accu 2021 VIRTUAL EVENT

Bloomberg Engineering

undo

mosaic CONSULTANTS TO FINANCIAL SERVICES

Rethinking the Way We Do Templates in C++

Mateusz Pusz

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);
```

Physical Units library in a nutshell

```
// simple numeric operations
static_assert(10q_km / 2 == 5q_km);
```

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

Physical Units library in a nutshell

```
// simple numeric operations
static_assert(10q_km / 2 == 5q_km);
```

```
// 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;
}
```

Toy example

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

```
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";
```

Toy example

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

```
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";
```

- Compile-time safety to make sure that the result is of a correct dimension

Toy example

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

```
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";
```

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

Toy example

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

```
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";
```

- **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 `doubles`

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-10.2.0

```
 In function 'constexpr 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> > > > > > > > > > >
avg_speed(boost::units::quantity<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> > > > > > > > > > >, boost::units::quantity<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
...
```

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-10.2.0 (CONTINUED)

```
<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> > > > > > > > > >)':
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
...
```

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-10.2.0 (CONTINUED)

```
<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 =
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>>,[...]>>,[...],[...]>,[...]>'
   37 |   return d * t;
      |          ~~^~~
      |            |
      |            quantity<unit<list<[...],list<dim<[...],static_rational<1>>,[...]>>,[...],[...]>,[...]>
```

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-11.0.1

```
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; }
```

CLANG-11.0.1

```
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 ;-)

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-11.0.1 (CONTINUED)

```
boost/units/quantity.hpp:106:25: note: candidate constructor not viable: no known conversion from 'typename
multiply_typeof_helper<quantity<unit<list<dim<length_base_dimension, static_rational<1, 1>>, dimensionless_type>,
homogeneous_system<list<meter_base_unit, list<scaled_base_unit<gram_base_unit, scale<10, static_rational<3>>>,
list<second_base_unit, list<ampere_base_unit, list<kelvin_base_unit, list<mole_base_unit, list<candela_base_unit,
list<radian_base_unit, list<steradian_base_unit, dimensionless_type>>>>>>>>>>, void>, double>, quantity<unit<list<dim<
time_base_dimension, static_rational<1, 1>>, dimensionless_type>, homogeneous_system<list<meter_base_unit, list<
scaled_base_unit<gram_base_unit, scale<10, static_rational<3>>>, list<second_base_unit, list<ampere_base_unit,
list<kelvin_base_unit, list<mole_base_unit, list<candela_base_unit, list<radian_base_unit, list<steradian_base_unit,
dimensionless_type>>>>>>>>>>, void>, double>>::type' (aka 'quantity<unit<boost::units::list<boost::units::dim<
boost::units::length_base_dimension, boost::units::static_rational<1, 1>>, boost::units::list<boost::units::dim<
boost::units::time_base_dimension, boost::units::static_rational<1, 1>>, boost::units::dimensionless_type>>,
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, 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>>>>>>>>>>, double>') to '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::list<boost::units::dim<boost::units::time_base_dimension, boost::units::static_rational<-1, 1>>,
...
```

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-11.0.1 (CONTINUED)

```
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,
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>::unspecified_null_pointer_constant_type' (aka 'void
(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::list<boost::units::dim<boost::units::time_base_dimension,
boost::units::static_rational<-1, 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, 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>::*)(int *******)') for 1st argument
        BOOST_CONSTEXPR quantity(unspecified_null_pointer_constant_type) : val_()
                        ^
...
```

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-11.0.1 (CONTINUED)

```
boost/units/quantity.hpp:111:25: note: candidate constructor not viable: no known conversion from 'typename
multiply_typeof_helper<quantity<unit<list<dim<length_base_dimension, static_rational<1, 1>>, dimensionless_type>,
homogeneous_system<list<meter_base_unit, list<scaled_base_unit<gram_base_unit, scale<10, static_rational<3>>>,
list<second_base_unit, list<ampere_base_unit, list<kelvin_base_unit, list<mole_base_unit, list<candela_base_unit,
list<radian_base_unit, list<steradian_base_unit, dimensionless_type>>>>>>>>>>, void>, double>, quantity<unit<list<dim<
time_base_dimension, static_rational<1, 1>>, dimensionless_type>, homogeneous_system<list<meter_base_unit, list<
scaled_base_unit<gram_base_unit, scale<10, static_rational<3>>>, list<second_base_unit, list<ampere_base_unit, list<
kelvin_base_unit, list<mole_base_unit, list<candela_base_unit, list<radian_base_unit, list<steradian_base_unit,
dimensionless_type>>>>>>>>>>, void>, double>>::type' (aka 'quantity<unit<boost::units::list<boost::units::dim<
boost::units::length_base_dimension, boost::units::static_rational<1, 1>>, boost::units::list<boost::units::dim<
boost::units::time_base_dimension, boost::units::static_rational<1, 1>>, boost::units::dimensionless_type>>,
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, 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>>>>>>>>>>, double>') to 'const
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::list<boost::units::dim<boost::units::time_base_dimension,
...
```

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-11.0.1 (CONTINUED)

```
boost::units::static_rational<-1, 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, 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>::this_type &'
(aka 'const quantity<boost::units::unit<boost::units::list<boost::units::dim<boost::units::length_base_dimension,
boost::units::static_rational<1, 1>>, boost::units::list<boost::units::dim<boost::units::time_base_dimension,
boost::units::static_rational<-1, 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, 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> &') for 1st argument
        BOOST_CONSTEXPR quantity(const this_type& source) : val_(source.val_)
                        ^
...
```

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-11.0.1 (CONTINUED)

```
boost/units/quantity.hpp:138:25: note: candidate template ignored: could not match 'unit<list<[...], list<dim<[...],
static_rational<-1, [...]>>, [...]>>, [2 * ...]>' against 'unit<list<[...], list<dim<[...], static_rational<1, [...]>>, [...]>>,
[2 * ...]>'
        BOOST_CONSTEXPR quantity(const quantity<Unit,YY>& source,
                        ^
boost/units/quantity.hpp:203:22: note: candidate template ignored: disabled by 'enable_if' [with Unit2 = boost::units::unit<
boost::units::list<boost::units::dim<boost::units::length_base_dimension, boost::units::static_rational<1, 1>>,
boost::units::list<boost::units::dim<boost::units::time_base_dimension, boost::units::static_rational<1, 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, 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>, YY = double]
                     mpl::and_<
                     ^
/opt/compiler-explorer/libs/boost_1_75_0/boost/units/quantity.hpp:147:34: note: explicit constructor is not a candidate
        explicit BOOST_CONSTEXPR quantity(const quantity<Unit,YY>& source,
                                 ^
...
```

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-11.0.1 (CONTINUED)

```
/opt/compiler-explorer/libs/boost_1_75_0/boost/units/quantity.hpp:183:25: note: explicit constructor is not a candidate
        BOOST_CONSTEXPR quantity(const quantity<Unit2,YY>& source,
                        ^
```

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-11.0.1 (CONTINUED)

```
/opt/compiler-explorer/libs/boost_1_75_0/boost/units/quantity.hpp:183:25: note: explicit constructor is not a candidate
        BOOST_CONSTEXPR quantity(const quantity<Unit2,YY>& source,
                        ^

<source>:35:42: error: no return statement in constexpr function
constexpr bu::quantity<bu::si::velocity> avg_speed(bu::quantity<bu::si::length> d, bu::quantity<bu::si::time> t)
```

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-10.2.0

```
units.h: In instantiation of 'constexpr T units::convert(const T&) [with UnitFrom = units::unit<std::ratio<1>, units::base_unit<
std::ratio<1>, std::ratio<0, 1>, std::ratio<1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<0, 1> >, std::ratio<0, 1>, std::ratio<0, 1> >; UnitTo = units::unit<std::ratio<1>,
units::base_unit<std::ratio<1>, std::ratio<0, 1>, std::ratio<-1> > >; T = double]':
units.h:1976:41:   required from 'constexpr units::unit_t<Units, T, NonLinearScale>::unit_t(const units::unit_t<UnitsRhs, Ty,
NlsRhs>&) [with UnitsRhs = units::unit<std::ratio<1>, units::base_unit<std::ratio<1>, std::ratio<0, 1>, std::ratio<1>,
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1> >, std::ratio<0, 1>,
std::ratio<0, 1> >; Ty = double; NlsRhs = units::linear_scale; Units = units::unit<std::ratio<1>, units::base_unit<
std::ratio<1>, std::ratio<0, 1>, std::ratio<-1> > >; T = double; NonLinearScale = units::linear_scale]'
 required from here
 in 'constexpr' expansion of 'avg_speed(units::unit_t<units::unit<std::ratio<1>, units::base_unit<std::ratio<1> > > >(
units::literals::operator""_km(220)), units::unit_t<units::unit<std::ratio<1>, units::base_unit<std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<1> > > >(units::literals::operator""_hr(2)))'
error: static assertion failed: 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; }
```

CLANG-11.0.1

```
units.h:1620:3: error: static_assert failed due to requirement 'traits::is_convertible_unit<units::unit<std::ratio<1, 1>,
units::base_unit<std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>, units::unit<std::ratio<1, 1>,
units::base_unit<std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<-1, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>>::value' "Units are not compatible."
                static_assert(traits::is_convertible_unit<UnitFrom, UnitTo>::value, "Units are not compatible.");
                ^             ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
units.h:1956:14: note: in instantiation of function template specialization 'units::convert<units::unit<std::ratio<1, 1>,
units::base_unit<std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>, units::unit<std::ratio<1, 1>,
units::base_unit<std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<-1, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>, double>' requested here
                nls(units::convert<UnitsRhs, Units, T>(rhs.m_value), std::true_type() /*store linear value*/)
                           ^
<source>:6:10: note: in instantiation of function template specialization 'units::unit_t<units::unit<std::ratio<1, 1>,
units::base_unit<std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<-1, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>, double, linear_scale>::unit_t<
units::unit<std::ratio<1, 1>, units::base_unit<std::ratio<1, 1>, std::ratio<0, 1>, std::ratio<1, 1>, std::ratio<0, 1>,
...
```

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-11.0.1 (CONTINUED)

```
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>,
double, linear_scale>' requested here
  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; }
```

CLANG-11.0.1 (CONTINUED)

```
std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>, std::ratio<0, 1>>, std::ratio<0, 1>, std::ratio<0, 1>>,
double, linear_scale>' requested here
  return d * t;
         ^
```

`static_assert` is often not the best solution

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

A need to modernize our toolbox

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

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*

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 (and similar) we have to rethink the way we do template metaprogramming!

User's experience: Debugging: Boost.Units

```cpp
template<typename LengthSystem, typename TimeSystem>
constexpr auto avg_speed(bu::quantity<bu::unit<bu::length_dimension, LengthSystem>> d,
                         bu::quantity<bu::unit<bu::time_dimension, TimeSystem>> t)
{
   return d / t;
}
```

User's experience: Debugging: Boost.Units

```
template<typename LengthSystem, typename TimeSystem>
constexpr auto avg_speed(bu::quantity<bu::unit<bu::length_dimension, LengthSystem>> d,
                         bu::quantity<bu::unit<bu::time_dimension, TimeSystem>> t)
{
    return d / t;
}
```

Variables | GDB

```
d = {boost::units::quantity<boost::units::unit, double>}
    val_ = {boost::units::quantity<boost::units::unit, double>::value_type} 220
t = {boost::units::quantity<boost::units::unit, double>}
    val_ = {boost::units::quantity<boost::units::unit, double>::value_type} 2
```

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
```

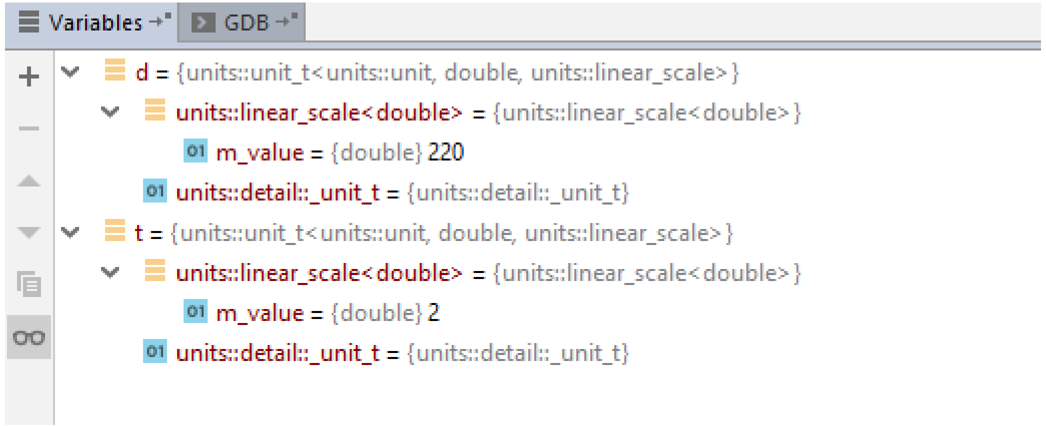
```
Breakpoint 1, avg_speed<boost::units::heterogeneous_system<boost::units::heterogeneous_system_impl
<boost::units::list<boost::units::heterogeneous_system_dim<boost::units::si::meter_base_unit, boost::units::static_rational<1> >,
boost::units::dimensionless_type>, boost::units::list<boost::units::dim<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: NHolthaus Units

```
template<typename Length, typename Time>
constexpr auto avg_speed(Length d, Time t)
{
    static_assert(units::traits::is_length_unit<Length>::value);
    static_assert(units::traits::is_time_unit<Time>::value);
    const auto v = d / t;
    static_assert(units::traits::is_velocity_unit<decltype(v)>::value);
    return v;
}
```

User's experience: Debugging: NHolthaus Units

```cpp
template<typename Length, typename Time>
constexpr auto avg_speed(Length d, Time t)
{
    static_assert(units::traits::is_length_unit<Length>::value);
    static_assert(units::traits::is_time_unit<Time>::value);
    const auto v = d / t;
    static_assert(units::traits::is_velocity_unit<decltype(v)>::value);
    return v;
}
```



User's experience: Debugging: NHolthaus Units

```
template<typename Length, typename Time>
constexpr auto avg_speed(Length d, Time t)
{
    static_assert(units::traits::is_length_unit<Length>::value);
    static_assert(units::traits::is_time_unit<Time>::value);
    const auto v = d / t;
    static_assert(units::traits::is_velocity_unit<decltype(v)>::value);
    return v;
}
```

```
Breakpoint 1, avg_speed<units::unit_t<units::unit<std::ratio<1000, 1>, units::unit<std::ratio<1>,
units::base_unit<std::ratio<1> > >, std::ratio<0, 1>, std::ratio<0, 1> > >, units::unit_t<units::unit<std::ratio<60>,
units::unit<std::ratio<60>, units::unit<std::ratio<1>, units::base_unit<std::ratio<0, 1>, std::ratio<0, 1>,
std::ratio<1> > > > > > >
(d=..., t=...) at velocity.cpp:28
28        const auto v = d / t;
```

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*

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*
- Type *aliases names are lost* quickly during compilation process

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*
- Type *aliases names are lost* quickly during compilation process
- As a result **end users** get **huge types in error messages**

A Quest Toward Strong/Opaque Typedefs

Toward Opaque typedefs in C++0X

Document #:	WG21/N1706 = J16/04-0146
Date:	September 10, 2004
Revises:	None
Project:	Programming Language C++
Reference:	ISO/IEC IS 14882:2003(E)
Reply to:	Walter E. Brown<wb@fnal.gov> CEPA Dept., Computing Division *Fermi National Accelerator Laboratory* Batavia, IL 60510-0500

A Quest Toward Strong/Opaque Typedefs

Progress toward Opaque Typedefs for C++0X

Document #:	WG21/N1891 = J16/05-0151
Date:	2005-10-18
Revises:	None
Project:	Programming Language C++
Reference:	ISO/IEC IS 14882:2003(E)
Reply to:	Walter E. Brown<wb@fnal.gov> CEPA Dept., Computing Division *Fermi National Accelerator Laboratory* Batavia, IL 60510-0500

A Quest Toward Strong/Opaque Typedefs

Toward Opaque Typedefs for C++1Y

Document #:	WG21/N3515
Date:	2013-01-11
Revises:	None
Project:	Programming Language C++
Reply to:	Walter E. Brown <webrown.cpp@gmail.com>

A Quest Toward Strong/Opaque Typedefs

Toward Opaque Typedefs for C++1Y, v2

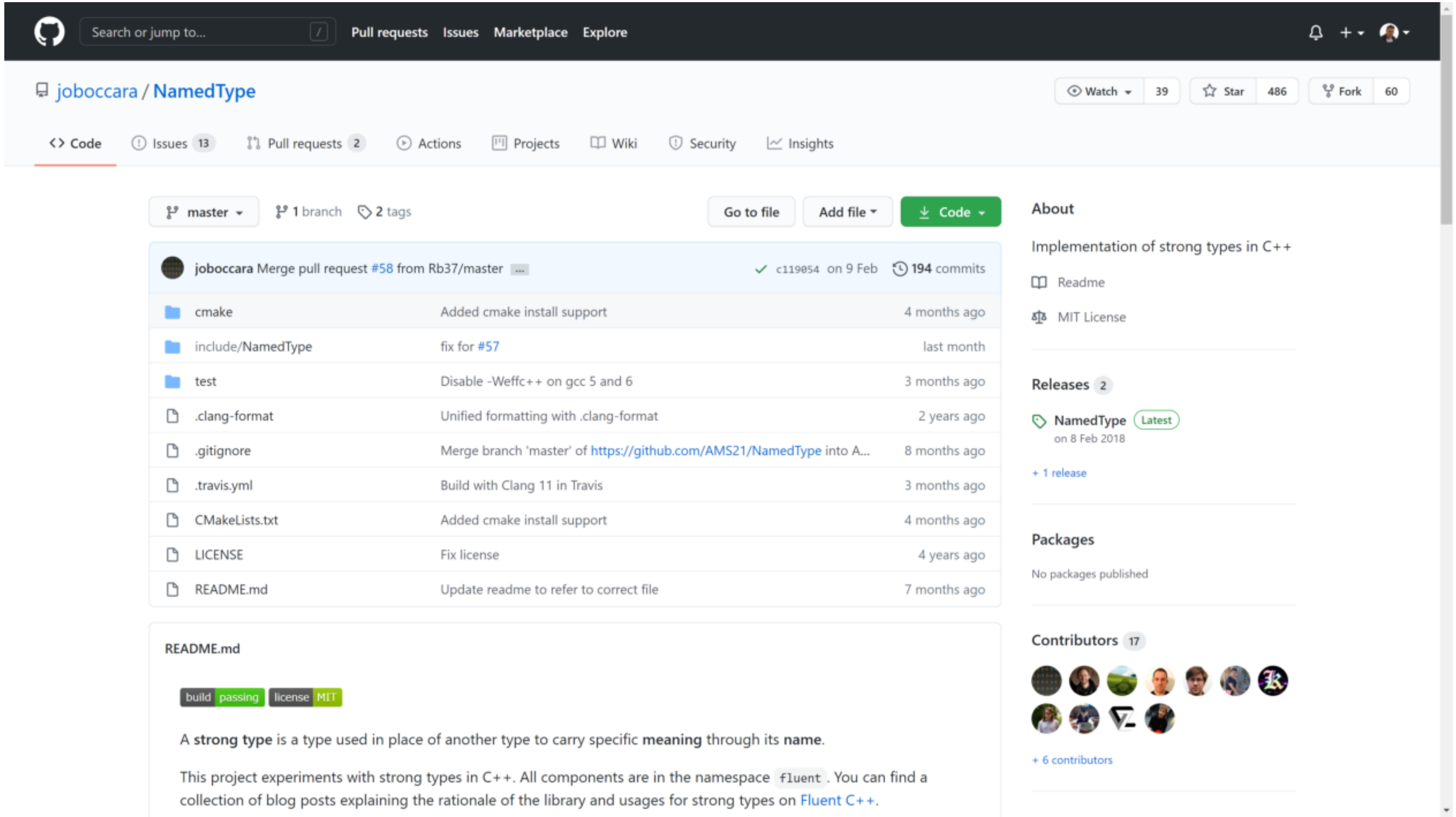
Document #:	WG21/N3741
Date:	2013-08-30
Revises:	N3515
Project:	JTC1.22.32 Programming Language C++
Reply to:	Walter E. Brown <webrown.cpp@gmail.com>

A Quest Toward Strong/Opaque Typedefs

Function Aliases + Extended Inheritance = Opaque Typedefs

Document #:	WG21/P0109R0
Date:	2015-09-25
Revises:	N3741, N3515
Project:	JTC1.22.32 Programming Language C++: EWG
Reply to:	Walter E. Brown <webrown.cpp@gmail.com>

A Quest Toward Strong/Opaque Typedefs



Inheritance as a workaround

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

Inheritance as a workaround

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

- 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==**)

Inheritance as a workaround

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

- **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==**)
- **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*

Inheritance as a workaround

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

- **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==**)
- **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**

Developer's experience: mp-units

```
using namespace units::physical;

constexpr si::speed<si::metre_per_second> avg_speed(si::length<si::metre> d,
                                                    si::time<si::second> t)
{
  return d / t;
}
```

User's experience: Compilation: mp-units

```
constexpr si::speed<si::metre_per_second> avg_speed(si::length<si::metre> d, si::time<si::second> t)
{ return d * t; }
```

User's experience: Compilation: mp-units

```
constexpr si::speed<si::metre_per_second> avg_speed(si::length<si::metre> d, si::time<si::second> t)
{ return d * t; }
```

GCC-10.2.0

```
<source>: In function 'constexpr units::physical::si::speed<units::physical::si::metre_per_second> avg_speed(
  units::physical::si::length<units::physical::si::metre>, units::physical::si::time<units::physical::si::second>)':
<source>:13:12: error: could not convert 'units::operator*<units::physical::si::dim_length, units::physical::si::metre, double,
  units::physical::si::dim_time, units::physical::si::second, double>(d, t)' from
  'quantity<units::unknown_dimension<units::exponent<units::physical::si::dim_length, 1, 1>, units::exponent<
  units::physical::si::dim_time, 1, 1> >,units::unknown_coherent_unit,[...]>' to 'quantity<units::physical::si::dim_speed,
  units::physical::si::metre_per_second,[...]>'
   13 |   return d * t;
      |          ~~^~~
      |            |
      |            quantity<units::unknown_dimension<units::exponent<units::physical::si::dim_length, 1, 1>, units::exponent<
  units::physical::si::dim_time, 1, 1> >,units::unknown_coherent_unit,[...]>
```

User's experience: Compilation: mp-units

```
constexpr si::speed<si::metre_per_second> avg_speed(si::length<si::metre> d, si::time<si::second> t)
{ return d * t; }
```

GCC-10.2.0

```
<source>: In function 'constexpr units::physical::si::speed<units::physical::si::metre_per_second> avg_speed(
  units::physical::si::length<units::physical::si::metre>, units::physical::si::time<units::physical::si::second>)':
<source>:13:12: error: could not convert 'units::operator*<units::physical::si::dim_length, units::physical::si::metre, double,
  units::physical::si::dim_time, units::physical::si::second, double>(d, t)' from
  'quantity<units::unknown_dimension<units::exponent<units::physical::si::dim_length, 1, 1>, units::exponent<
  units::physical::si::dim_time, 1, 1> >,units::unknown_coherent_unit,[...]>' to 'quantity<units::physical::si::dim_speed,
  units::physical::si::metre_per_second,[...]>'
   13 |   return d * t;
      |          ~~^~~
      |            |
      |            quantity<units::unknown_dimension<units::exponent<units::physical::si::dim_length, 1, 1>, units::exponent<
  units::physical::si::dim_time, 1, 1> >,units::unknown_coherent_unit,[...]>
```

User's experience: Compilation: mp-units

```
constexpr si::speed<si::metre_per_second> avg_speed(si::length<si::metre> d, si::time<si::second> t)
{ return d * t; }
```

GCC-10.2.0

```
<source>: In function 'constexpr units::physical::si::speed<units::physical::si::metre_per_second> avg_speed(
  units::physical::si::length<units::physical::si::metre>, units::physical::si::time<units::physical::si::second>)':
<source>:13:12: error: could not convert 'units::operator*<units::physical::si::dim_length, units::physical::si::metre, double,
  units::physical::si::dim_time, units::physical::si::second, double>(d, t)' from
  'quantity<units::unknown_dimension<units::exponent<units::physical::si::dim_length, 1, 1>, units::exponent<
  units::physical::si::dim_time, 1, 1> >,units::unknown_coherent_unit,[...]>' to 'quantity<units::physical::si::dim_speed,
  units::physical::si::metre_per_second,[...]>'
   13 |   return d * t;
      |          ~~^~~
      |            |
      |            quantity<units::unknown_dimension<units::exponent<units::physical::si::dim_length, 1, 1>, units::exponent<
  units::physical::si::dim_time, 1, 1> >,units::unknown_coherent_unit,[...]>
```

User's experience: Debugging

```cpp
using namespace units::physical;

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

User's experience: Debugging

```cpp
using namespace units::physical;

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

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's experience: Debugging

```cpp
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;
```

Dimension mismatch: Boost.Units

```cpp
#include <boost/units/quantity.hpp>
#include <boost/units/systems/si/length.hpp>
#include <boost/units/systems/si/time.hpp>
#include <boost/units/systems/si/velocity.hpp>
#include <boost/units/systems/si/acceleration.hpp>
#include <boost/units/systems/si/prefixes.hpp>

namespace bu = boost::units;

bu::quantity<bu::si::acceleration> a = 100. * bu::si::meters / (10 * bu::si::second);
```

Dimension mismatch: Boost.Units

```cpp
#include <boost/units/quantity.hpp>
#include <boost/units/systems/si/length.hpp>
#include <boost/units/systems/si/time.hpp>
#include <boost/units/systems/si/velocity.hpp>
#include <boost/units/systems/si/acceleration.hpp>
#include <boost/units/systems/si/prefixes.hpp>

namespace bu = boost::units;

bu::quantity<bu::si::acceleration> a = 100. * bu::si::meters / (10 * bu::si::second);
```

```
<source>:10:62: error: conversion from 'quantity<unit<list<[...],list<dim<[...],static_rational<-1>>,[...]>>,[...]>,[...]>'
 to non-scalar type 'quantity<unit<list<[...],list<dim<[...],static_rational<-2>>,[...]>>,[...]>,[...]>' requested
   10 | bu::quantity<bu::si::acceleration> a = 100. * bu::si::meters / (10 * bu::si::second);
      |                                        ~~~~~~~~~~~~~~~~~~~~~~^~~~~~~~~~~~~~~~~~~~~~~
Compiler returned: 1
```

Dimension mismatch: Nic Holthaus

```
#include <units.h>

using namespace units;
using namespace units::literals;

acceleration::meters_per_second_squared_t a = 100_m / 10_s;
```

Dimension mismatch: Nic Holthaus

```
#include <units.h>

using namespace units;
using namespace units::literals;

acceleration::meters_per_second_squared_t a = 100_m / 10_s;
```

```
units.h: In instantiation of 'constexpr T units::convert(const T&) [with UnitFrom = units::unit<std::ratio<1>, units::base_unit<
std::ratio<1>, std::ratio<0, 1>, std::ratio<-1> > >; UnitTo = units::unit<std::ratio<1>, units::base_unit<std::ratio<1>,
std::ratio<0, 1>, std::ratio<-2> > >; T = double]':
units.h:1956:41:   required from 'constexpr units::unit_t<Units, T, NonLinearScale>::unit_t(const units::unit_t<UnitsRhs, Ty,
NlsRhs>&) [with UnitsRhs = units::unit<std::ratio<1>, units::base_unit<std::ratio<1>, std::ratio<0, 1>, std::ratio<-1> > >;
Ty = double; NlsRhs = units::linear_scale; Units = units::unit<std::ratio<1>, units::base_unit<std::ratio<1>, std::ratio<0, 1>,
std::ratio<-2> > >; T = double; NonLinearScale = units::linear_scale]'
<source>:6:55:   required from here
units.h:1620:64: error: static assertion failed: Units are not compatible.
Compiler returned: 1
```

Dimension mismatch: mp-units

```
#include <units/physical/si/derived/acceleration.h>

using namespace units::physical;
using namespace units::physical::si::literals;

si::acceleration<si::metre_per_second_sq> a = 100_q_m / 10_q_s;
```

Dimension mismatch: mp-units

```cpp
#include <units/physical/si/derived/acceleration.h>

using namespace units::physical;
using namespace units::physical::si::literals;

si::acceleration<si::metre_per_second_sq> a = 100_q_m / 10_q_s;
```

```
<source>:6:55: error: conversion from 'quantity<units::physical::si::dim_speed,units::physical::si::metre_per_second,long int>'
 to non-scalar type 'quantity<units::physical::si::dim_acceleration,units::physical::si::metre_per_second_sq,double>' requested
    6 | si::acceleration<si::metre_per_second_sq> a = 100_q_m / 10_q_s;
      |                                               ~~~~~~~~^~~~~~~~
Compiler returned: 1
```

Dimension mismatch: mp-units

```
#include <units/physical/si/derived/acceleration.h>

using namespace units::physical;
using namespace units::physical::si::literals;

si::acceleration<si::metre_per_second_sq> a = 100_q_m / 10_q_s;
```

```
<source>:6:55: error: conversion from 'quantity<units::physical::si::dim_speed,units::physical::si::metre_per_second,long int>'
 to non-scalar type 'quantity<units::physical::si::dim_acceleration,units::physical::si::metre_per_second_sq,double>' requested
    6 | si::acceleration<si::metre_per_second_sq> a = 100_q_m / 10_q_s;
      |                                               ~~~~~~~~^~~~~~~~
Compiler returned: 1
```

The library is able to reconstruct a nicely named strong type from pieces (the Downcasting Facility).

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)

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

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

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> {};
```

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)

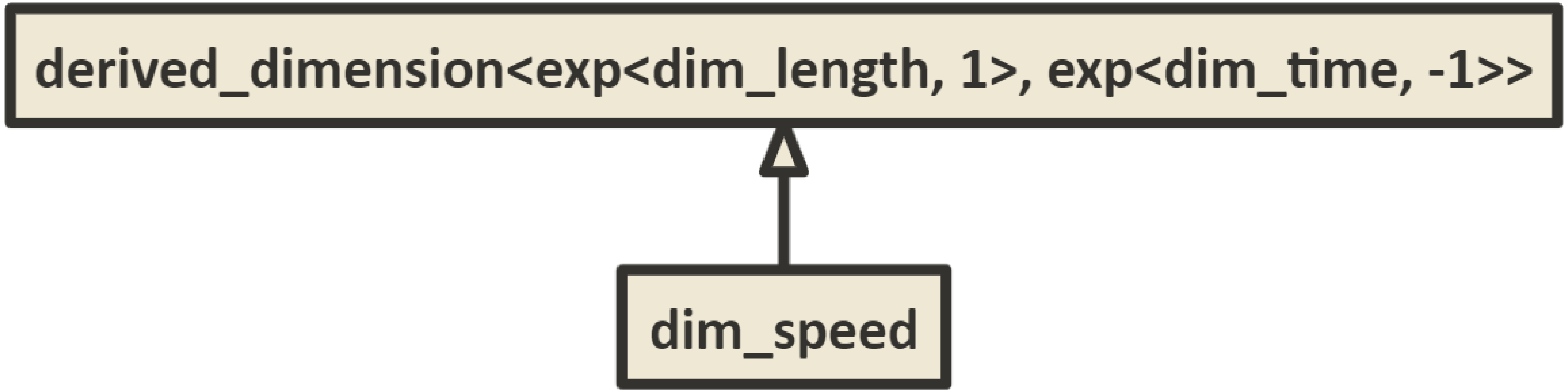
```
template<typename T>
struct downcast_traits : std::type_identity<T> {};

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> {};
```

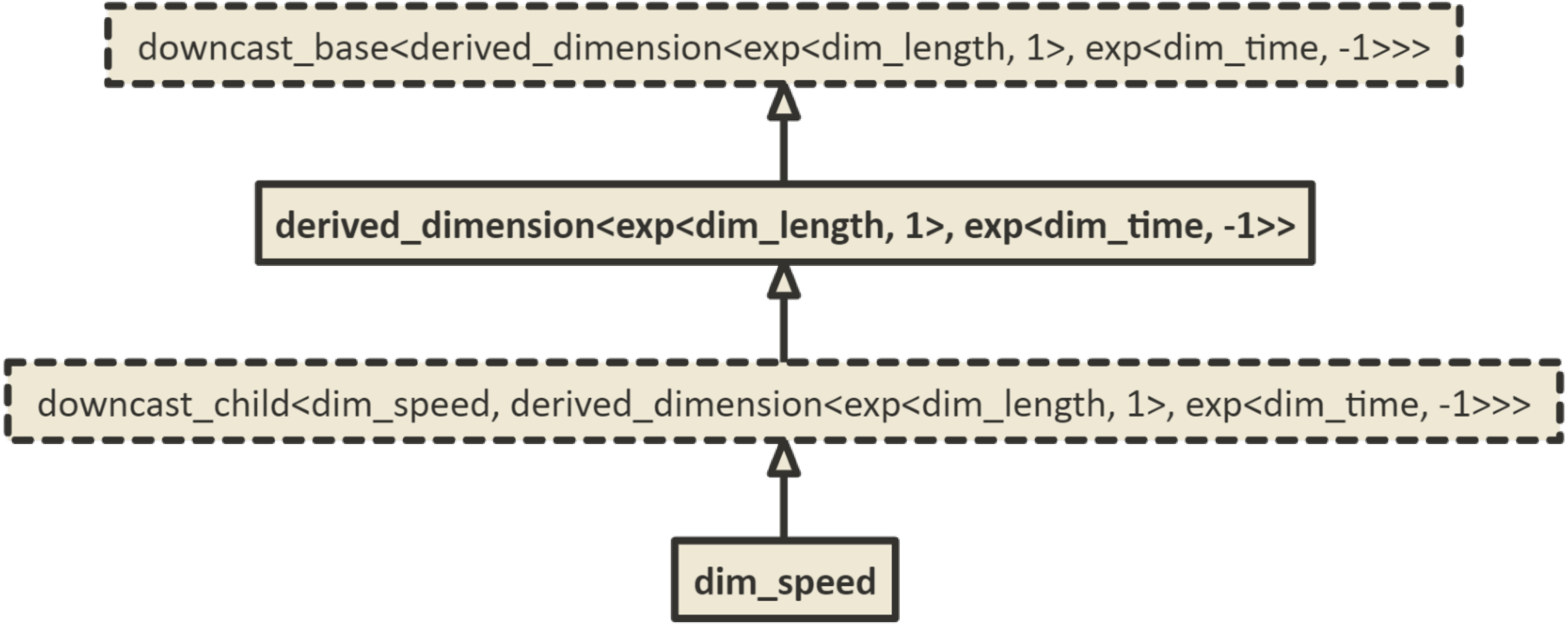
```
struct dim_area : derived_dimension<exp<dim_length, 2>> {};
template<>
struct downcast_traits<derived_dimension<exp<dim_length, 2>>> : std::type_identity<dim_area> {};
```

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

Downcasting facility (Version 2.0): Overview



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 T::downcast_base)
  { return std::type_identity<Target>(); }
};
```

Downcasting facility: Design

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

Downcasting facility: Design

```
namespace detail {




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

}

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

Downcasting facility: Design

```
namespace detail {

  template<typename T>
  concept has_downcast_guide = requires(T t) { downcast_guide(t); };

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

}

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

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`

```cpp
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`

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

```cpp
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<any_ratio R1, any_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
- **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
- **Array** type with template argument equivalent elements

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

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
- **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(ratio_equal<ratio_multiply<ratio<2>, ratio<3, 8>>, ratio<3, 4>>);
```

NTTP in action

BEFORE

```
static_assert(ratio_equal<ratio_multiply<ratio<2>, ratio<3, 8>>, ratio<3, 4>>);
```

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?

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

How do you feel about such an interface?

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

```
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

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*

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::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 any_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 any_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 any_ratio = is_ratio<T>;
```

- Name follows **any_** prefix
- Previously reserved for polymorphic wrappers
  - obsolete with renaming of **`any_invocable`** to **`move_only_function`**

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 any_ratio = is_ratio<T>;
```

- Name follows **any_** prefix
- Previously reserved for polymorphic wrappers
  - obsolete with renaming of **`any_invocable`** to **`move_only_function`**

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)*

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"*

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;
```

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;
```

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

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;
```

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

Is this concept easy to prove correct?

What about our `std::ratio_multiply`?

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

What about our `std::ratio_multiply`?

```
template<any_ratio R1, any_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<any_ratio R1, any_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 (any_ratio<R1>) &&
  (any_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 'any_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 any_ratio = is_ratio<T>;
      |                     ^~~~~~~~~~~
```

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

ratio-LIKE TYPE

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

Is this concept easy to prove correct?

What about our `std::ratio_multiply`?

```
template<ratio_like R1, ratio_like 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_like R1, ratio_like 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_like<R1>) &&
  (ratio_like<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_like<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_specialization_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_specialization_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_specialization_of<T, derived_dimension_base>;

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

template<typename T>
concept Quantity = is_specialization_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_specialization_of<T, derived_dimension_base>;

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

template<typename T>
concept Quantity = is_specialization_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*

```
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 additional 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?

```cpp
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);

  // ...
};
```

```cpp
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?

```cpp
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);

  // ...
};
```

```cpp
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.
Concepts just work as expected.

Benefits of using C++ Concepts

Benefits of using C++ Concepts

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

Benefits of using C++ Concepts

1. Clearly **state the design intent** of the interface of a class/function template
2. **Embedded in a template signature**

Benefits of using C++ Concepts

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
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*
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*

Oral Session C++ Concepts: Constraining C++ Templates in C++20 and Before

Sunday, 14 March **10:00 - 18:00**

Presenter
Mateusz Pusz

Biography
A software architect, chief engineer, and security champion with more than 15 years of experience in designing, writing and maintaining C++ code for fun and living. C++ consultant, trainer, conference speaker, and evangelist focused on Modern C++. His main areas of interest and expertise are code performance, low latency, stability, and security. Mateusz worked at Intel for 13 years, and now he is the head of the C++ Competency Center at EPAM Systems. He is also a founder of Train IT that provides dedicated C++ trainings and consultant services to corporations. Mateusz is a contributor and an active voting member of the ISO C++ Committee (WG21) where, together with the best C++ experts in the world, he shapes the future of the C++ language. He is also a co-chair of WG21 Study Group 14 (SG14) responsible for driving performance and low latency subjects in the Committee. In 2013 Mateusz won "Bench Games 2013" – worldwide competition in the C++ language knowledge.

Title
C++ Concepts: Constraining C++ Templates in C++20 and Before

Session Type
Fullday Workshop

Session Tag
C++

Abstract
C++ Concepts is one of the most significant and long-awaited features of C++20. They improve template interfaces by explicitly stating the compile-time contract between the user and the architect of the code, which limits the number of compilation errors and make them much more user-friendly when they occur. The workshop will describe this C++20 feature, its similarities and differences from

And you know what? It is round ;-)

WISHFUL THINKING

Sometimes you do not want a named concept

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

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>;
```

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>
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 :-(

Template template parameter kind works only for class templates

Making variable templates a first class citizen (P2008)

CLASS TEMPLATES

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

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>;
```

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>;
```

Making variable templates a first class citizen (P2008)

CUSTOMIZATION POINTS

- Similar, but still distinct, use case

```
template<class T>
inline constexpr bool enable_borrowed_range = false;

template<class>
inline constexpr bool disable_sized_range = false;

template<class T>
inline constexpr bool enable_view = see below;
```

Making variable templates a first class citizen (P2008)

`std::numbers`

```
template<Unit U, ratio R, template<typename> auto IrrationalFactor>
struct scaled_unit;
```

```
struct degree : scaled_unit<radian, ratio(2, 360), std::numbers::pi_v> {};
```

Making variable templates a first class citizen (P2008)

`std::numbers`

```
template<Unit U, ratio R, template<typename> auto IrrationalFactor>
struct scaled_unit;
```

```
struct degree : scaled_unit<radian, ratio(2, 360), std::numbers::pi_v> {};
```

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

Template Parameter Kinds

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

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;
```

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 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;
```

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)

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)

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_specialization_of = false;

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

Concept to check for an instantiation of a class template

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

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

```cpp
template<typename T, template<template auto...> typename Type>
concept specialization_of = is_specialization_of<T, Type>;
```

What about our `std::ratio_multiply`?

```
template<specialization_of<std::ratio> R1, specialization_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<specialization_of<std::ratio> R1, specialization_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
   (specialization_of<R1, std::ratio>) && (specialization_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 'specialization_of<std::__cxx11::basic_string<char, std::char_traits<char>,
   std::allocator<char> >, std::ratio>'
<source>:21:14: note: the expression 'is_specialization_of<T, Type>' evaluated to 'false'
   21 | concept specialization_of = is_specialization_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);
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);
```

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

- Started in 2016 by *Louis Dionne*
- *CMake module* that simplifies compile-time microbenchmarking

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

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

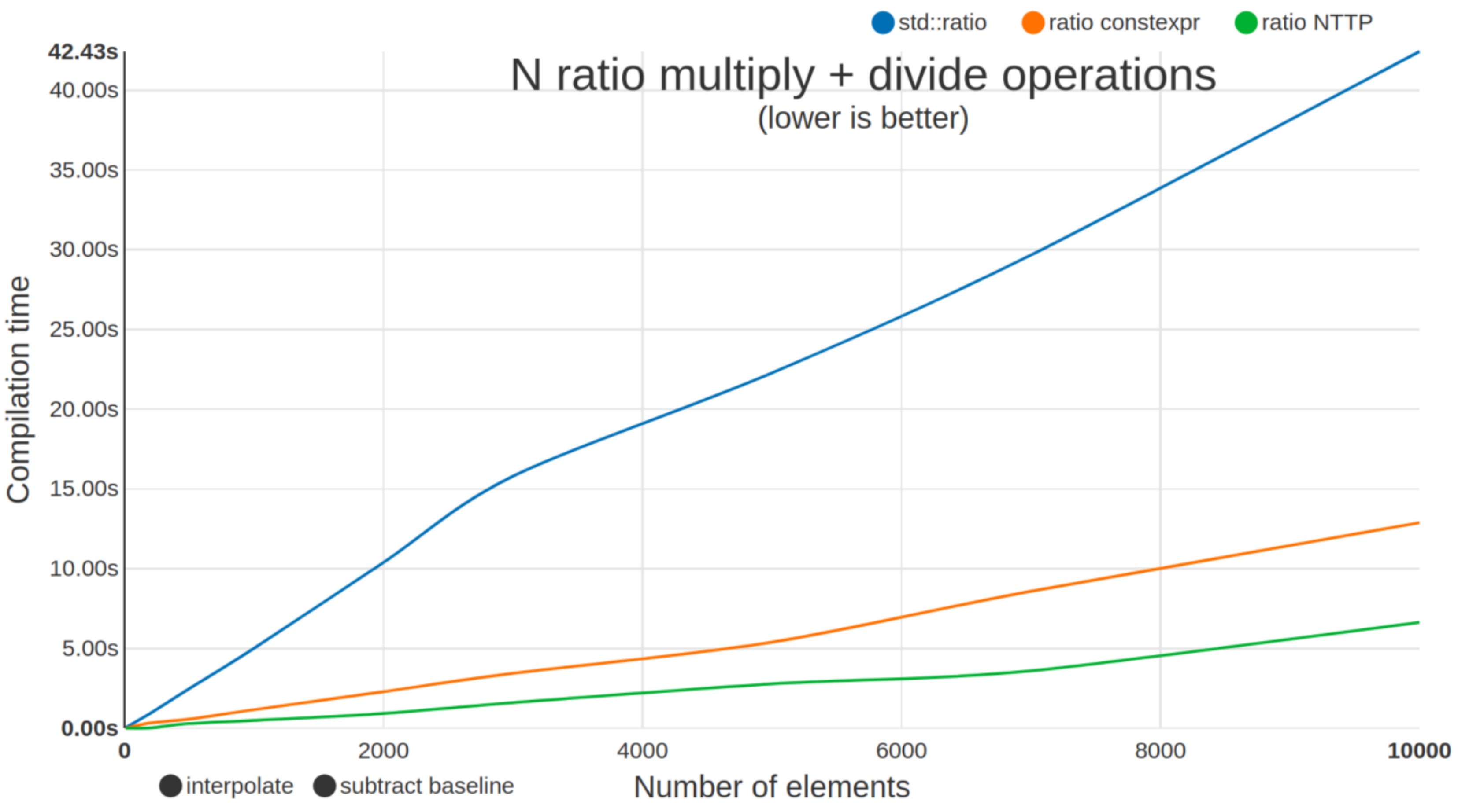
```cpp
#include "ratio_type_constexpr.h"

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() {}
```

A short intro to Metabench: Generated C++ code

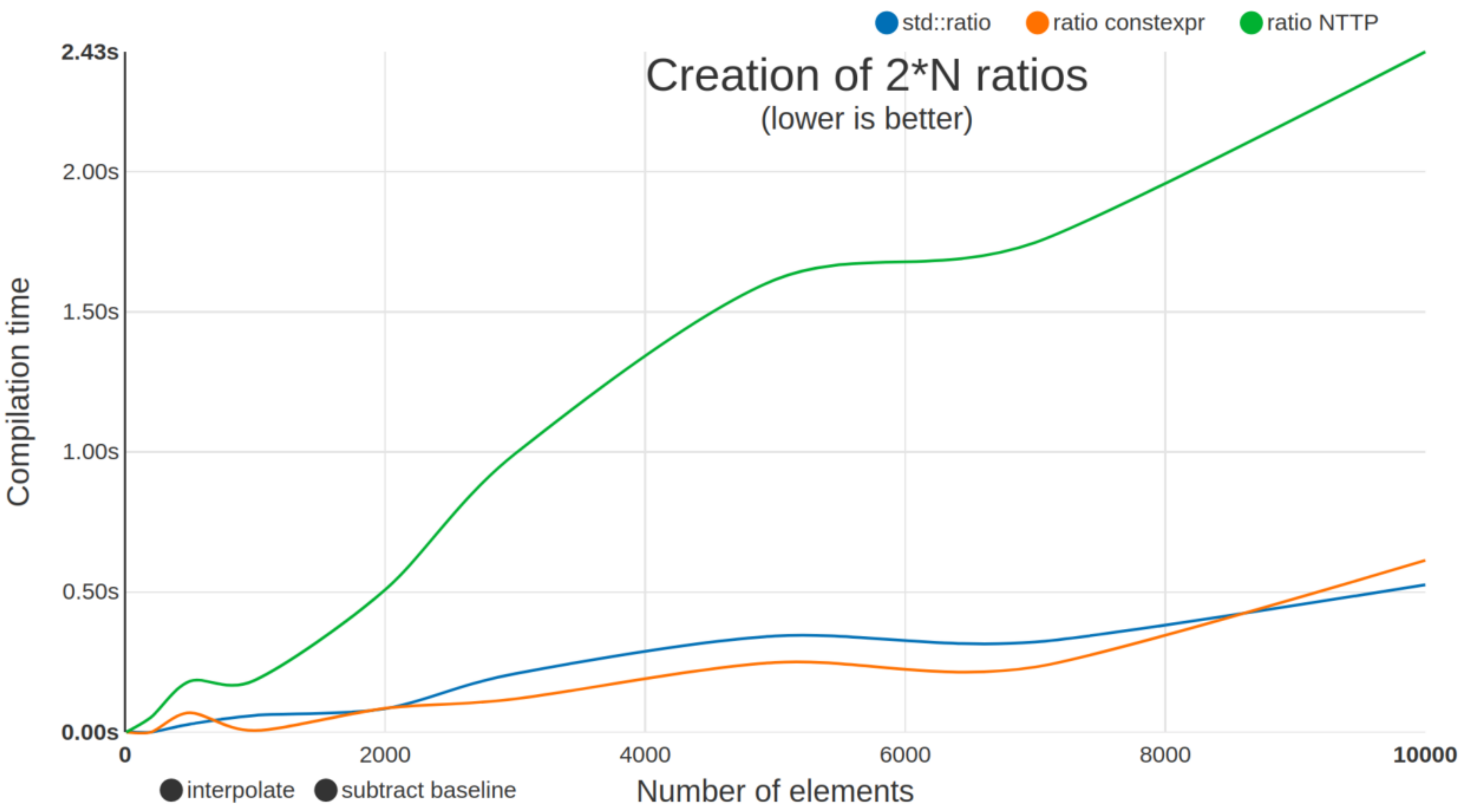
```cpp
#include "ratio_type_constexpr.h"

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() {}
```

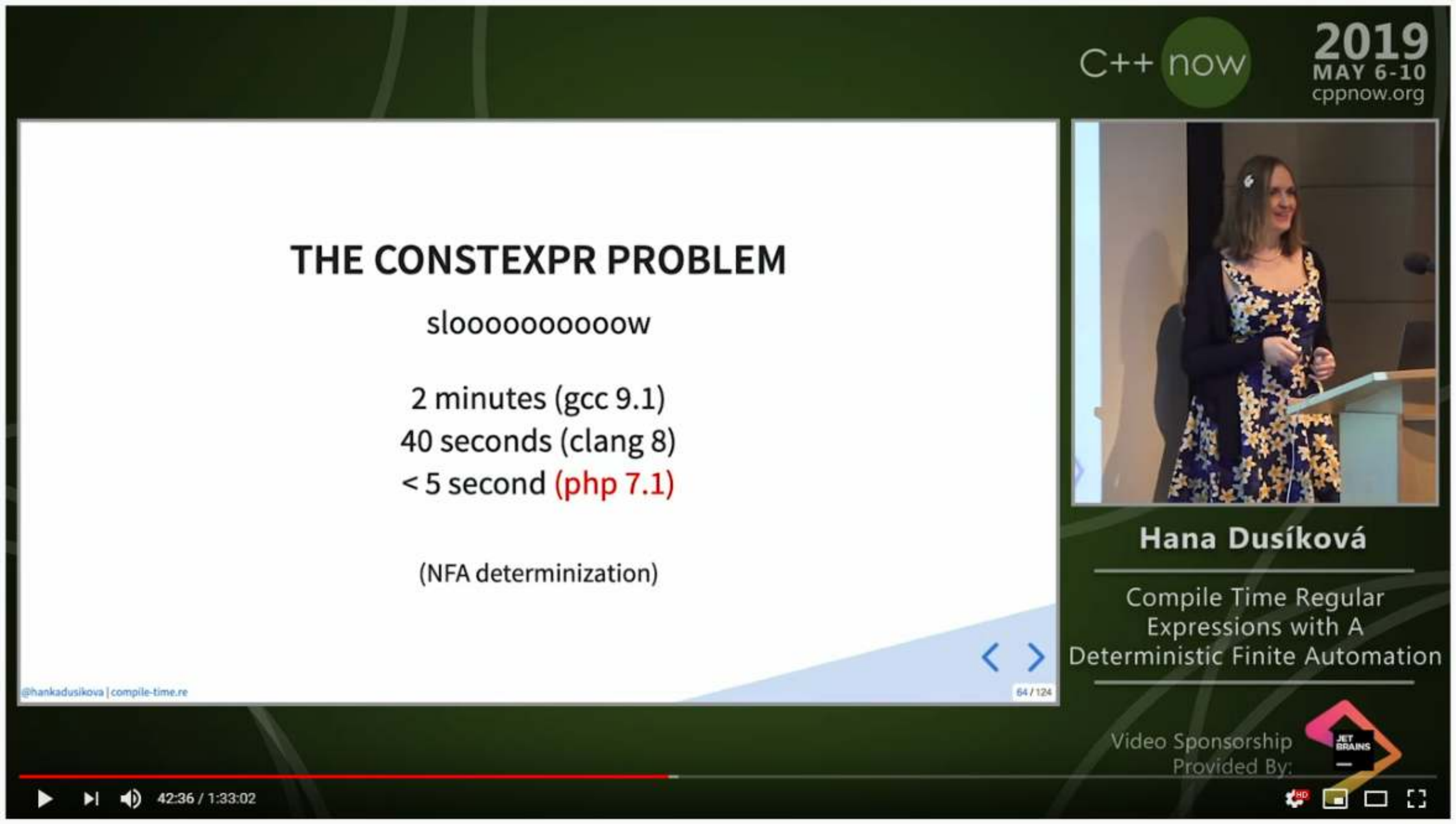
`ratio` performance



`ratio` performance



Current constexpr QoI is slow



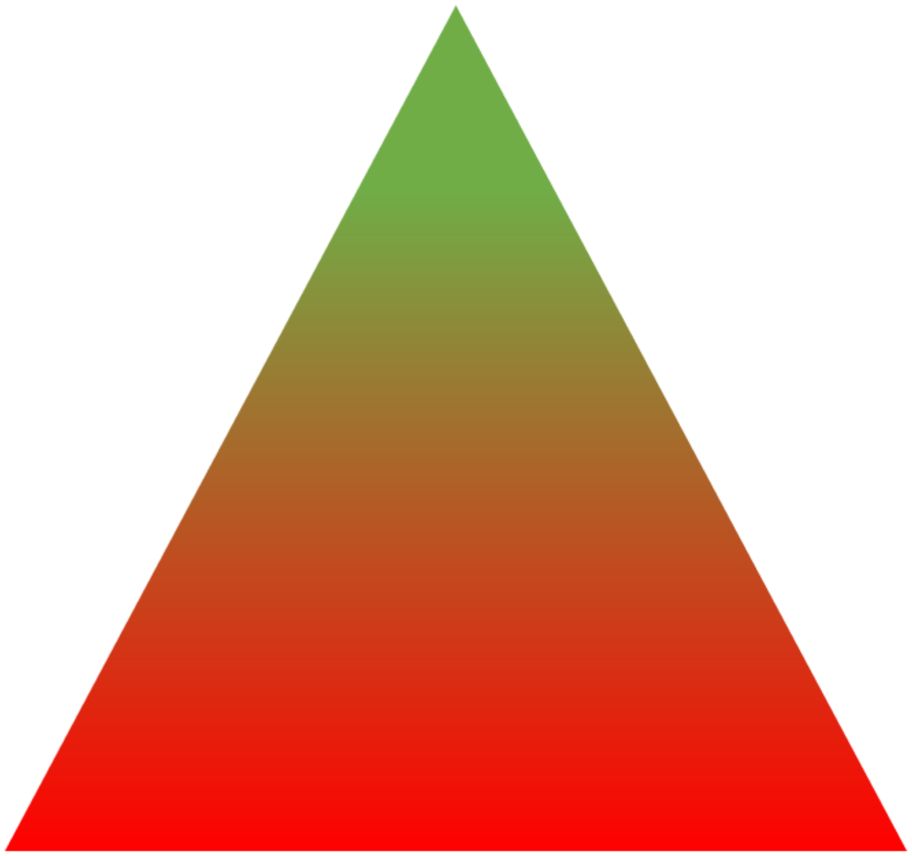
C++Now 2019: Hana Dusíková "Compile Time Regular Expressions with A Deterministic Finite Automaton"

The Rule of Chiel

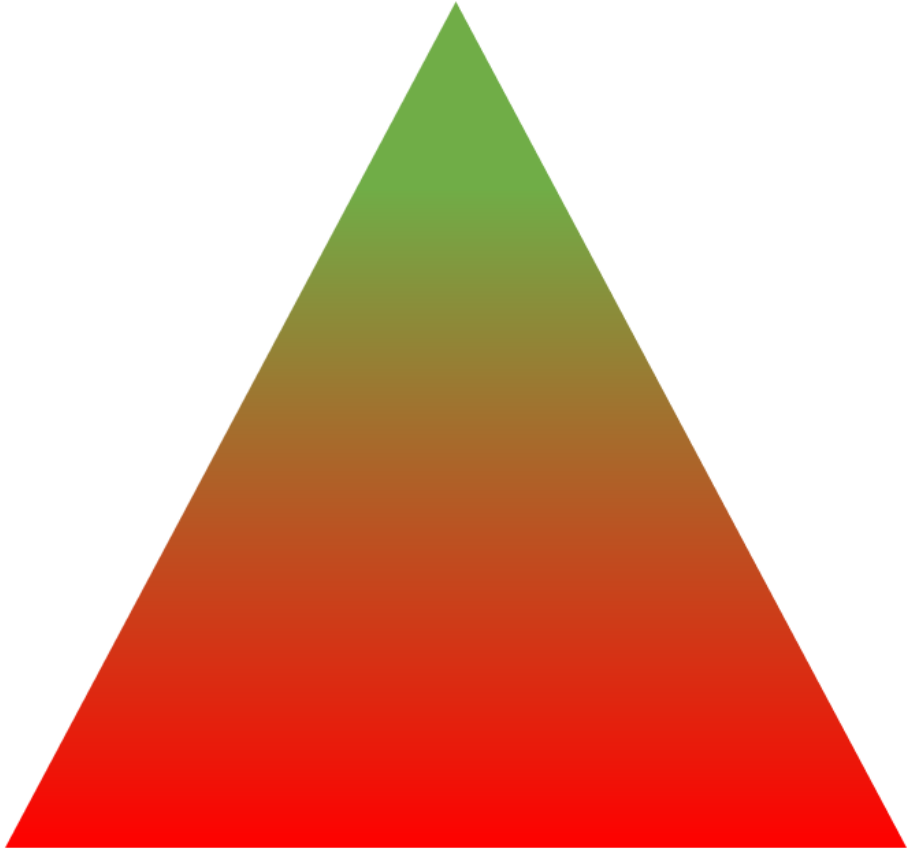
The Rule of Chiel

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

Cost of operations: The Rule of Chiel

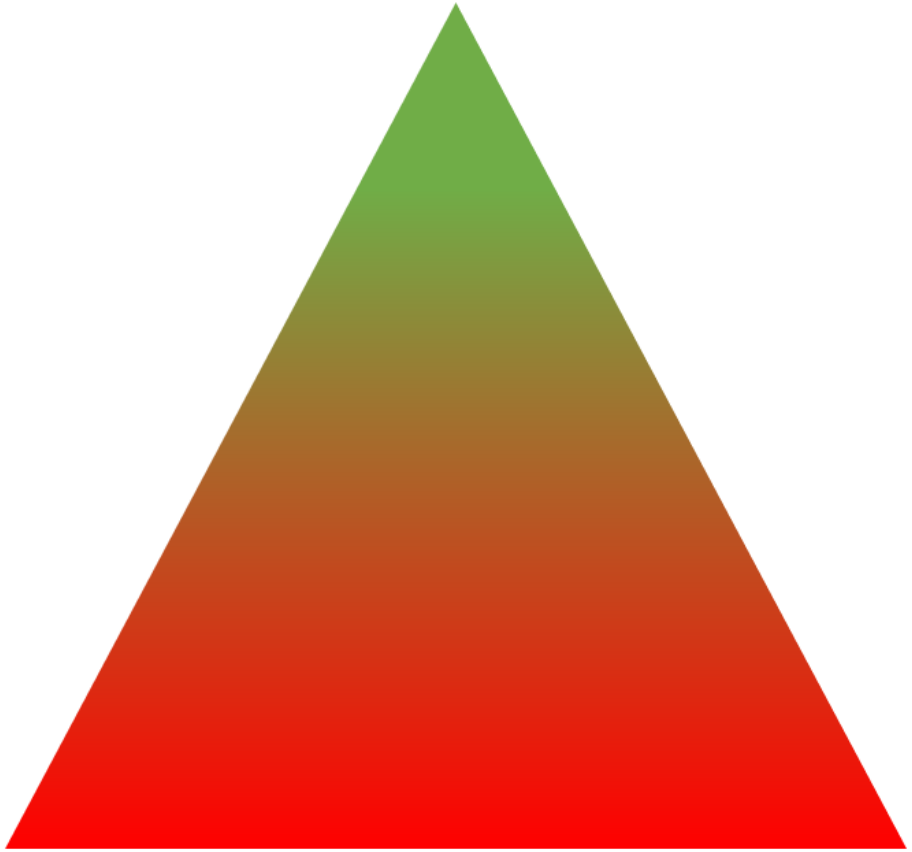


Cost of operations: The Rule of Chiel



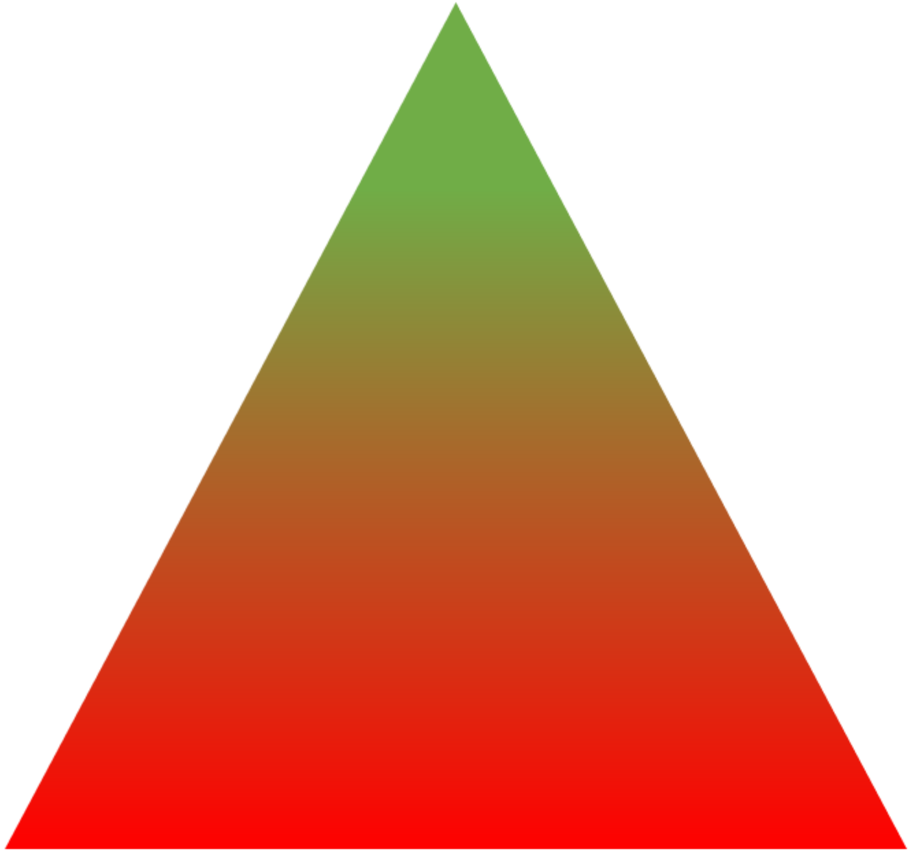
1 Looking up a memoized type

Cost of operations: The Rule of Chiel



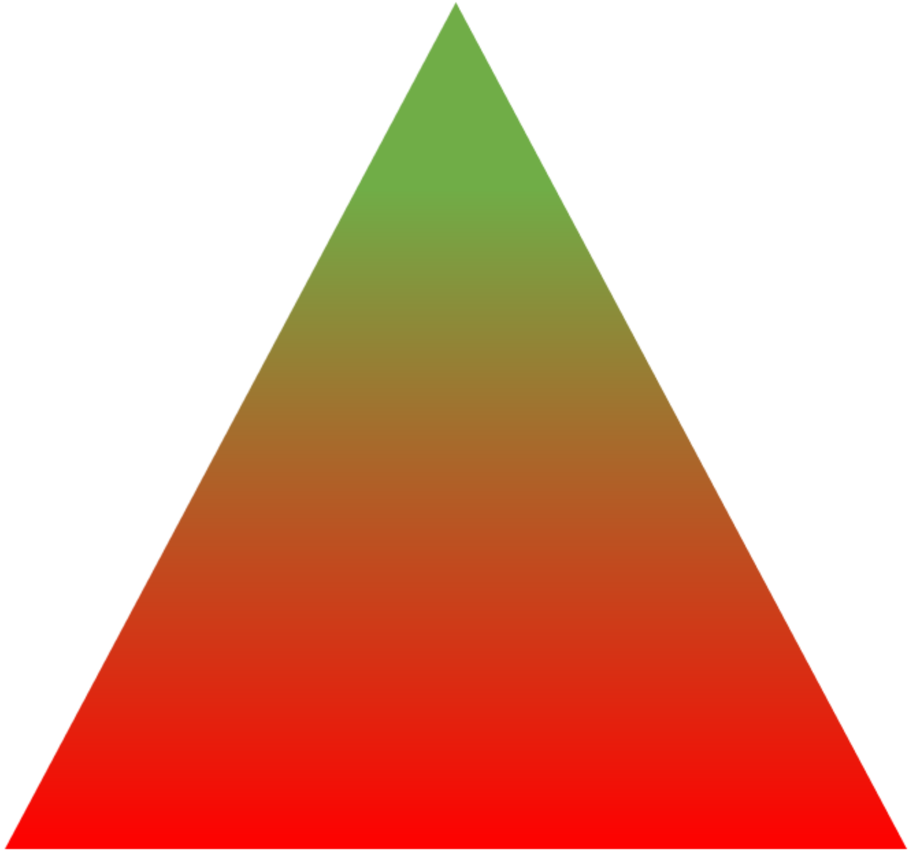
1. Looking up a memoized type
2. Adding a parameter to an alias call

Cost of operations: The Rule of Chiel



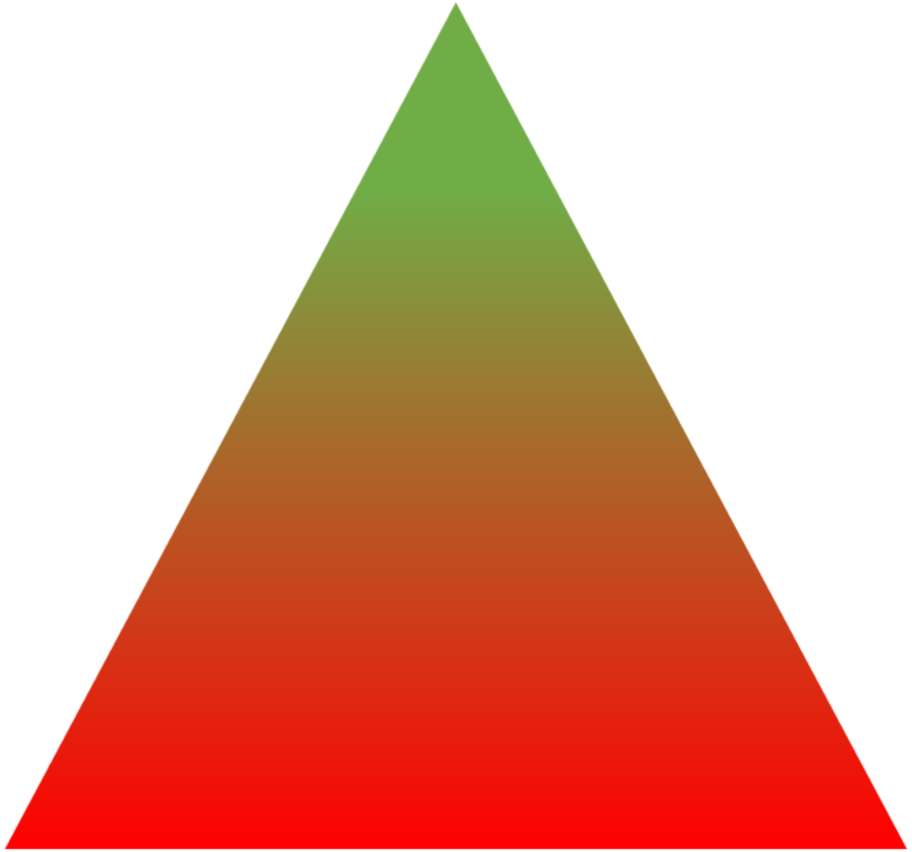
1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type

Cost of operations: The Rule of Chiel



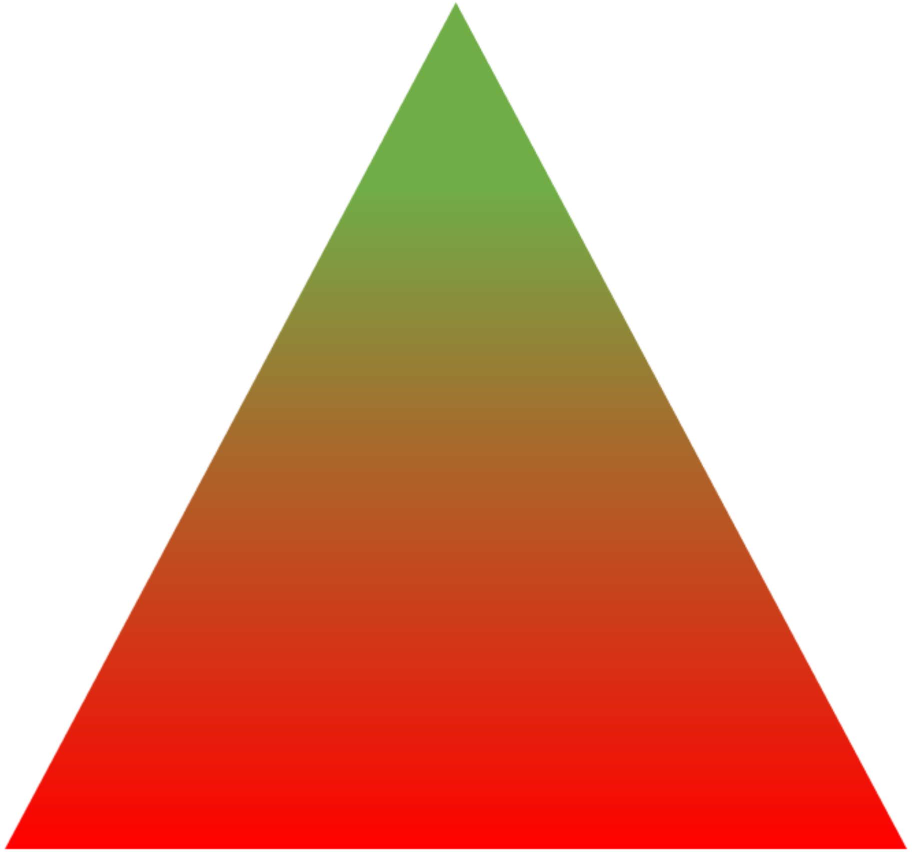
1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type
4. Calling an alias

Cost of operations: The Rule of Chiel



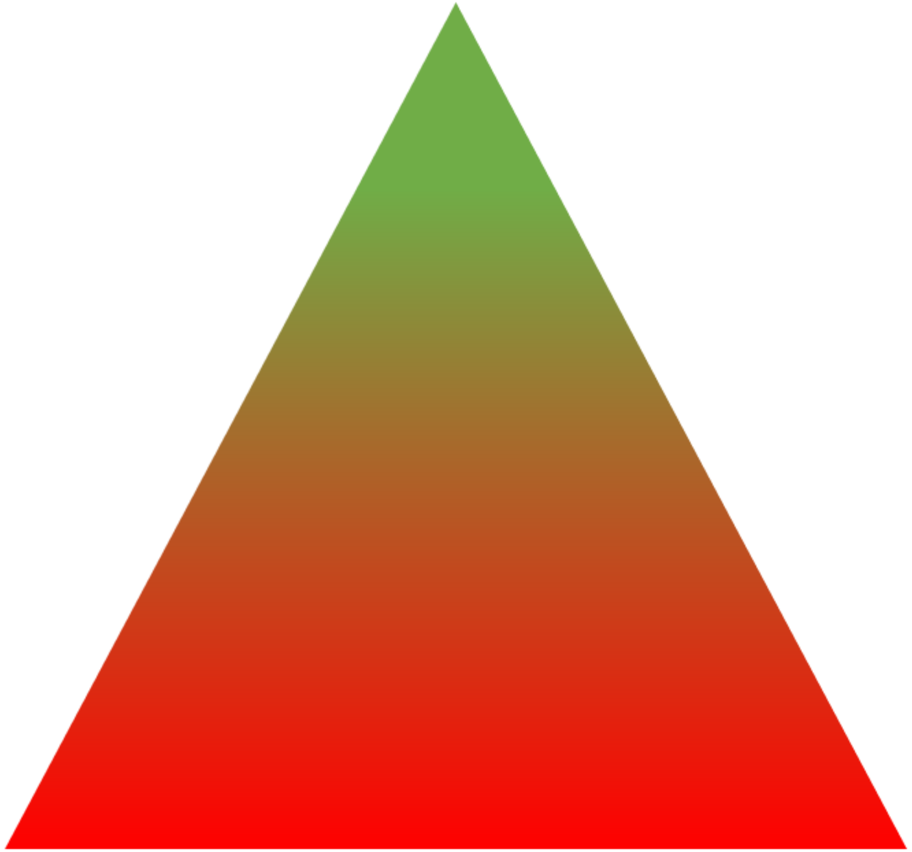
1. Looking up a memoized type
2. Adding a parameter to an alias call
3. Adding a parameter to a type
4. Calling an alias
5. Instantiating a class

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>

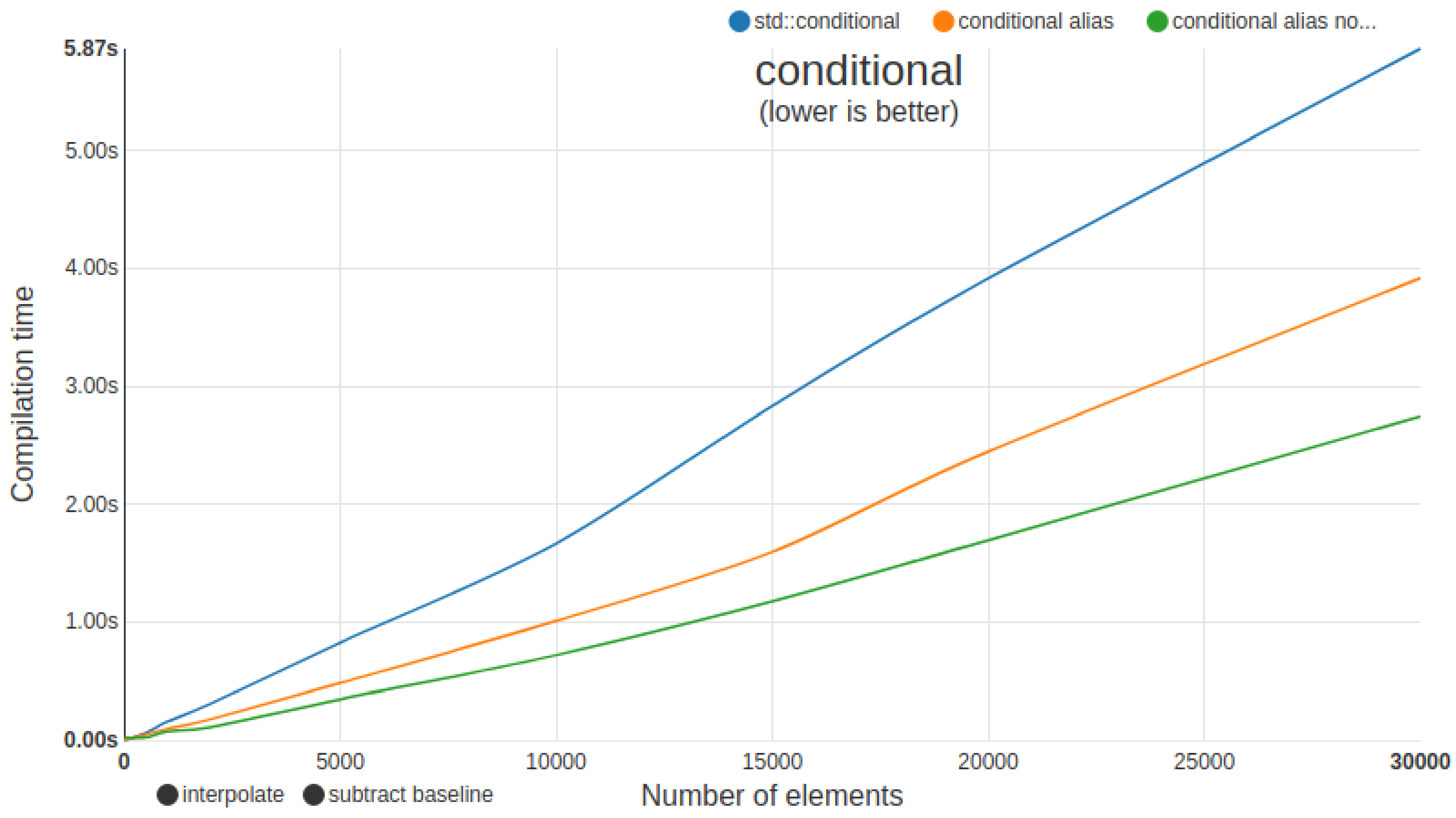
TRADITIONAL

```
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;
```

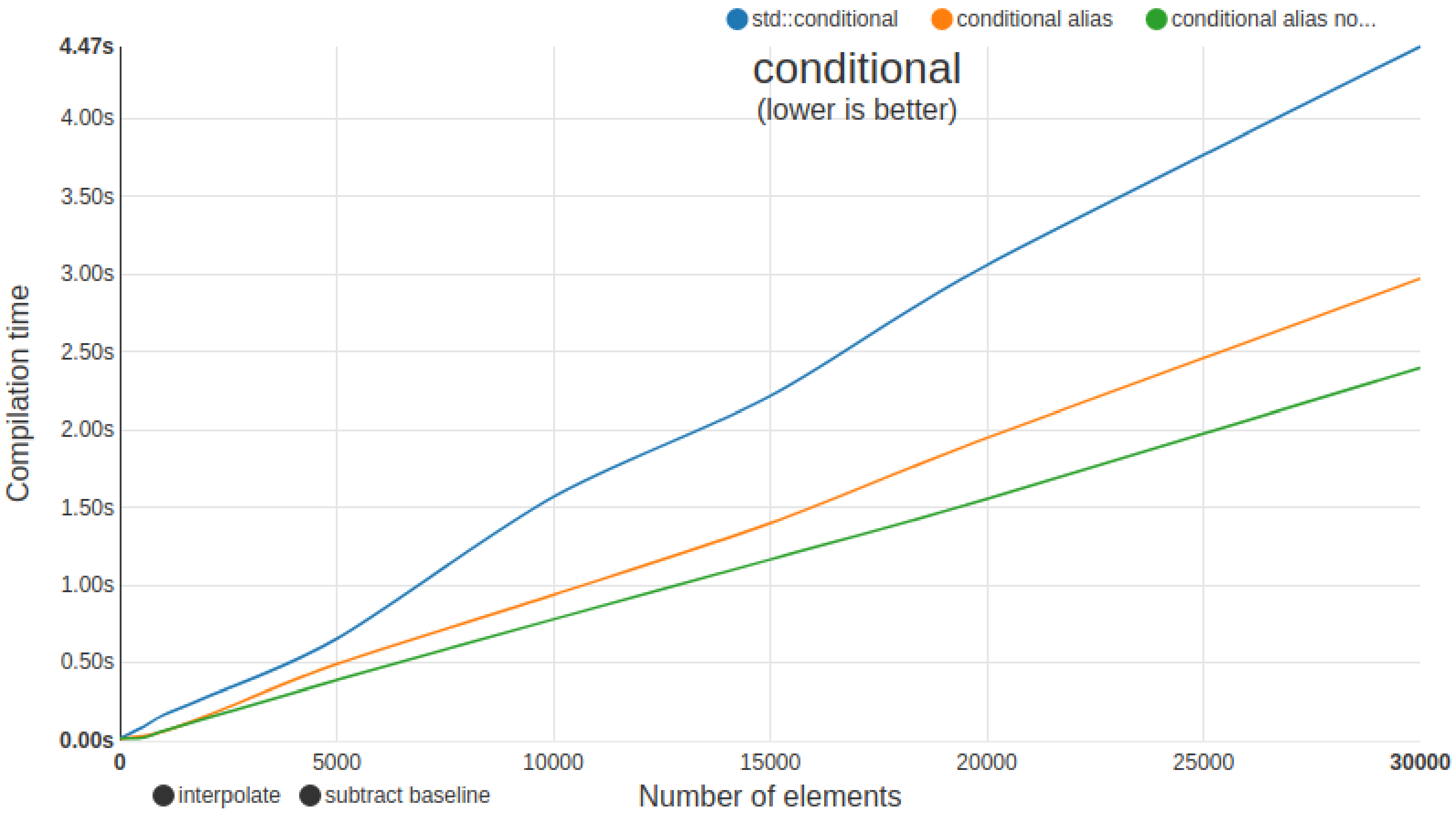
WITH ALIAS TEMPLATE

```
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 {};
```

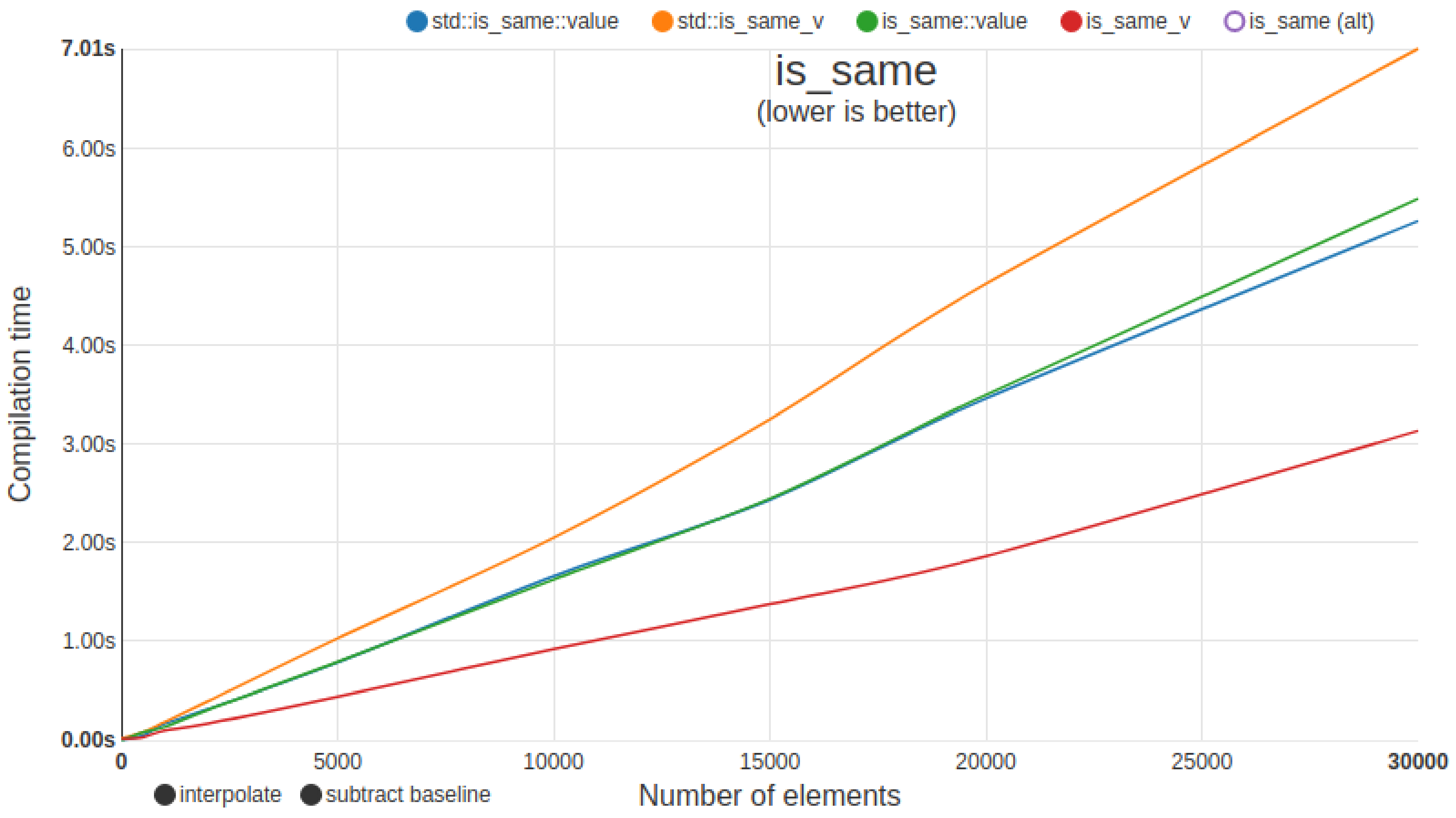
```
template<class T, class U>
inline constexpr bool is_same_v =
  is_same<T, U>::value;
```

USING VARIABLE TEMPLATES

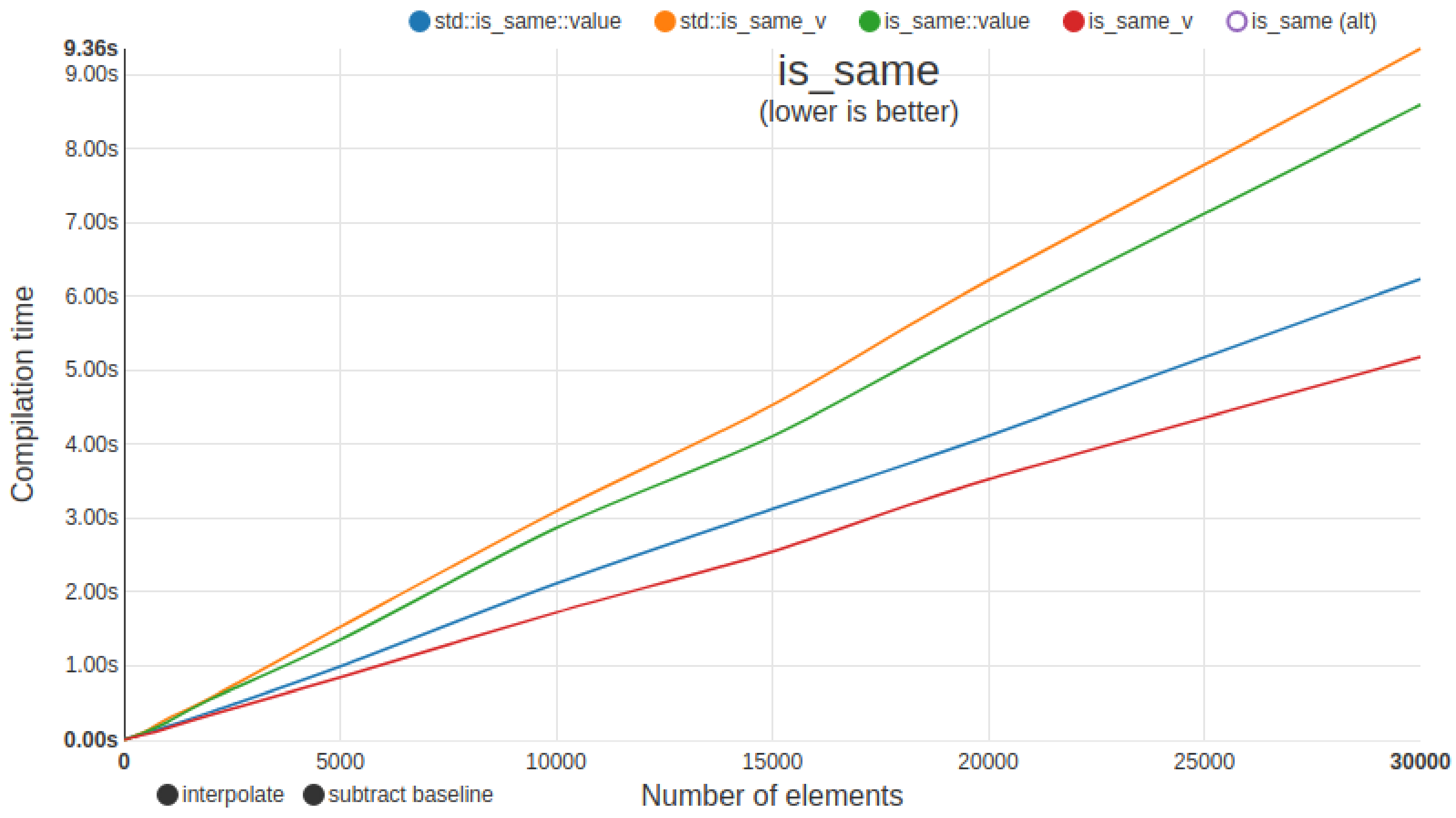
```
template<class T, class U>
inline constexpr bool is_same_v = false;

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)



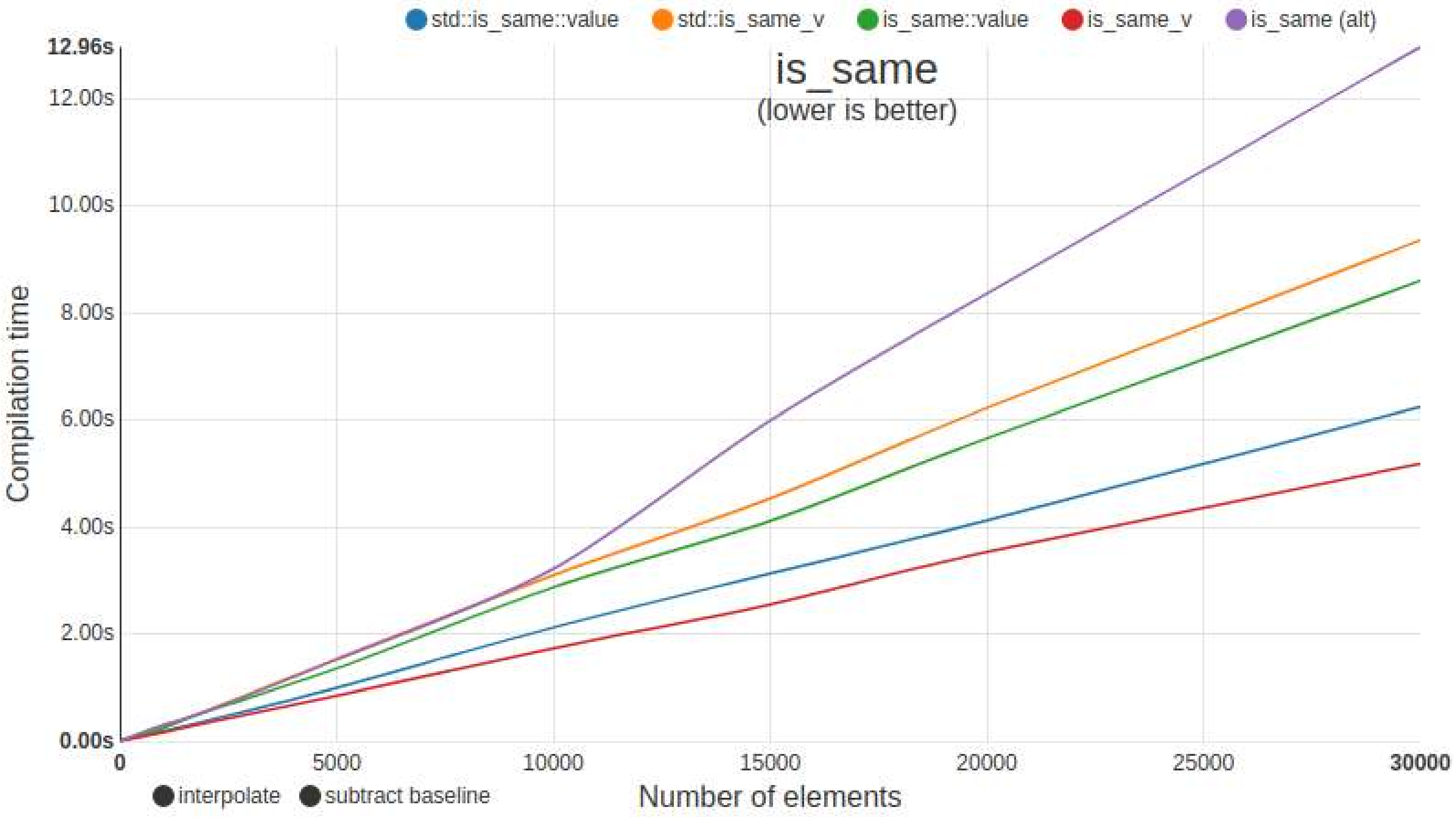
is_same performance (clang-10)



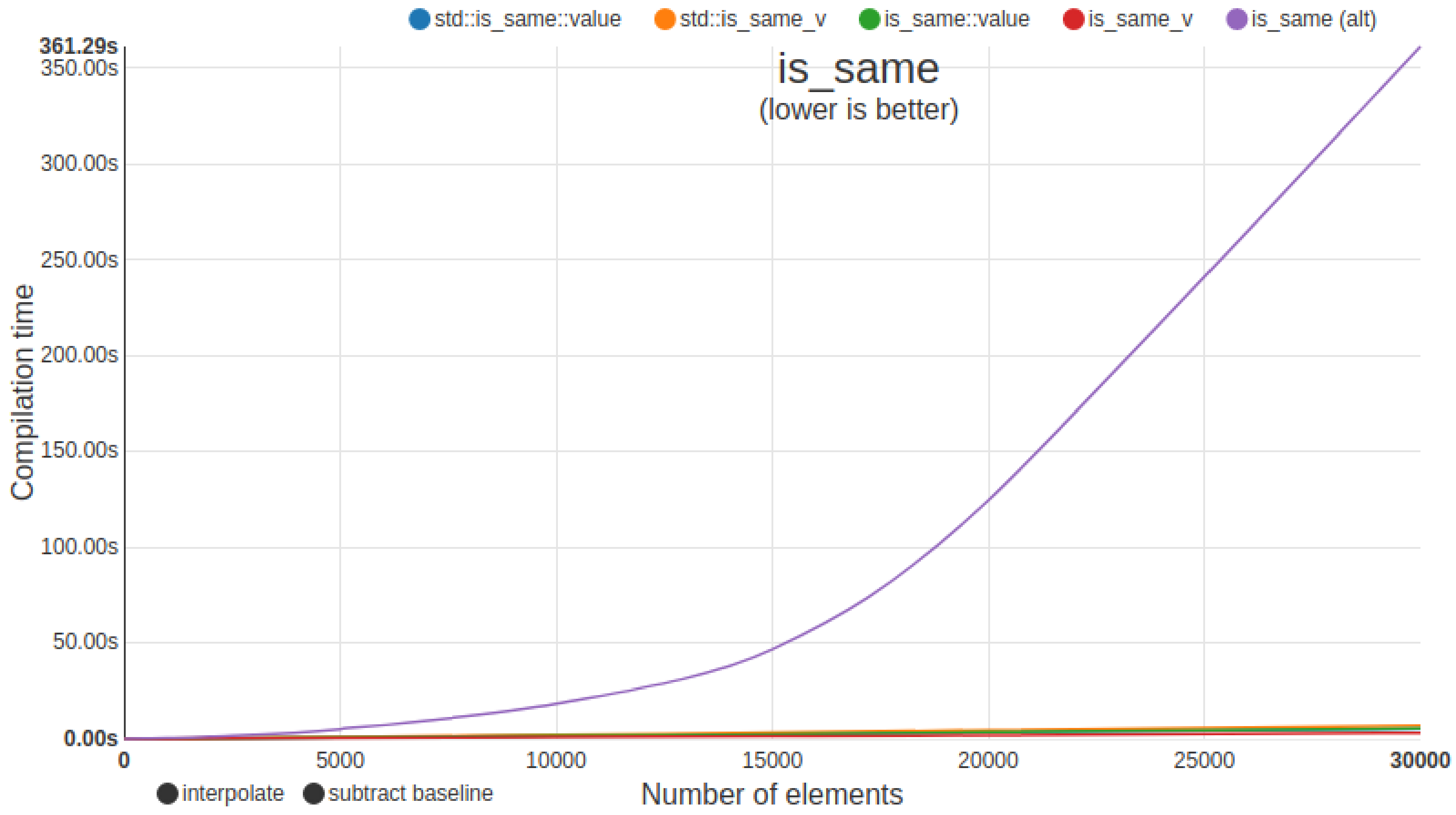
Alternative `is_same` implementation from CppCon 2019

```cpp
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?

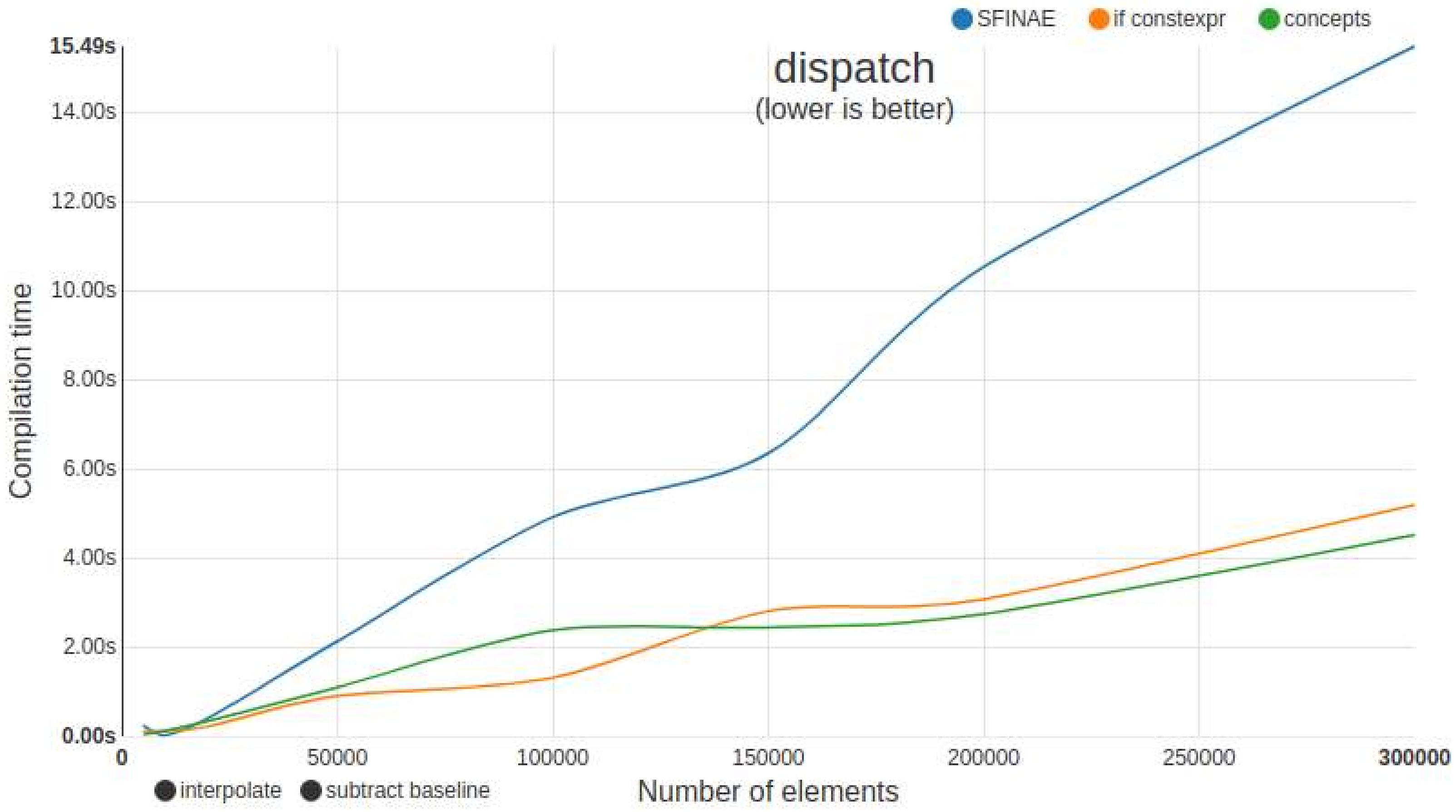
IF CONSTEXPR

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

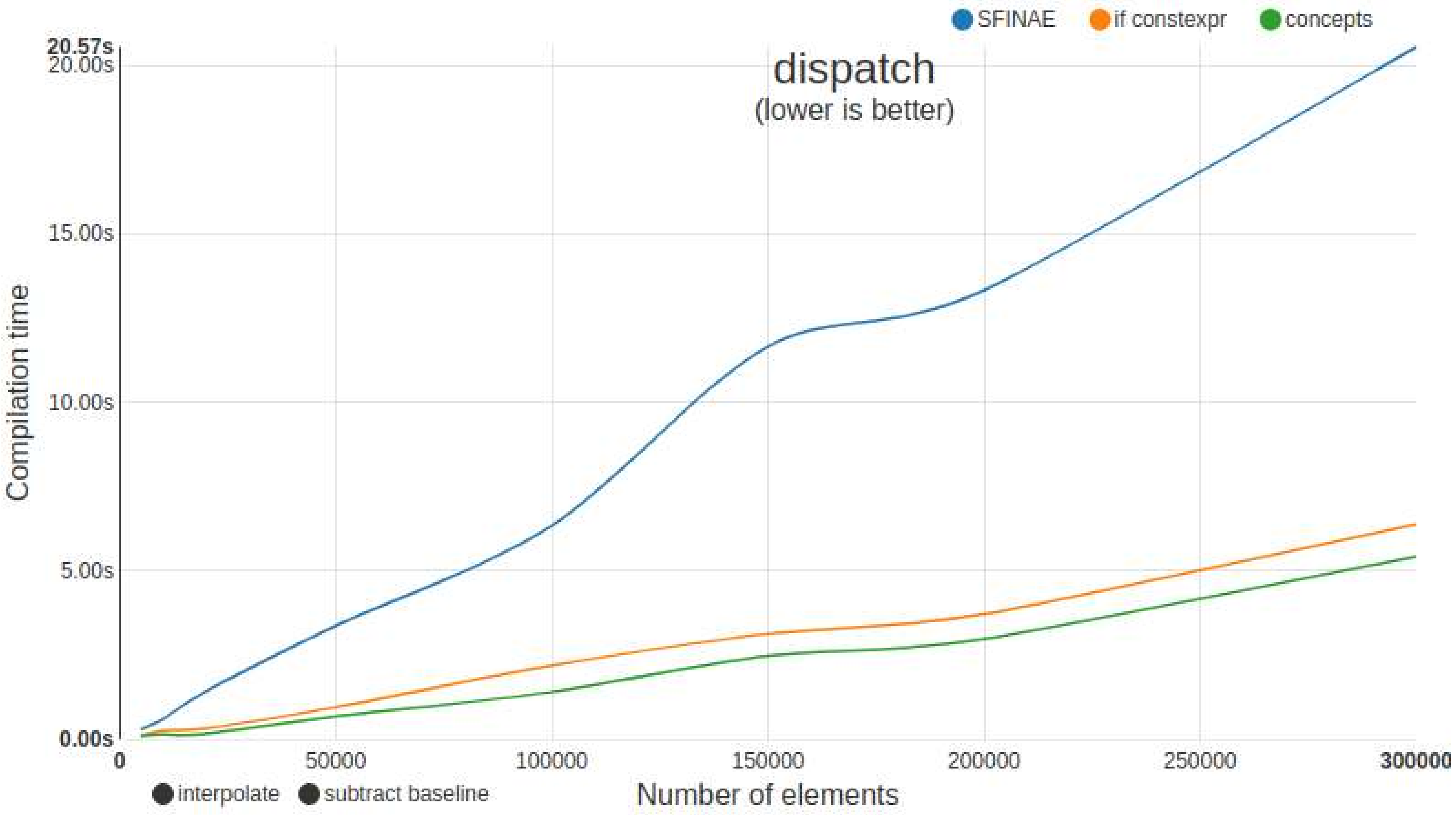
CONCEPTS

```
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*

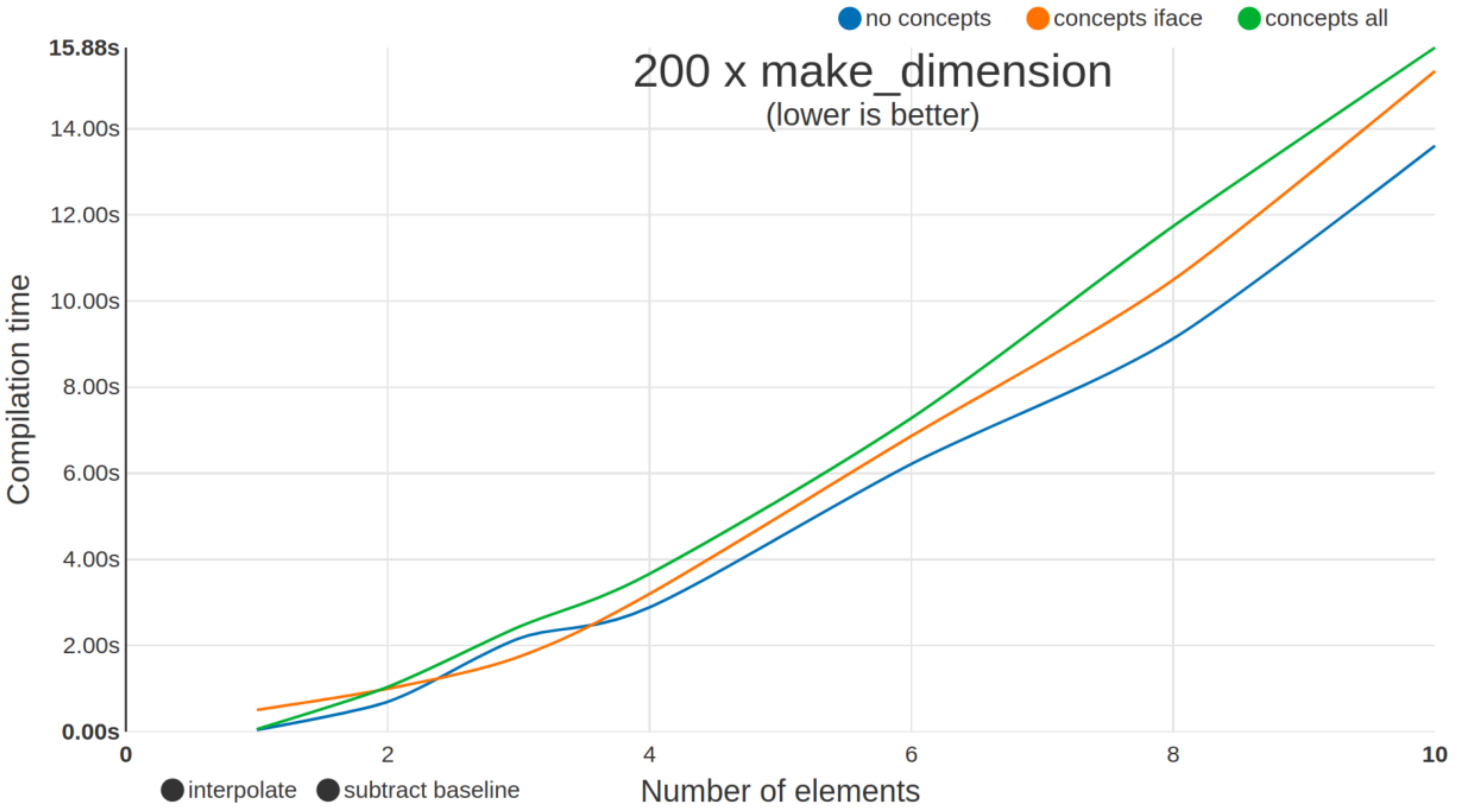
```
template<Exponent... Es>
struct dimension : downcast_base<dimension<Es...>> {};

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?

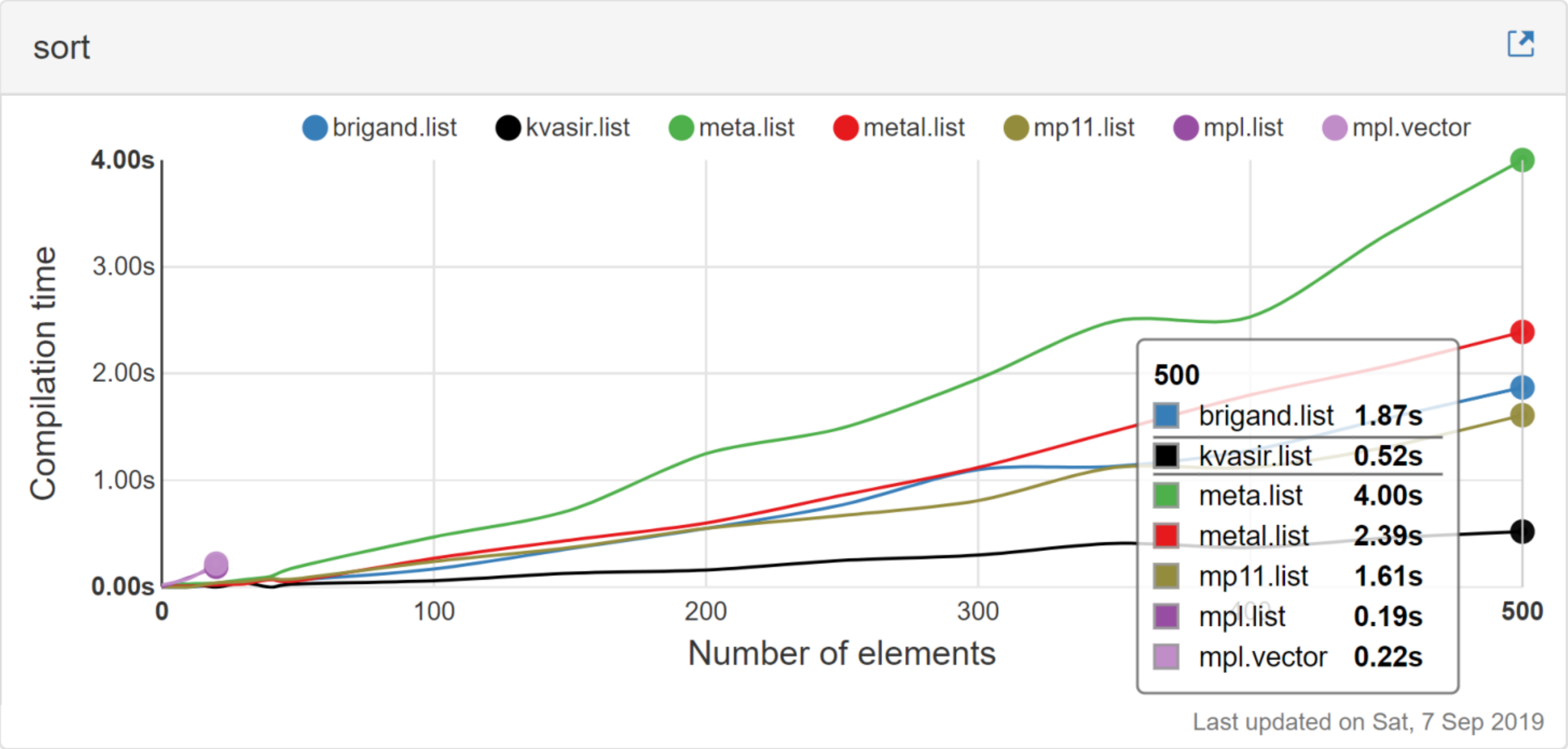
- Compile-time performance impact might be *limited by using concepts only in the user interfaces*

```
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

Rethinking C++ templates

Rethinking C++ templates

1. Think about **end users' experience** and not only about your convenience as a developer

Rethinking C++ templates

1. Think about **end users' experience** and not only about your convenience as a developer
2. Use **C++ Concepts** to
   - express compile-time contracts
   - improve productivity
   - improve compile-time errors

Rethinking C++ templates

1. Think about **end users' experience** and not only about your convenience as a developer
2. Use **C++ Concepts** to
   - express compile-time contracts
   - improve productivity
   - improve compile-time errors
3. **Use NTTPs** when a template parameter represents a value rather than a type

Rethinking C++ templates

1. Think about **end users' experience** and not only about your convenience as a developer
2. Use **C++ Concepts** to
   - express compile-time contracts
   - improve productivity
   - improve compile-time errors
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)