol, ratio r, prefix_type pt);
unit named_deduced_derived_unit(dimension dim, string symbol, prefix_type pt, unit u, ...);
unit deduced_derived_unit(dimension dim, unit u, ...);
unit prefixed_derived_unit(prefix p, unit u);
```

Which style do you prefer?

```
// C-like
unit named_coherent_derived_unit(void* dimension, void* symbol, void* prefix_type);
unit coherent_derived_unit(void* dimension);
unit named_scaled_derived_unit(void* dimension, void* symbol, void* ratio, void* prefix_type);
unit named_deduced_derived_unit(void* dimension, void* symbol, void* prefix_type, void* unit, ...);
unit deduced_derived_unit(void* dimension, void* unit, ...);
unit prefixed_derived_unit(void* prefix, void* unit);
```

```
// strong types + C-like functions
unit named_coherent_derived_unit(dimension dim, string symbol, prefix_type pt);
unit coherent_derived_unit(dimension dim);
unit named_scaled_derived_unit(dimension dim, string symbol, ratio r, prefix_type pt);
unit named_deduced_derived_unit(dimension dim, string symbol, prefix_type pt, unit u, ...);
unit deduced_derived_unit(dimension dim, unit u, ...);
unit prefixed_derived_unit(prefix p, unit u);
```

```
// strong types + function overloading
unit derived_unit(dimension dim, string symbol, prefix_type pt);
unit derived_unit(dimension dim);
unit derived_unit(dimension dim, string symbol, ratio r, prefix_type pt);
unit derived_unit(dimension dim, string symbol, prefix_type pt, unit u, ...);
unit derived_unit(dimension dim, unit u, ...);
unit derived_unit(prefix p, unit u);
```

What about class templates?

PRE-CONCEPTS

```
template<typename Child, typename Dim, basic_fixed_string Symbol, typename PT>
struct named_coherent_derived_unit;

template<typename Child, typename Dim>
struct coherent_derived_unit;

template<typename Child, typename Dim, basic_fixed_string Symbol, typename R, typename PT = no_prefix>
struct named_scaled_derived_unit;

template<typename Child, typename Dim, basic_fixed_string Symbol, typename PT, typename U, typename... Us>
struct named_deduced_derived_unit;

template<typename Child, typename Dim, typename U, typename... Us>
struct deduced_derived_unit;

template<typename Child, typename P, typename U>
struct prefixed_derived_unit;
```

What about class templates?

CONCEPTS

```
template<typename Child, Dimension Dim, basic_fixed_string Symbol, PrefixType PT>
struct named_coherent_derived_unit;

template<typename Child, Dimension Dim>
struct coherent_derived_unit;

template<typename Child, Dimension Dim, basic_fixed_string Symbol, Ratio R, PrefixType PT = no_prefix>
struct named_scaled_derived_unit;

template<typename Child, Dimension Dim, basic_fixed_string Symbol, PrefixType PT, Unit U, Unit... Us>
struct named_deduced_derived_unit;

template<typename Child, Dimension Dim, Unit U, Unit... Us>
  requires U::is_named && (Us::is_named && ... && true)
struct deduced_derived_unit;

template<typename Child, Prefix P, Unit U>
  requires (!std::same_as<typename U::prefix_type, no_prefix>)
struct prefixed_derived_unit;
```

What about class templates?

CLASS TEMPLATE PARTIAL SPECIALIZATION OVERLOADING

```
template<template auto...>
struct derived_unit;
```

What about class templates?

CLASS TEMPLATE PARTIAL SPECIALIZATION OVERLOADING

```
template<template auto...>
struct derived_unit;
```

```
template<typename Child, Dimension Dim, basic_fixed_string Symbol, PrefixType PT>
struct derived_unit<Child, Dim, Symbol, PT>;

template<typename Child, Dimension Dim>
struct derived_unit<Child, Dim>;

template<typename Child, Dimension Dim, basic_fixed_string Symbol, Ratio R, PrefixType PT = no_prefix>
struct derived_unit<Child, Dim, Symbol, R, PT>;

template<typename Child, Dimension Dim, basic_fixed_string Symbol, PrefixType PT, Unit U, Unit... Us>
struct derived_unit<Child, Dim, Symbol, PT, U, Us...>;

template<typename Child, Dimension Dim, Unit U, Unit... Us>
  requires U::is_named && (Us::is_named && ... && true)
struct derived_unit<Child, Dim, U, Us...>;

template<typename Child, Prefix P, Unit U>
  requires (!std::same_as<typename U::prefix_type, no_prefix>)
struct derived_unit<Child, P, U>;
```

Speed definition example (Today)

LENGTH

```
struct metre : named_coherent_derived_unit<metre, length, "m", si_prefix> {};
struct kilometre : prefixed_derived_unit<kilometre, kilo, metre> {};
struct yard : named_scaled_derived_unit<yard, length, "yd", ratio(9'144, 10'000)> {};
struct mile : named_scaled_derived_unit<mile, length, "mi", 1'760 * yard::ratio> {};
```

Speed definition example (Today)

LENGTH

```
struct metre : named_coherent_derived_unit<metre, length, "m", si_prefix> {};
struct kilometre : prefixed_derived_unit<kilometre, kilo, metre> {};
struct yard : named_scaled_derived_unit<yard, length, "yd", ratio(9'144, 10'000)> {};
struct mile : named_scaled_derived_unit<mile, length, "mi", 1'760 * yard::ratio> {};
```

TIME

```
struct second : named_coherent_derived_unit<second, time, "s", si_prefix> {};
struct hour : named_scaled_derived_unit<hour, time, "h", 3600 * second::ratio> {};
```

Speed definition example (Today)

LENGTH

```
struct metre : named_coherent_derived_unit<metre, length, "m", si_prefix> {};
struct kilometre : prefixed_derived_unit<kilometre, kilo, metre> {};
struct yard : named_scaled_derived_unit<yard, length, "yd", ratio(9'144, 10'000)> {};
struct mile : named_scaled_derived_unit<mile, length, "mi", 1'760 * yard::ratio> {};
```

TIME

```
struct second : named_coherent_derived_unit<second, time, "s", si_prefix> {};
struct hour : named_scaled_derived_unit<hour, time, "h", 3600 * second::ratio> {};
```

SPEED

```
struct metre_per_second : coherent_derived_unit<metre_per_second, speed> {};
struct kilometre_per_hour : deduced_derived_unit<kilometre_per_hour, speed, kilometre, hour> {};
struct mile_per_hour : deduced_derived_unit<mile_per_hour, speed, mile, hour> {};
```

Speed definition example (Future)

LENGTH

```
struct metre : derived_unit<metre, length, "m", si_prefix> {};
struct kilometre : derived_unit<kilometre, kilo, metre> {};
struct yard : derived_unit<yard, length, "yd", ratio(9'144, 10'000)> {};
struct mile : derived_unit<mile, length, "mi", 1'760 * yard::ratio> {};
```

TIME

```
struct second : derived_unit<second, time, "s", si_prefix> {};
struct hour : derived_unit<hour, time, "h", 3600 * second::ratio> {};
```

SPEED

```
struct metre_per_second : derived_unit<metre_per_second, speed> {};
struct kilometre_per_hour : derived_unit<kilometre_per_hour, speed, kilometre, hour> {};
struct mile_per_hour : derived_unit<mile_per_hour, speed, mile, hour> {};
```

PERFORMANCE

Compile-time benchmarking with Metabench

- Started in 2016 by *Louis Dionne*

Compile-time benchmarking with Metabench

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- *CMake module* that simplifies compile-time microbenchmarking

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Compile-time benchmarking with Metabench

- Started in 2016 by *Louis Dionne*
- *CMake module* that simplifies compile-time microbenchmarking
- Can be used *to benchmark precise parts* of a C++ file, such as the instantiation of a single function
- http://metaben.ch *compares the performance* of several MPL algorithms implemented in various libraries

A short intro to Metabench: CMake

```
metabench_add_dataset(metabench.data.ratio.create.std_ratio
    all_std_ratio.cpp.erb "[10, 50, 100, 250, 500, 750, 1000, 1500, 2000]"
    NAME "std::ratio"
)
metabench_add_dataset(metabench.data.ratio.create.ratio_type_constexpr
    all_ratio_type_constexpr.cpp.erb "[10, 50, 100, 250, 500, 750, 1000, 1500, 2000]"
    NAME "ratio constexpr"
)
metabench_add_dataset(metabench.data.ratio.create.ratio_nttp
    all_ratio_nttp.cpp.erb "[10, 50, 100, 250, 500, 750, 1000, 1500, 2000]"
    NAME "ratio NTTP"
)
metabench_add_chart(metabench.chart.ratio.all
    TITLE "Creation of 2*N ratios"
    SUBTITLE "(smaller is better)"
    DATASETS
        metabench.data.ratio.create.std_ratio
        metabench.data.ratio.create.ratio_type_constexpr
        metabench.data.ratio.create.ratio_nttp
)
```

A short intro to Metabench: ERB file

CREATE_RATIO_TYPE_CONSTEXPR.CPP.ERB

```
#include "ratio_type_constexpr.h"

<% (1..n).each do |i| %>
struct test<%= i %> {
#if defined(METABENCH)
  using r1 = std::ratio<<%= 2 * i - 1 %>, <%= 2 * n %>>;
  using r2 = std::ratio<<%= 2 * i %>, <%= 2 * n %>>;
#else
  using r1 = void;
  using r2 = void;
#endif
};
<% end %>

int main() {}
```

A short intro to Metabench: Generated C++ code

```
#include "ratio_type_constexpr.h"

struct test1 {
#if defined(METABENCH)
  using r1 = std::ratio<1, 20>;
  using r2 = std::ratio<2, 20>;
#else
  using r1 = void;
  using r2 = void;
#endif
};

struct test2 {
#if defined(METABENCH)
  using r1 = std::ratio<3, 20>;
  using r2 = std::ratio<4, 20>;
#else
  using r1 = void;
  using r2 = void;
#endif
};

// ...

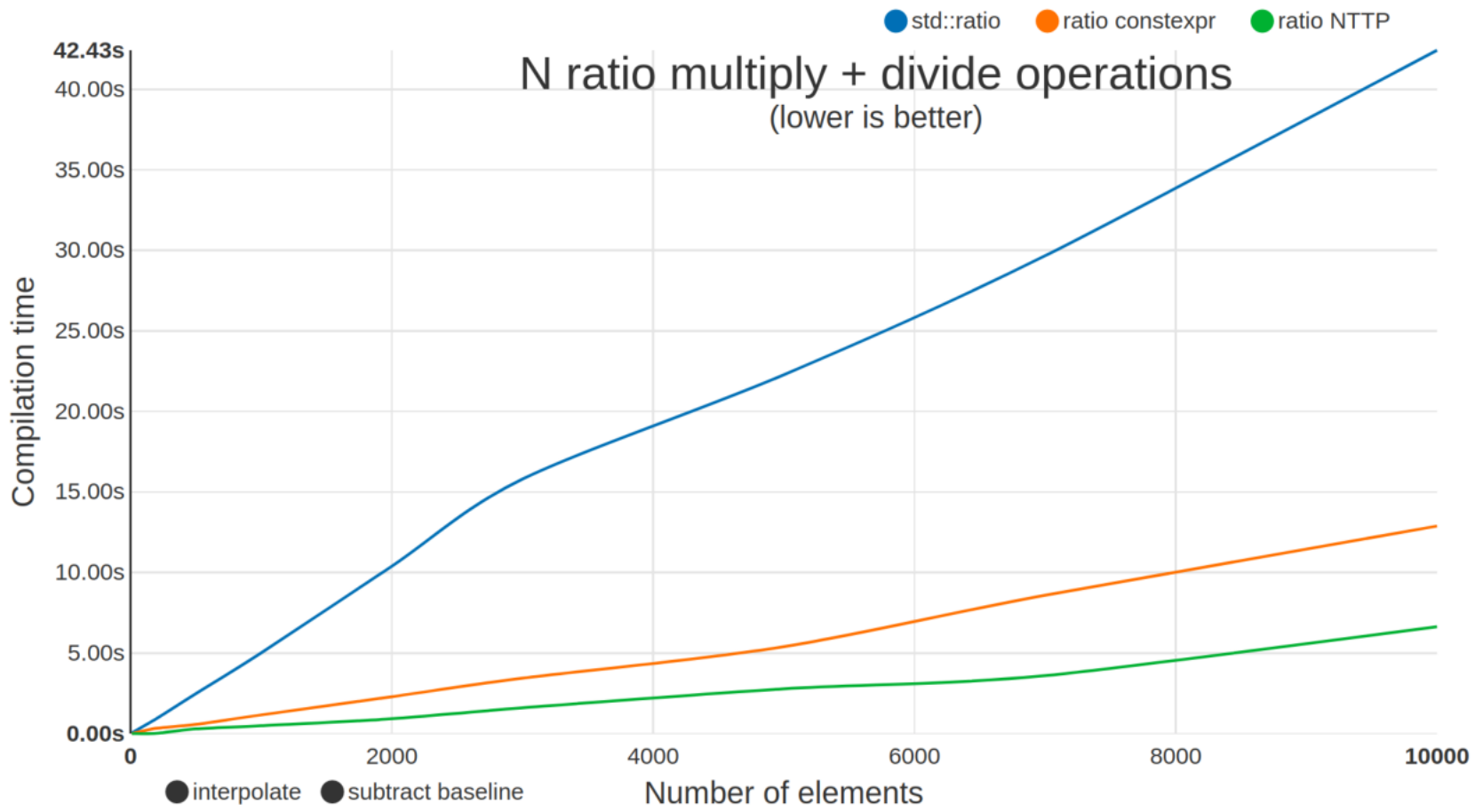
int main() {}
```

A short intro to Metabench: Generated C++ code

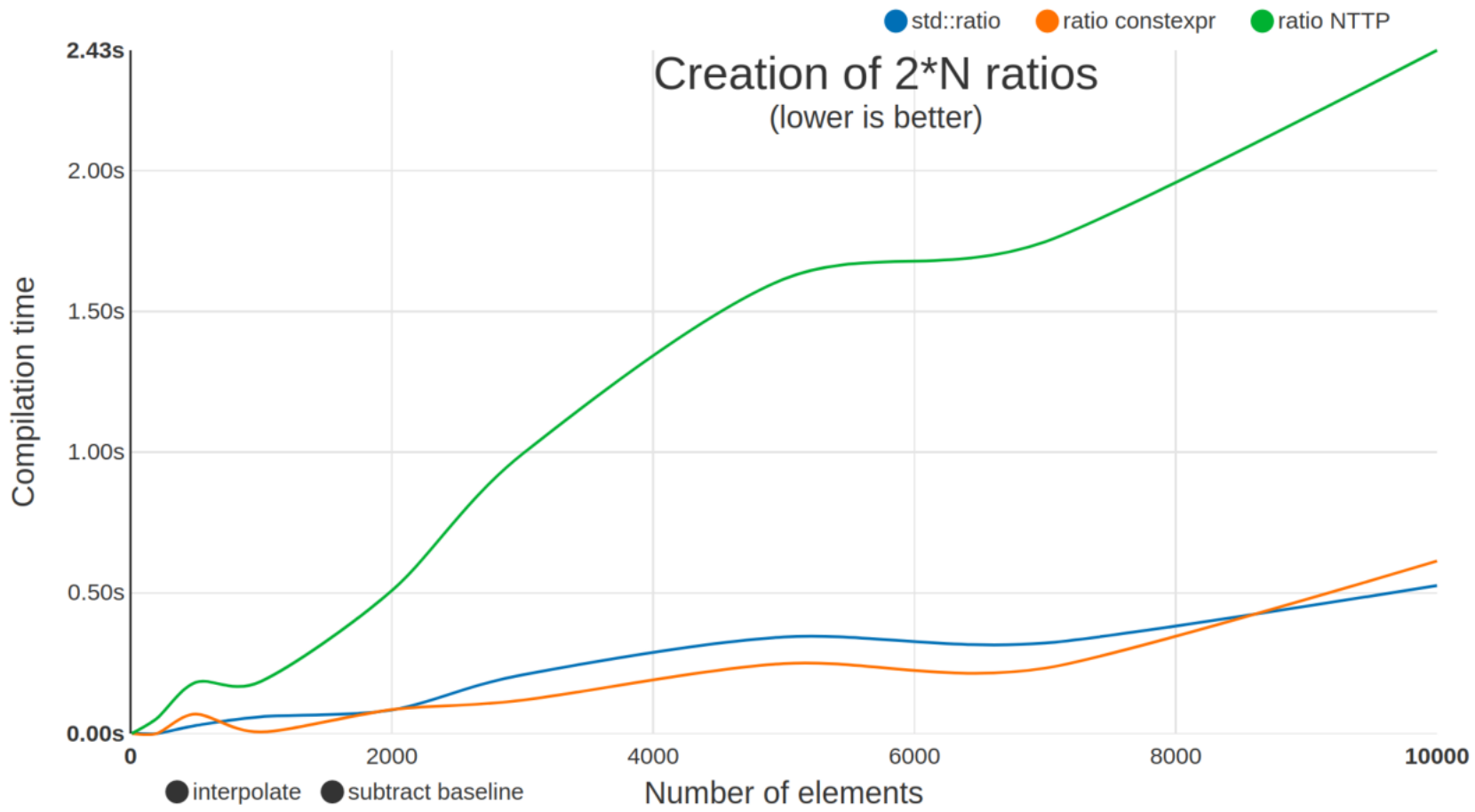
```cpp
#include "ratio_type_constexpr.h"

struct test1 {
#if defined(METABENCH)
  using r1 = std::ratio<1, 20>;
  using r2 = std::ratio<2, 20>;
#else
  using r1 = void;
  using r2 = void;
#endif
};

struct test2 {
#if defined(METABENCH)
  using r1 = std::ratio<3, 20>;
  using r2 = std::ratio<4, 20>;
#else
  using r1 = void;
  using r2 = void;
#endif
};

// ...

int main() {}
```

```cpp
#include "ratio_nttp.h"

struct test1 {
#if defined(METABENCH)
  static constexpr units::ratio r1{1, 20};
  static constexpr units::ratio r2{2, 20};
#else
  static constexpr bool r1 = false;
  static constexpr bool r2 = false;
#endif
};

struct test2 {
#if defined(METABENCH)
  static constexpr units::ratio r1{3, 20};
  static constexpr units::ratio r2{4, 20};
#else
  static constexpr bool r1 = false;
  static constexpr bool r2 = false;
#endif
};

// ...

int main() {}
```

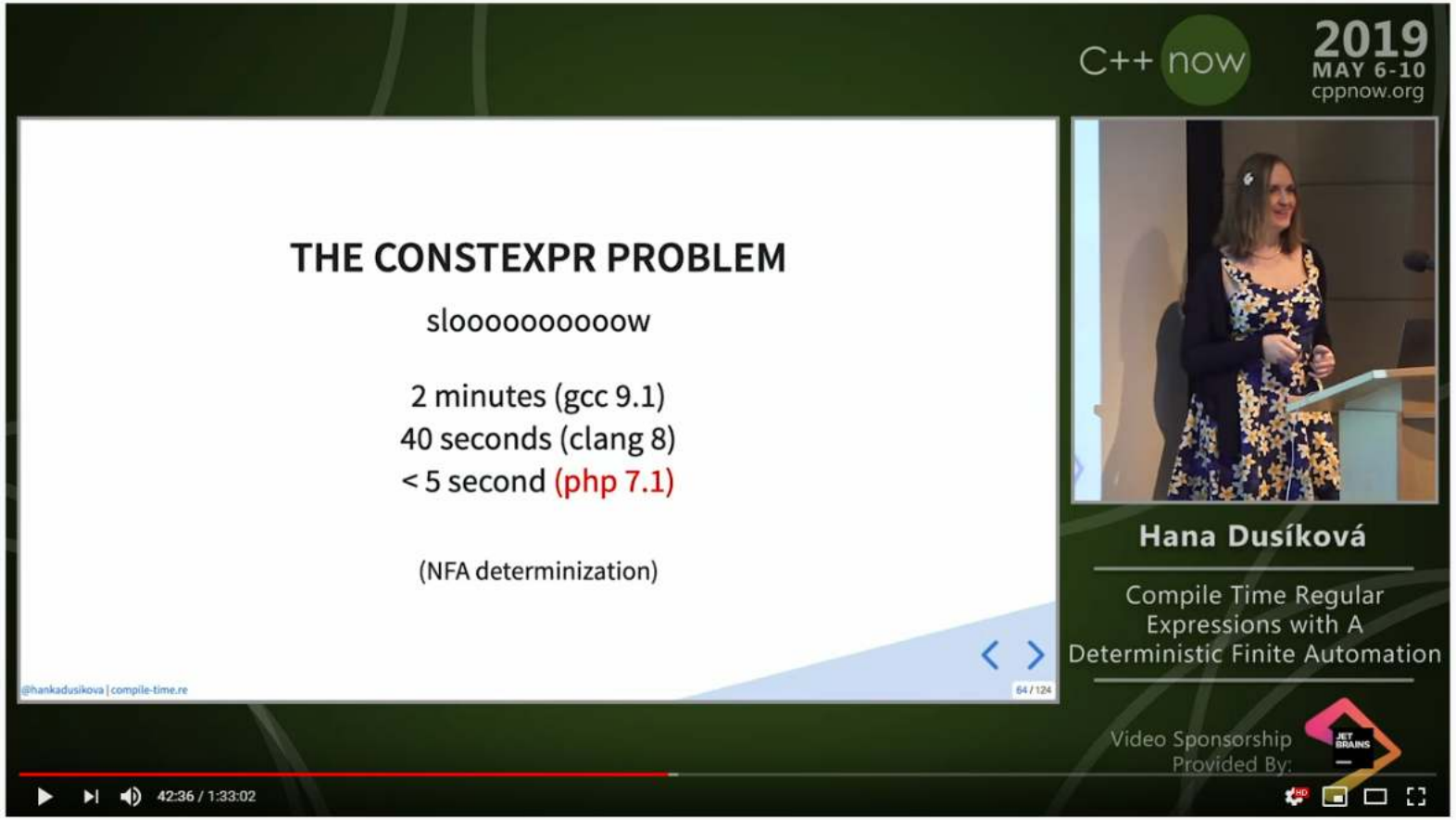
`ratio` performance



`ratio` performance



Current `constexpr` QoI is slow



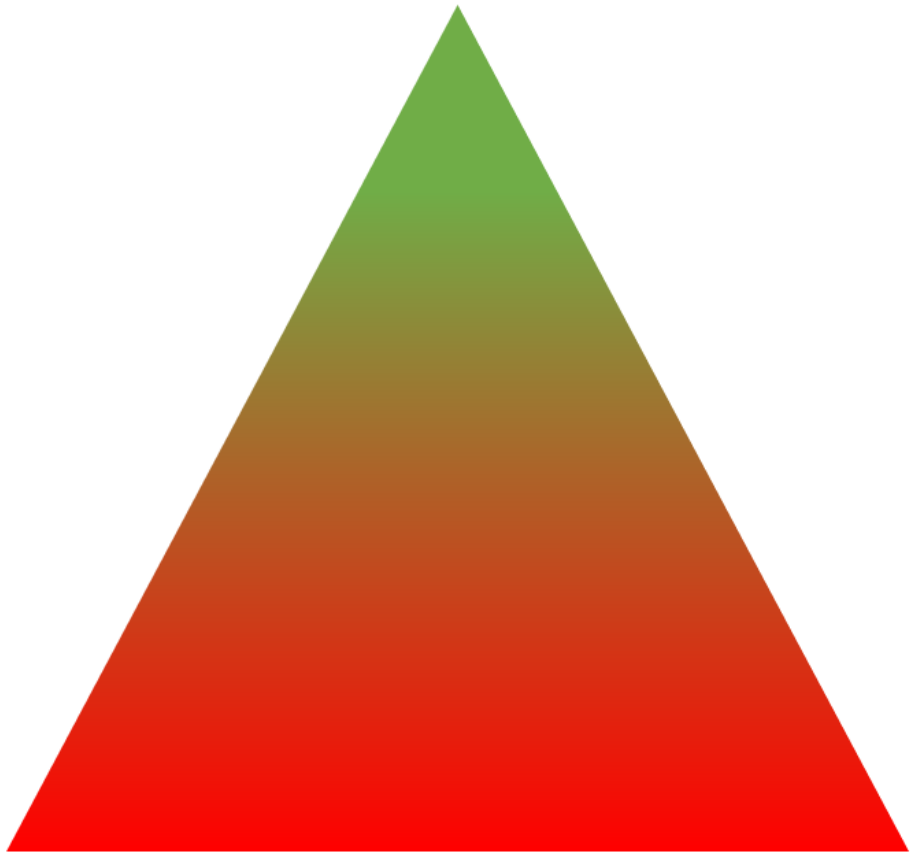
C++Now 2019: Hana Dusíková "Compile Time Regular Expressions with A Deterministic Finite Automaton"

The Rule of Chiel

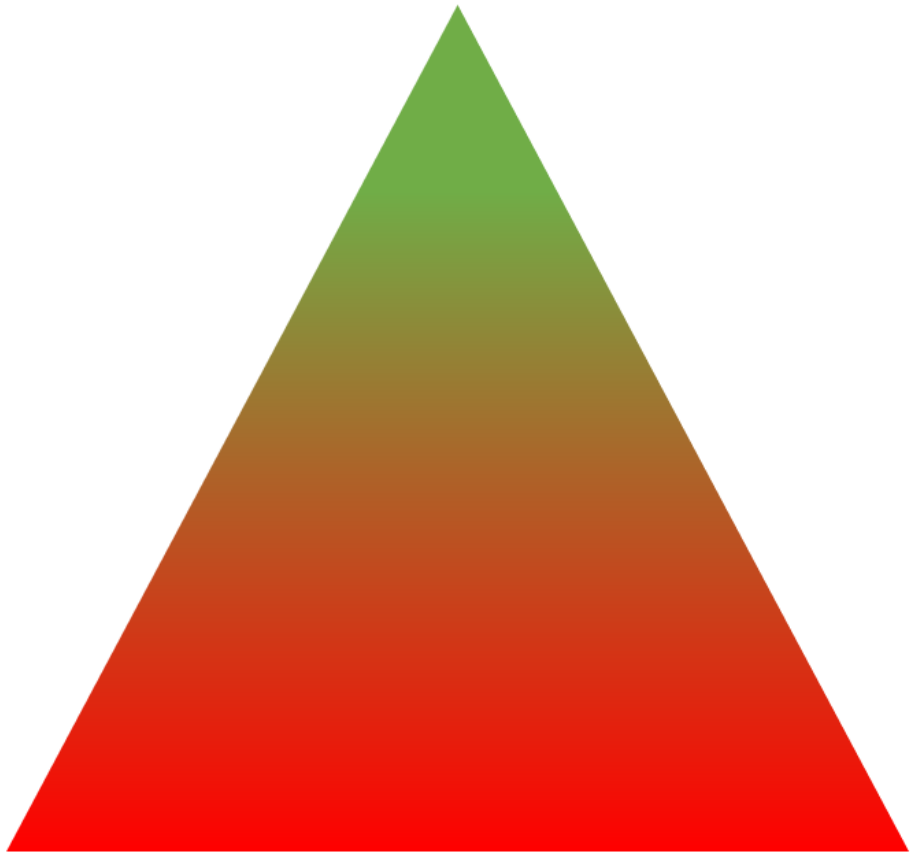
The Rule of Chiel

code::dive 2017 – Odin Holmes – The fastest template metaprogramming in the West

Cost of operations: The Rule of Chiel

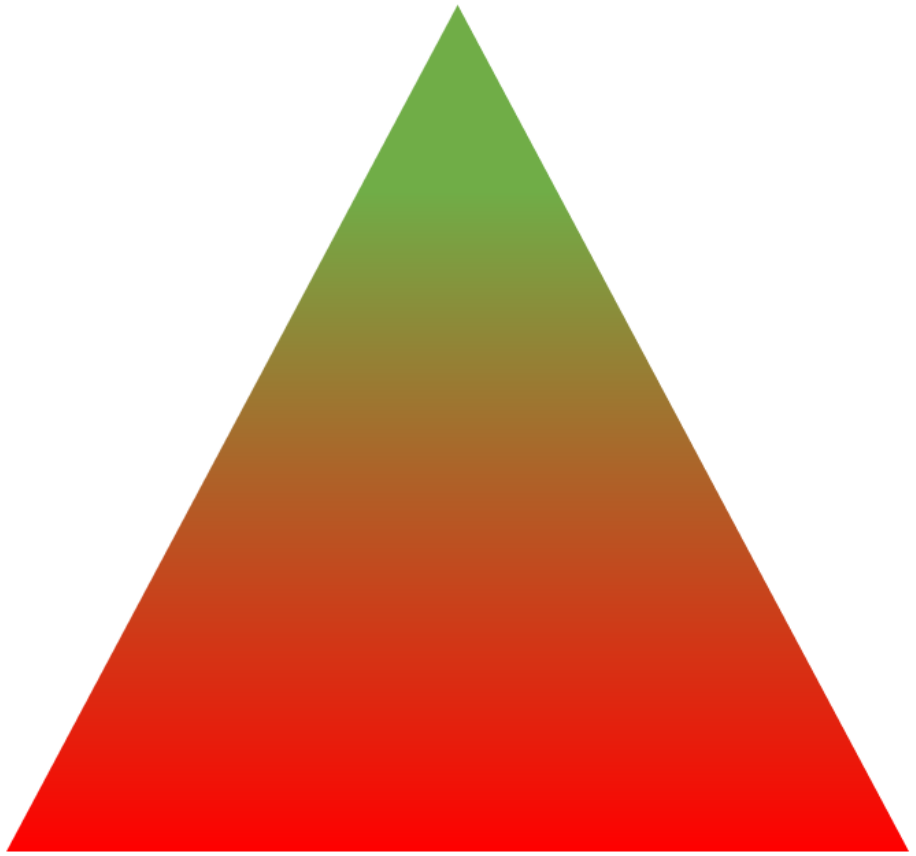


Cost of operations: The Rule of Chiel



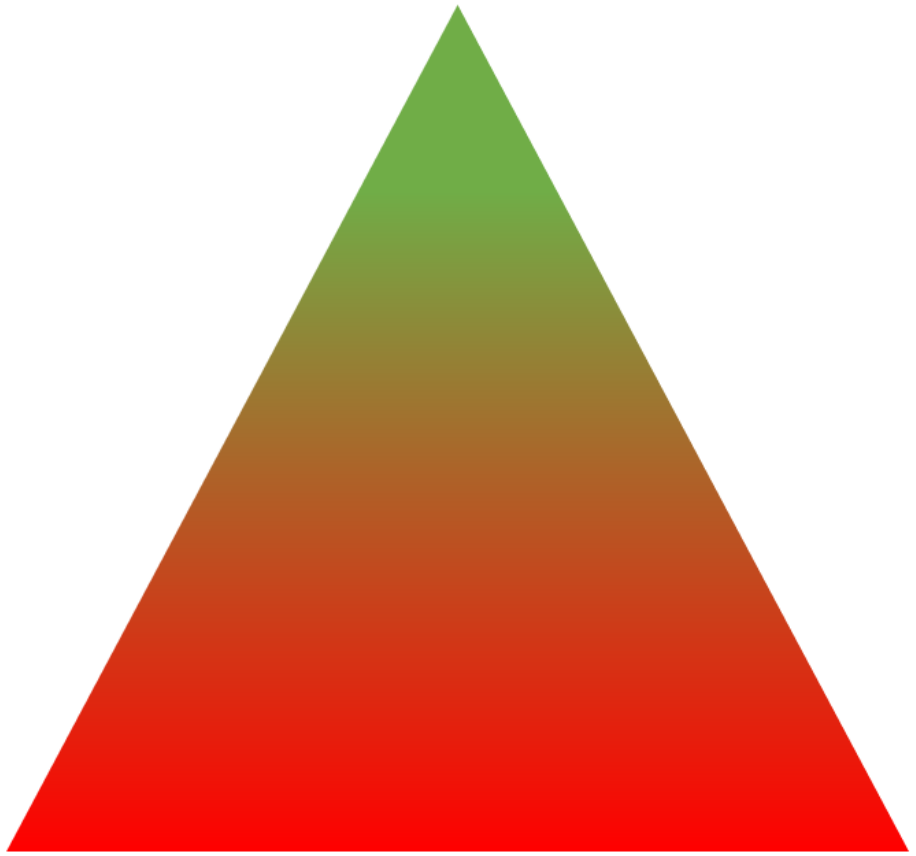
1. Looking up a memoized type

Cost of operations: The Rule of Chiel



1. Looking up a memoized type
2. Adding a parameter to an alias call

Cost of operations: The Rule of Chiel



1. Looking up a memoized type
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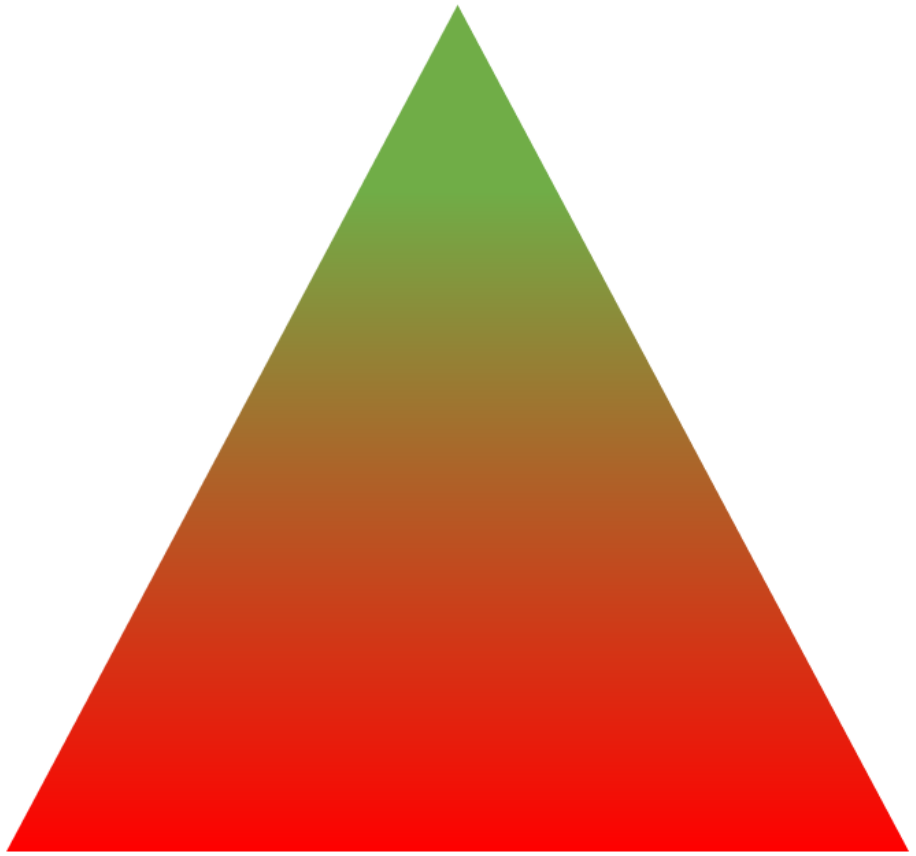
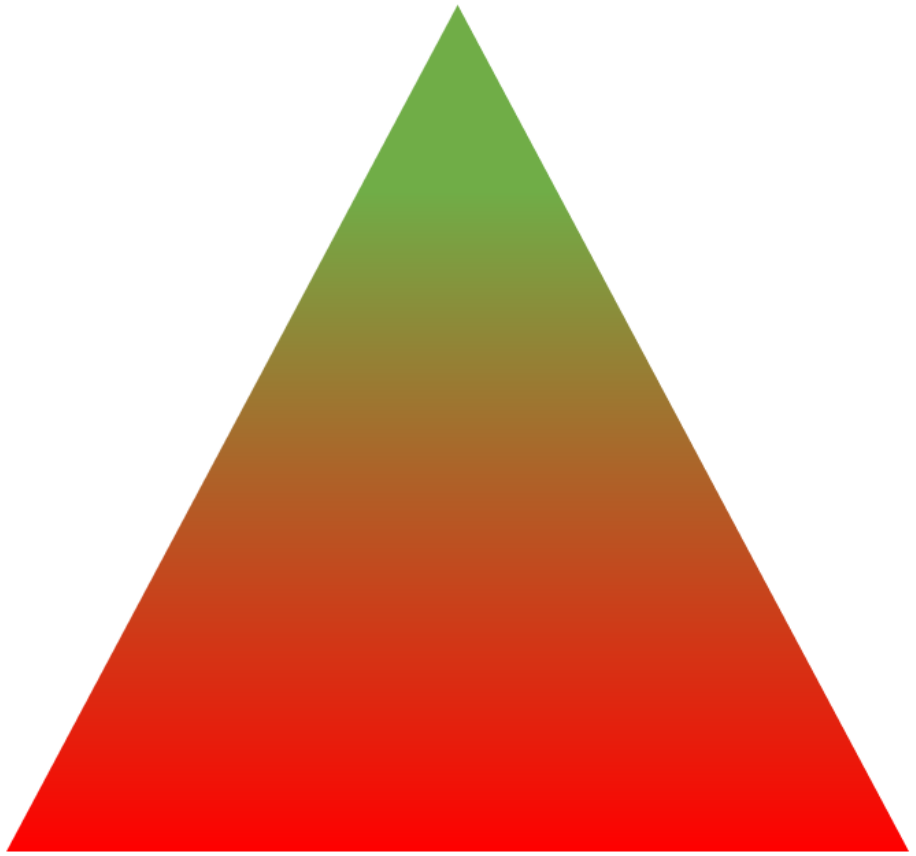
3. Adding a parameter to a type

Cost of operations: The Rule of Chiel



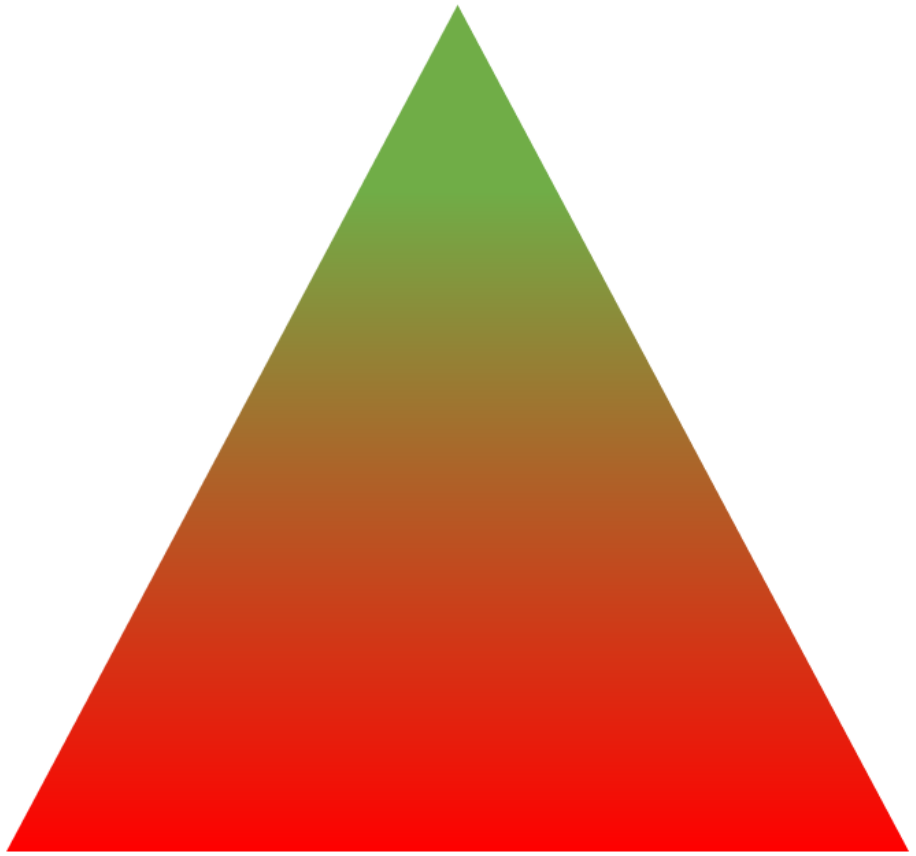
1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type
4. Calling an alias

Cost of operations: The Rule of Chiel



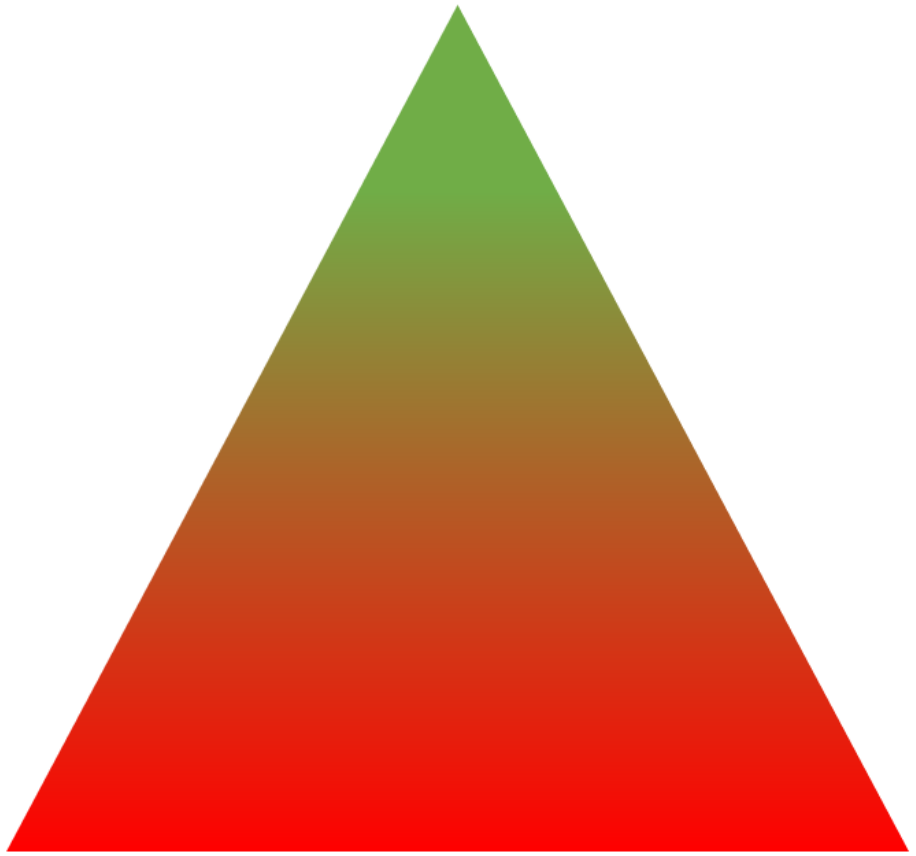
1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type
4. Calling an alias
5. Instantiating a class

Cost of operations: The Rule of Chiel



1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type
4. Calling an alias
5. Instantiating a class
6. Instantiating a function template

Cost of operations: The Rule of Chiel



1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type
4. Calling an alias
5. Instantiating a class
6. Instantiating a function template
7. SFINAE

std::conditional<B, T, F>

TRADITIONAL

```
template<bool B, class T, class F>
struct conditional {
  using type = T;
};

template<class T, class F>
struct conditional<false, T, F> {
  using type = F;
};

template<bool B, class T, class F>
using conditional_t = conditional<B,T,F>::type;
```

std::conditional<B, T, F>

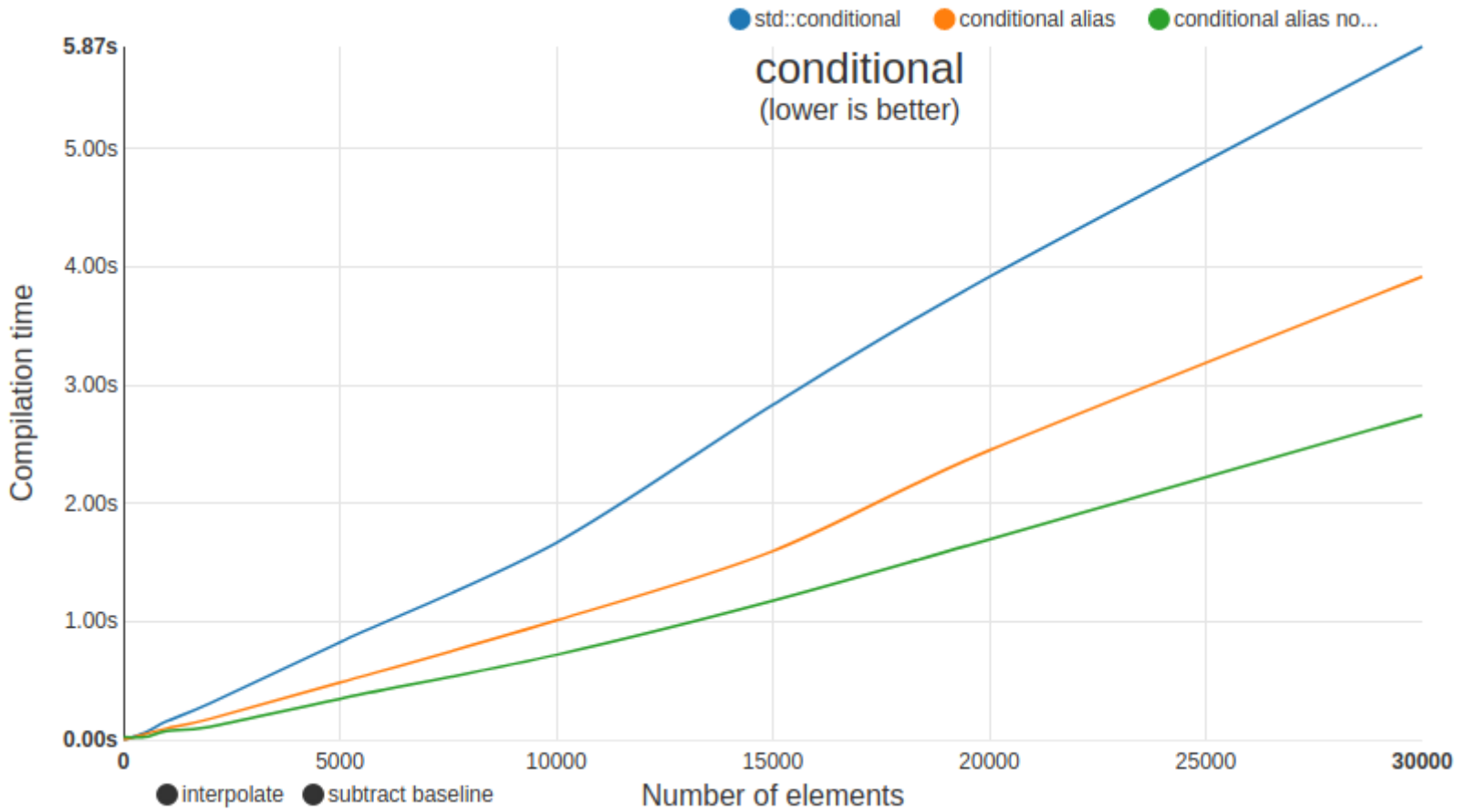
TRADITIONAL

```
template<bool B, class T, class F>
struct conditional {
  using type = T;
};

template<class T, class F>
struct conditional<false, T, F> {
  using type = F;
};

template<bool B, class T, class F>
using conditional_t = conditional<B,T,F>::type;
```

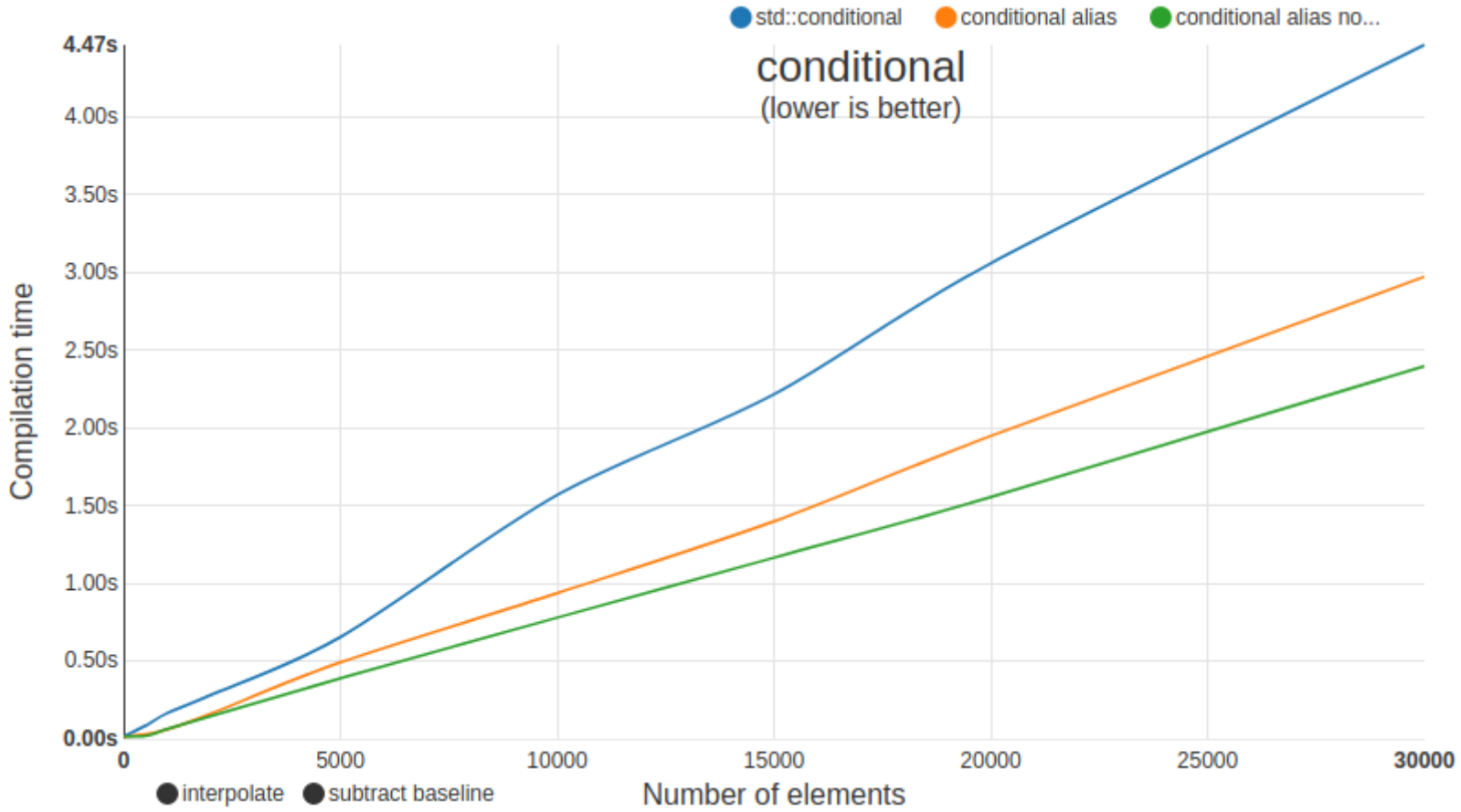
WITH ALIAS TEMPLATE

```
template<bool>
struct conditional {
  template<typename T, typename F>
  using type = F;
};

template<>
struct conditional<true> {
  template<typename T, typename F>
  using type = T;
};

template<bool B, typename T, typename F>
using conditional_t =
  conditional<B>::template type<T, F>;
```

`conditional` performance (gcc-10)



`conditional` performance (clang-10)



Which template is missing in the Rule of Chiel?

Which template is missing in the Rule of Chiel?

What about variable templates?

Which template is missing in the Rule of Chiel?

What about variable templates?

- Chiel did not measure the performance of variable templates
- Let's measure it by ourselves...

std::is_same<T, U>

TRADITIONAL

```
template<class T, class U>
struct is_same : std::false_type {};

template<class T>
struct is_same<T, T> : std::true_type {};
```

```
template<class T, class U>
inline constexpr bool is_same_v =
  is_same<T, U>::value;
```

std::is_same<T, U>

TRADITIONAL

```
template<class T, class U>
struct is_same : std::false_type {};

template<class T>
struct is_same<T, T> : std::true_type {};
```

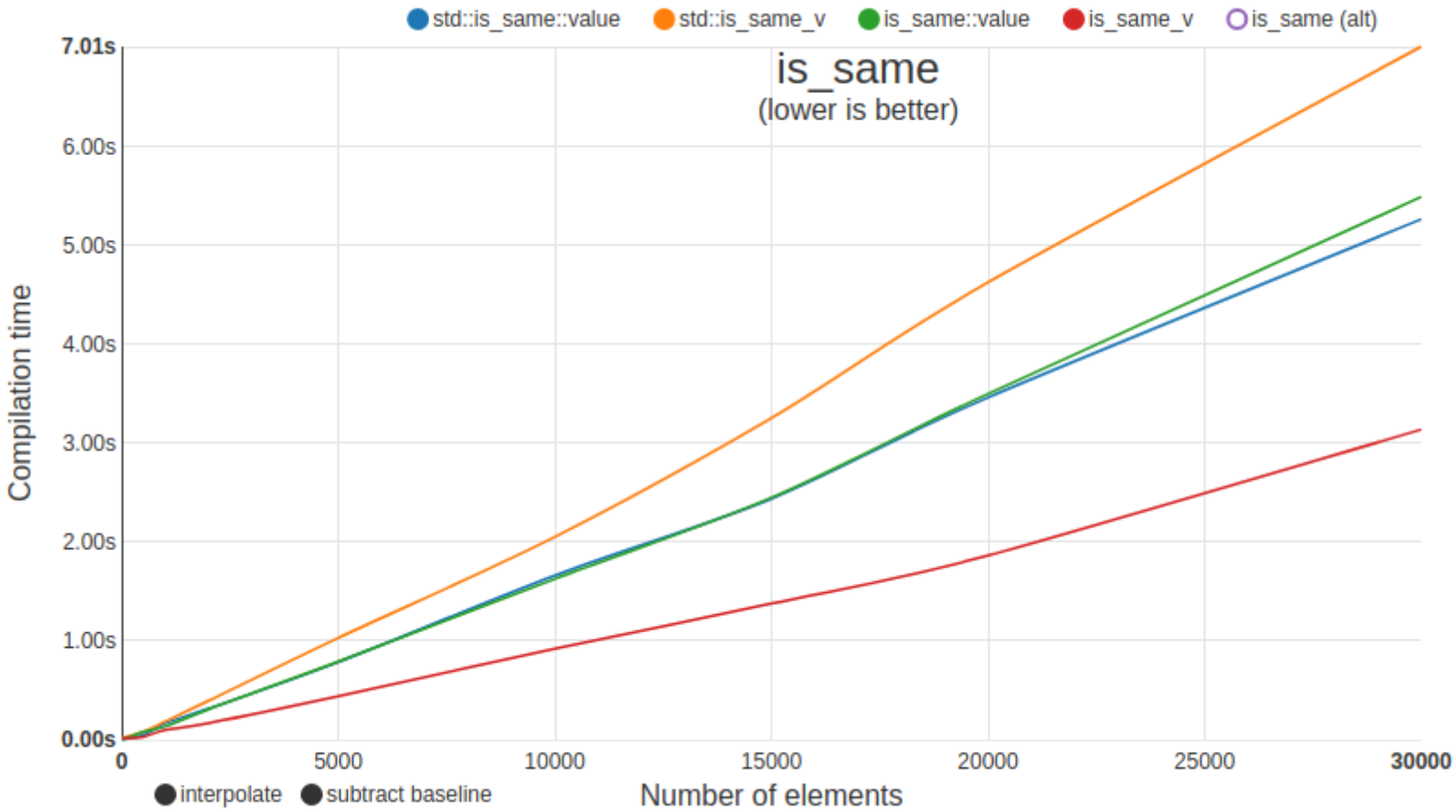
```
template<class T, class U>
inline constexpr bool is_same_v =
  is_same<T, U>::value;
```

USING VARIABLE TEMPLATES

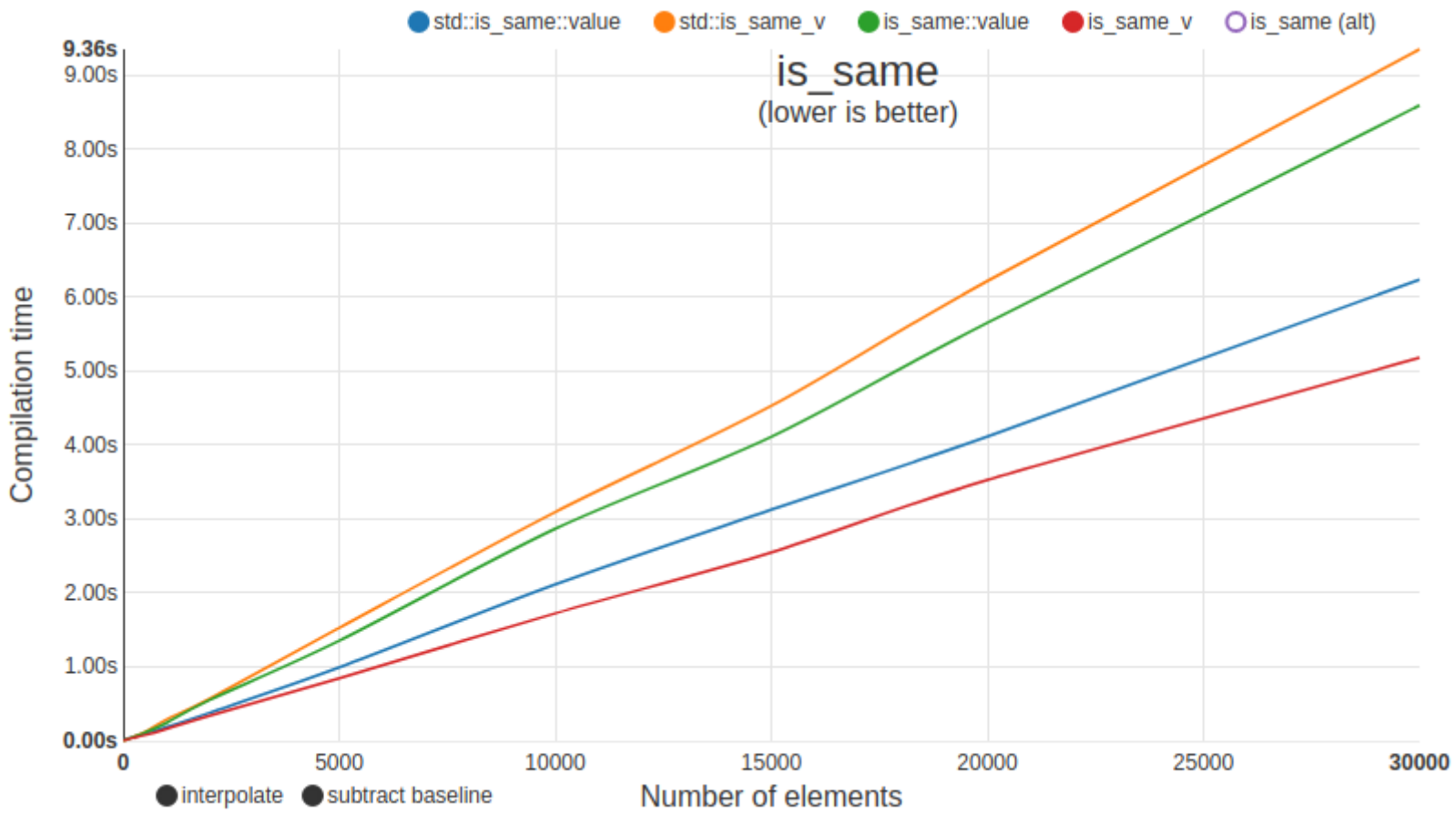
```
template<class T, class U>
inline constexpr bool is_same_v = false;

template<class T>
inline constexpr bool is_same_v<T, T> = true;
```

```
template<class T, class U>
using is_same =
  std::bool_constant<is_same_v<T, U>>;
```

`is_same` performance (gcc-10)



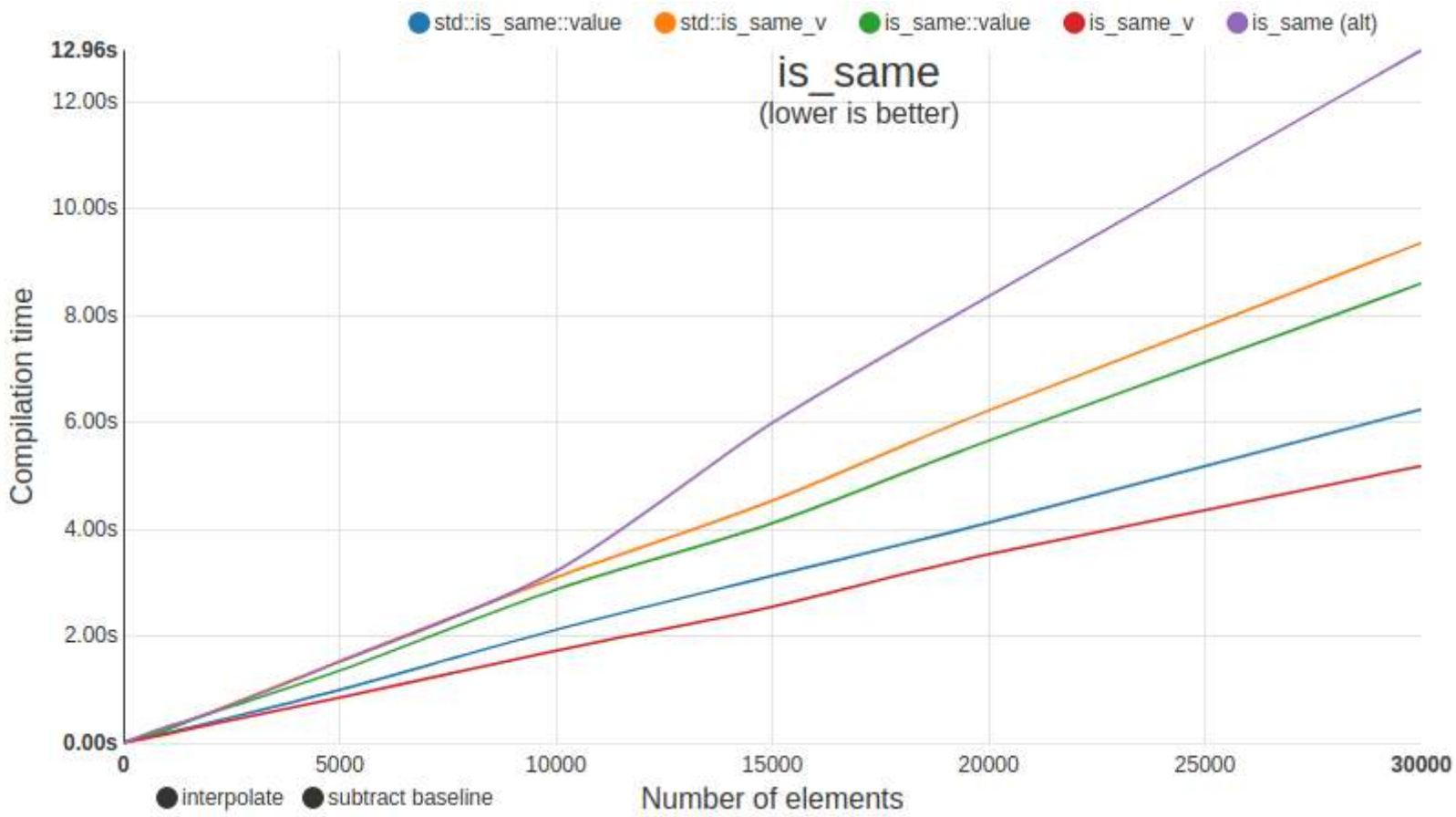
`is_same` performance (clang-10)



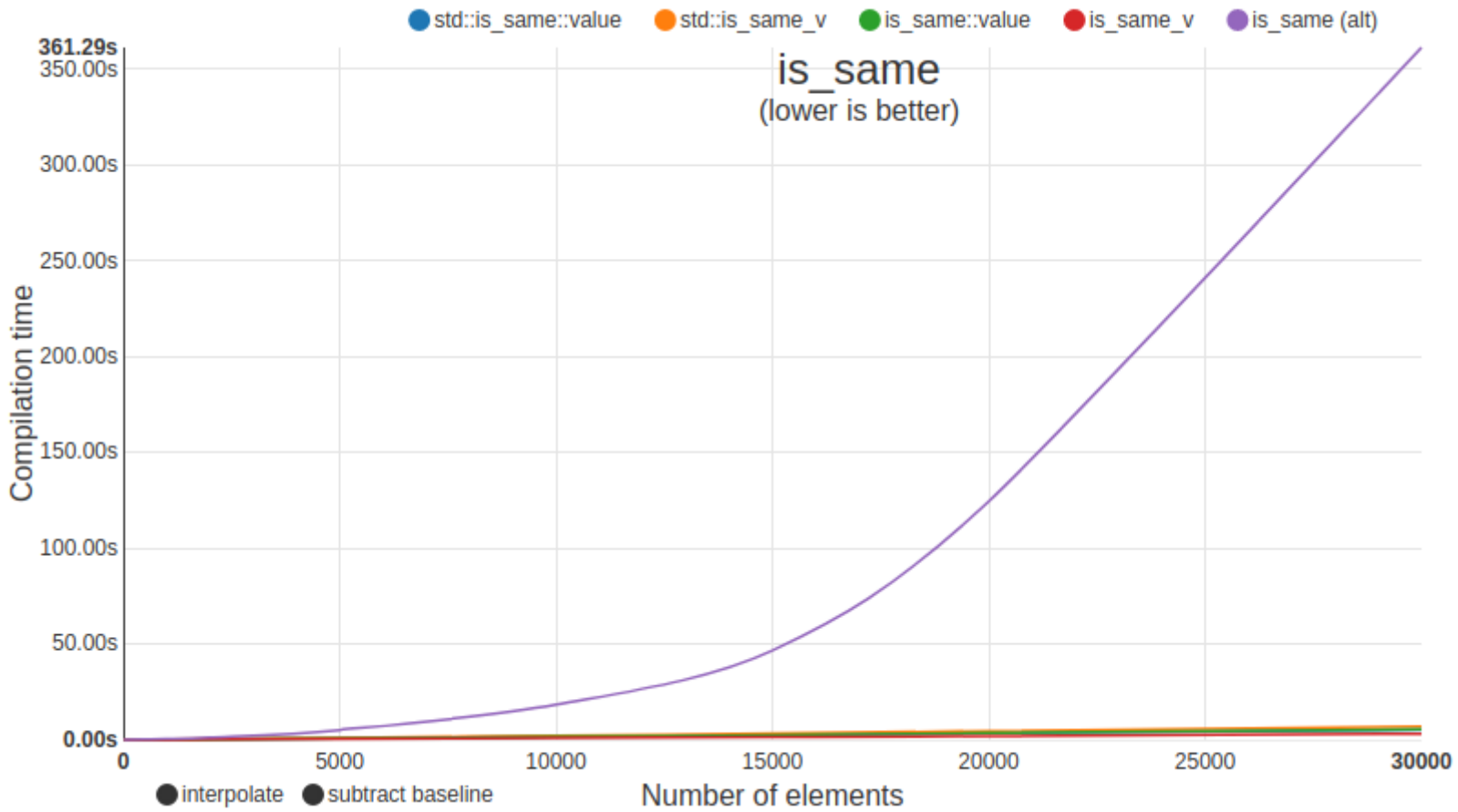
Alternative `is_same` implementation from CppCon 2019

```
struct WrapperBase {
  static constexpr bool IsSame(void*) { return false; }
};

template<typename T>
struct Wrapper : WrapperBase {
  using WrapperBase::IsSame;
  static constexpr bool IsSame(Wrapper<T>*) { return true; }
};

template<class T, class U>
using is_same = std::integral_constant<bool, Wrapper<T>::IsSame((Wrapper<U>*)(nullptr))>;
```

`is_same` performance (clang-10)



`is_same` performance (gcc-10)



What about C++ Concepts?

What about C++ Concepts?

SFINAE

```
template<long long N>
struct X {
  template<long long M = N>
  typename std::enable_if<M % 2 == 0, int>::type
  static constexpr foo()
  {
    return 0;
  }

  template<long long M = N>
  typename std::enable_if<M % 2 != 0, int>::type
  static constexpr foo()
  {
    return 1;
  }
};
```

CONCEPTS

```
template<long long N>
struct X {
  static constexpr int foo()
    requires (N % 2 == 0)
  {
    return 0;
  }

  static constexpr int foo()
  {
    return 1;
  }
};
```

What about C++ Concepts?

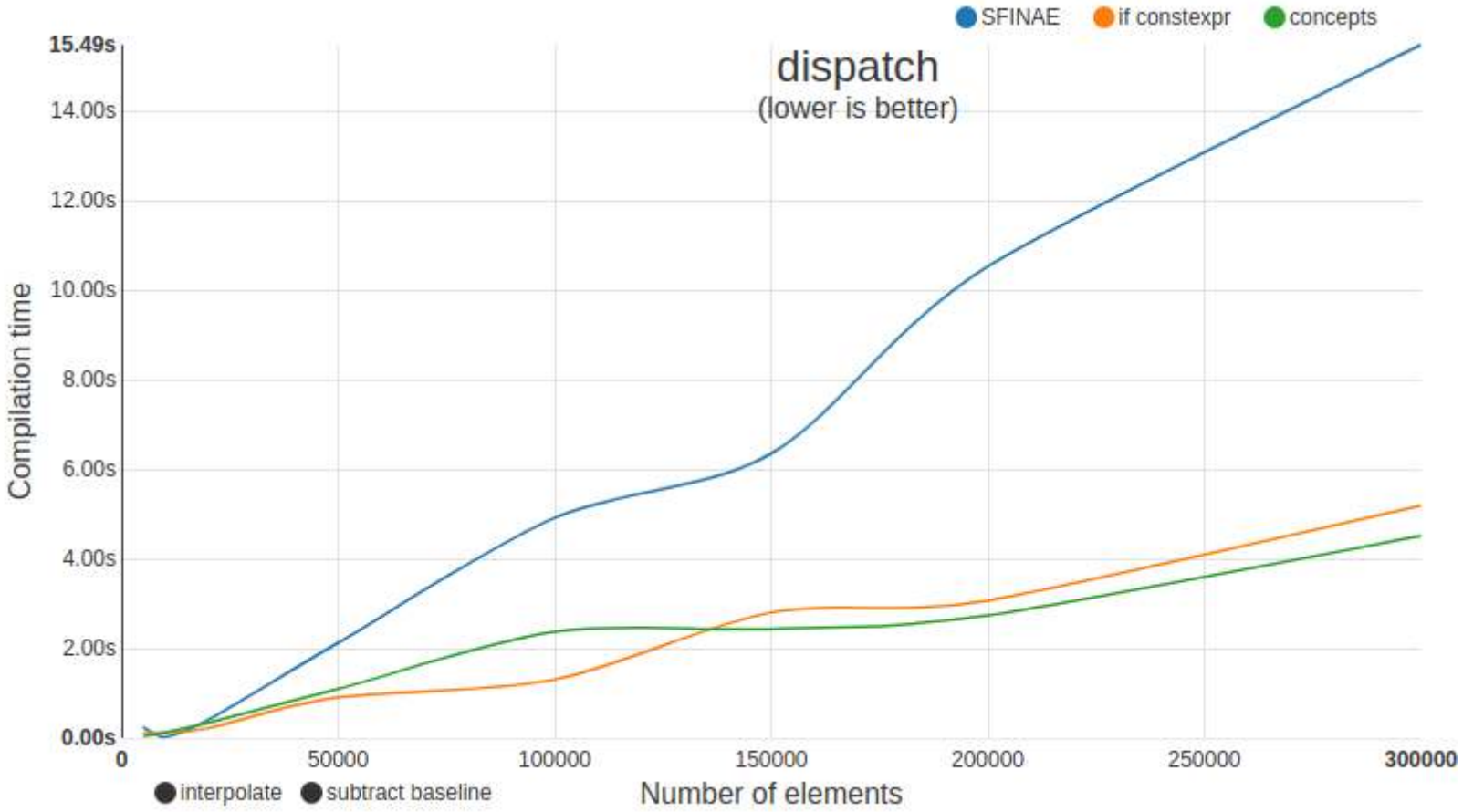
IF CONSTEXPR

```
template<long long N>
struct X {
  static constexpr int foo()
  {
    if constexpr(N % 2 == 0)
      return 0;
    else
      return 1;
  }
};
```

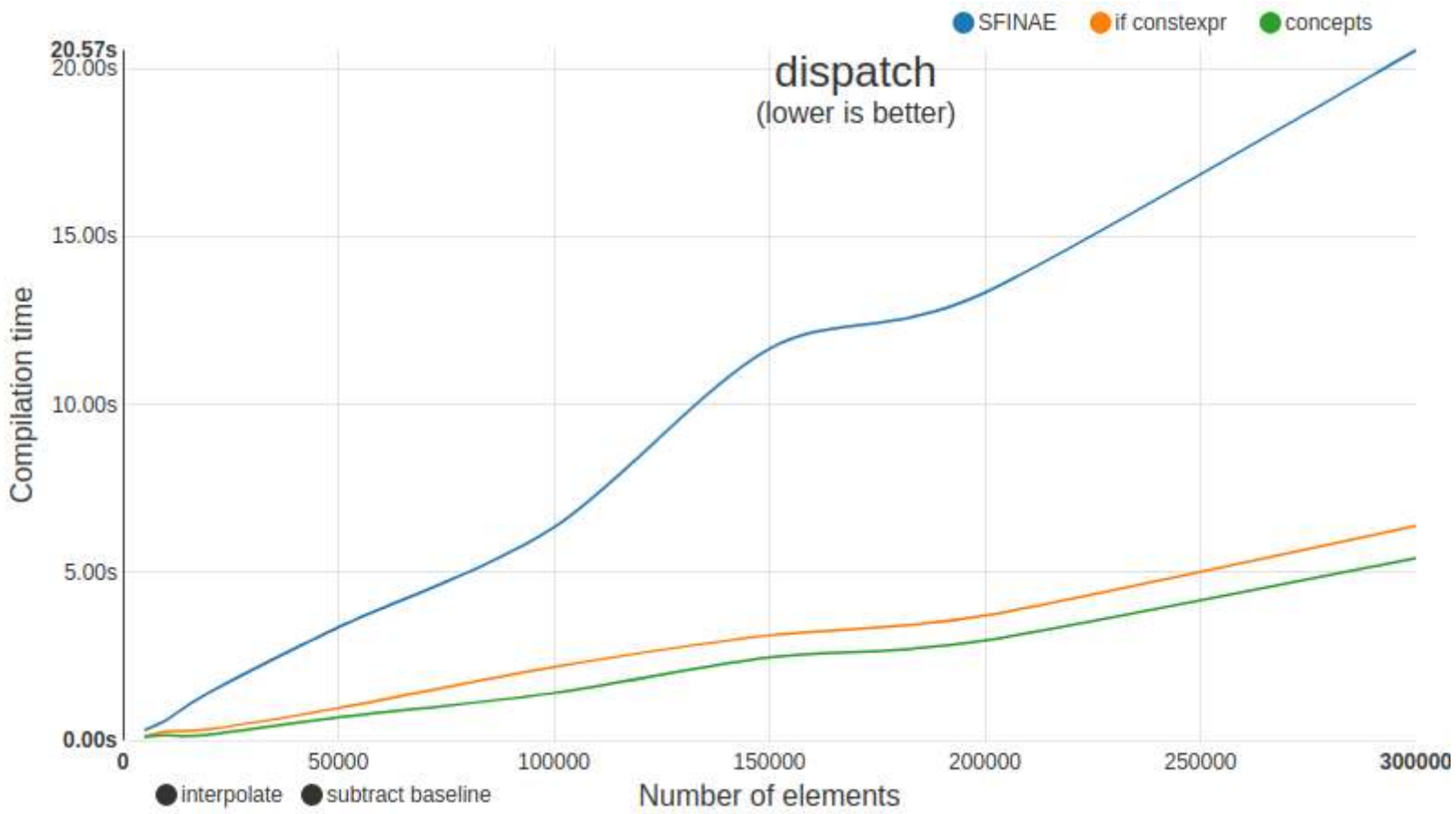
CONCEPTS

```
template<long long N>
struct X {
  static constexpr int foo()
    requires (N % 2 == 0)
  {
    return 0;
  }

  static constexpr int foo()
  {
    return 1;
  }
};
```

Dispatch performance (gcc-10)



Dispatch performance (clang-10)



Where Concepts are not needed?

- Compile-time performance impact might be *limited by using concepts only in the user interfaces*

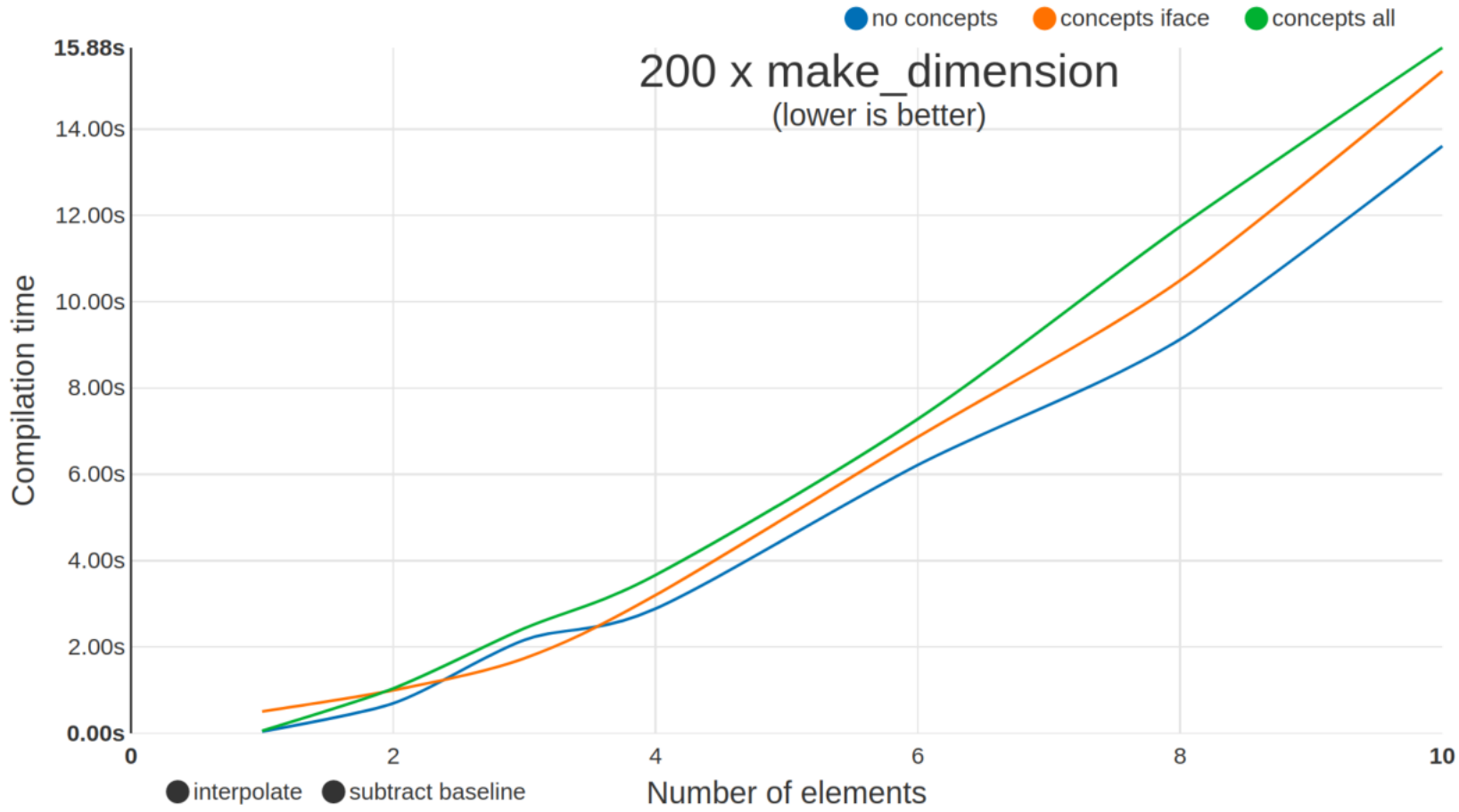
```
template<Exponent... Es>
struct dimension : downcast_base<dimension<Es...>> {};

namespace detail {
  template<typename D1, typename D2>
  struct dimension_divide;

  template<typename... E1, typename... E2>
  struct dimension_divide<dimension<E1...>, dimension<E2...>>
      : dimension_multiply<dimension<E1...>, dimension<exp_invert_t<E2>...>> {
  };
}

template<Dimension D1, Dimension D2>
using dimension_divide_t = detail::dimension_divide<typename D1::downcast_base_type,
                                                    typename D2::downcast_base_type>::type;
```

Where Concepts are not needed?

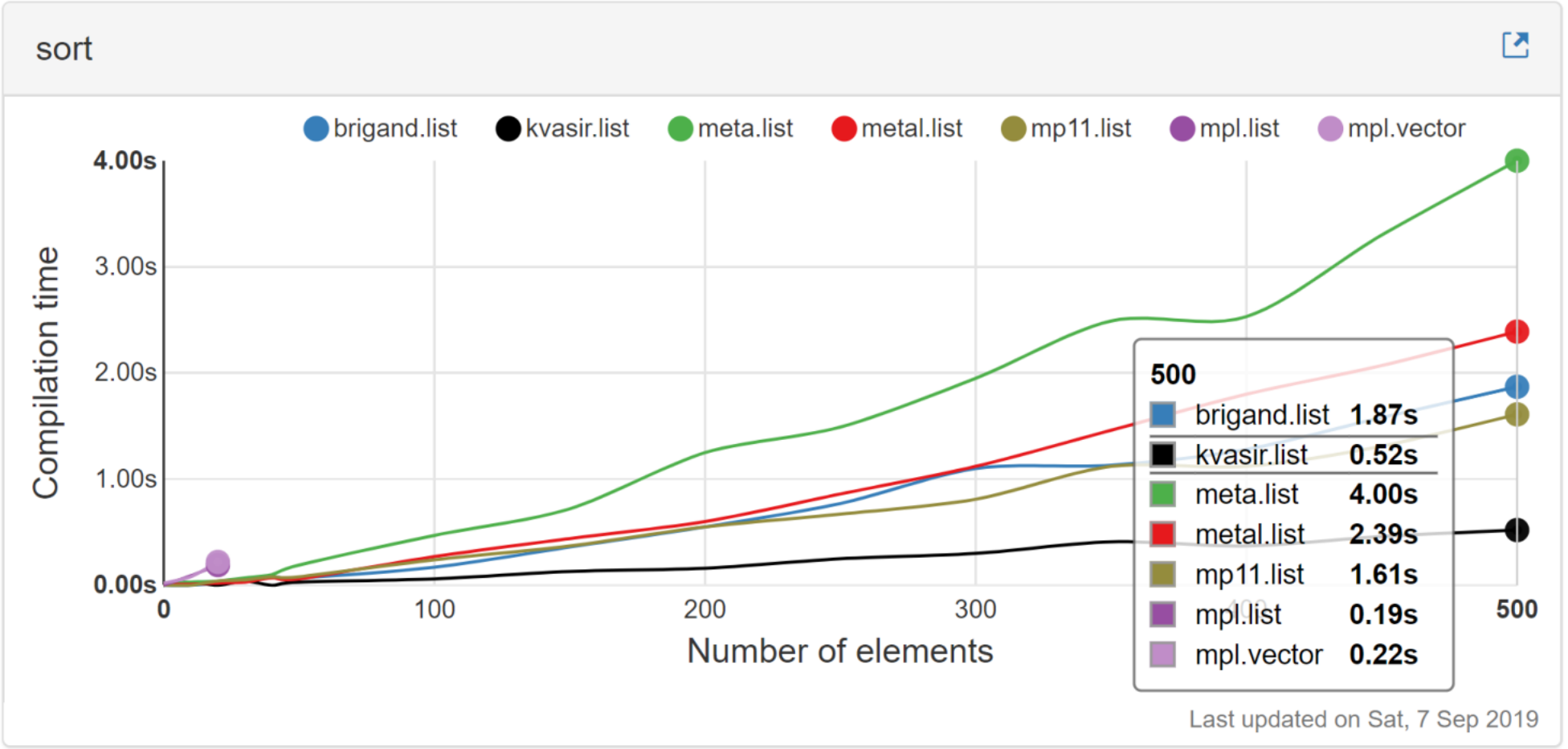
- Compile-time performance impact might be *limited by using concepts only in the user interfaces*

```
template<Exponent... Es>
struct dimension : downcast_base<dimension<Es...>> {};

namespace detail {
  template<typename D1, typename D2>
  struct dimension_divide;

  template<typename... E1, typename... E2>
  struct dimension_divide<dimension<E1...>, dimension<E2...>>
      : dimension_multiply<dimension<E1...>, dimension<exp_invert_t<E2>...>> {
  };
}

template<Dimension D1, Dimension D2>
using dimension_divide_t = detail::dimension_divide<typename D1::downcast_base_type,
                                                    typename D2::downcast_base_type>::type;
```

C++ Concepts performance



More info on MPL performance on http://metaben.ch



TAKEAWAYS

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3. **Use NTTPs** when a template parameter represents a value rather than a type
4. **Optimize compile-time performance**
   - MPL is free at run-time but can be really expensive at compile-time
   - there is more than one way to do it
   - **ALWAYS MEASURE** and check different compilers as your milage may vary


CAUTION
Programming
is addictive
(and too much fun)