Notes for PDF users

If you're reading these slides as a PDF, know that this is **not their intended format**. You shouldn't expect to be able to read the slides and understand the presentation. The biggest missing piece is the **speaker's notes**. Without them, the slides will **not all make sense**, and you could easily **misinterpret** some of them.

Additionally: some individual slides have rendered incorrectly, such as "Embedded Friendliness" and "Feature Inspirations".

To view with the speaker's notes, you can view the online slides, and press s to invoke the notes. You can also go to the repository itself, chiphogg/cppcon-2023-au-units, either to host the slides locally, or to see how the talk is implemented or was made.

The Au Library:

Handling Physical Units Safely, Quickly, and Broadly

CHIP HOGG

Cppcon
The C++ Conference

2023 | October 01 - 06

Units library: basic concept

```
1 // No units library:
2 double distance_m;
3
4
5
```

Units library: basic concept

```
1 // No units library:
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4 // With units library:
5 Quantity<Meters, double> distance;
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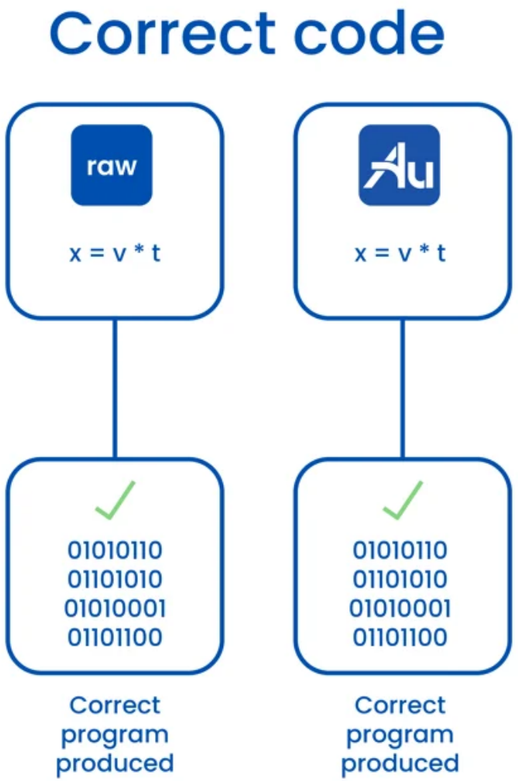

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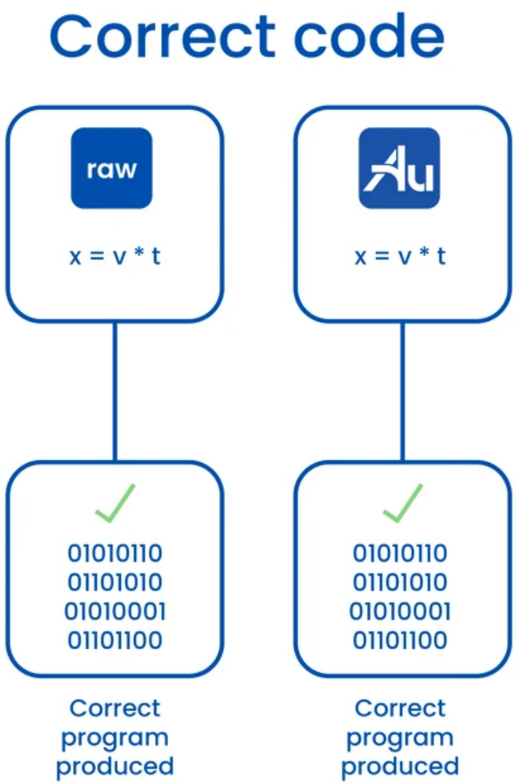

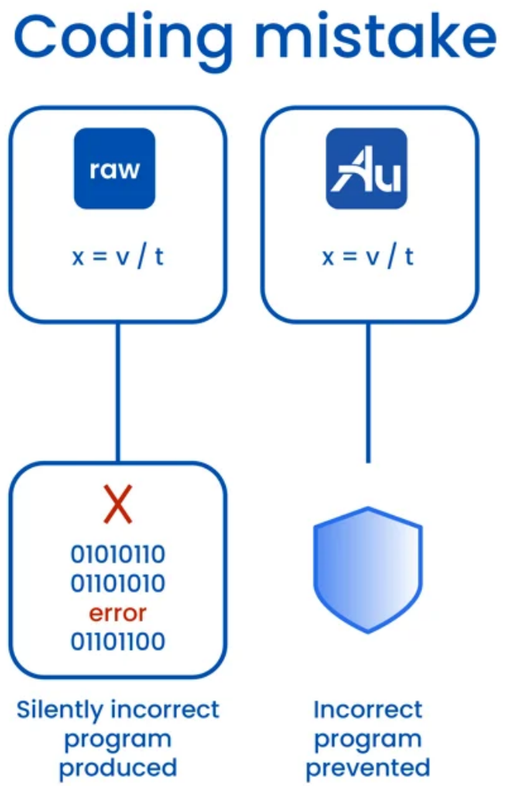

Aurora Innovation

Aurora Innovation

Flashback: CppCon 2021

A taste of Au

Example: time to goal

Example: time to goal

No units library

```
const double dist_to_goal_m = 30.0;
const double speed_mph = 25.0;
const double speed_mps =
  speed_mph * MPS_PER_MPH;
const double time_to_goal_s =
  dist_to_goal_m / speed_mps;
```

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```
// unit_conversions.hh
constexpr auto CM_PER_MI =
  2.54 * 12.0 * 5280.0;
constexpr auto M_PER_MI =
  CM_PER_MI / 100.0;
constexpr auto S_PER_H = 3600.0;

constexpr auto MPS_PER_MPH =
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```

Au

```
const auto dist_to_goal = meters(30.0);
const auto speed = (miles / hour)(25.0);


const auto time_to_goal =
  (dist_to_goal / speed).as(seconds);
```

Example: “CPU ticks” time units

```
1 constexpr uint64_t CPU_CLOCK_HZ = 400'000'000;
2
3 // API to implement:
4 std::chrono::nanoseconds elapsed_time(uint64_t num_cpu_ticks);
```

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```

```
1 std::chrono::nanoseconds elapsed_time(uint64_t num_cpu_ticks) {
2     using NS_PER_TICK = std::ratio<1'000'000'000, CPU_CLOCK_HZ>;
3     return std::chrono::nanoseconds{
4         num_cpu_ticks * NS_PER_TICK::num / NS_PER_TICK::den
5     };
6 }
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```

```
std::chrono::nanoseconds elapsed_time(uint64_t num_cpu_ticks) {
    constexpr auto cpu_ticks = inverse(hertz * mag<CPU_CLOCK_HZ>());
    return cpu_ticks(num_cpu_ticks).as(nano(seconds));
}
```

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```

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// API to implement:
std::chrono::nanosecon
```

```
std::chrono::nanosecon
    using NS_PER_TICK
    return std::chrono
        num_cpu_ticks
    };
}
```

```
no_au::elapsed_time(unsigned long):
        lea     rax, [rdi+rdi*4]
        shr     rax
        ret
au::elapsed_time(unsigned long):
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```

Au: Interfaces and Idioms

Au: Interfaces and Idioms

```
Quantity<Meters, T>

T value_;
```

Au: Interfaces and Idioms

```
T x = 1.75;
```

```
Quantity<Meters, T>

T value_;
```

Au: Interfaces and Idioms

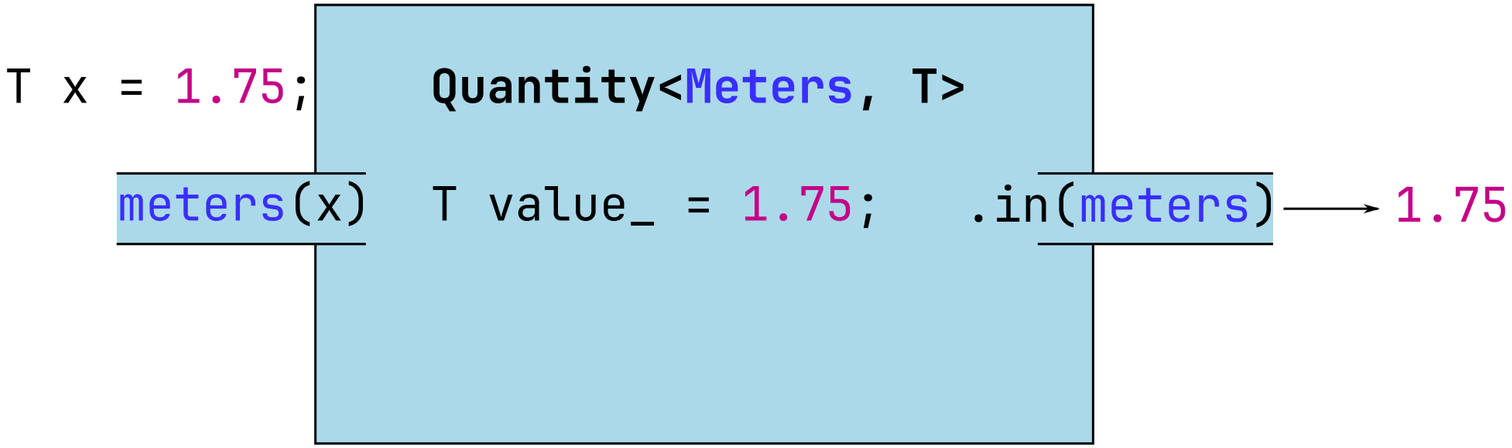
```
T x = 1.75;
```

```
meters(x)
```

```
Quantity<Meters, T>

T value_ = 1.75;
```

Au: Interfaces and Idioms



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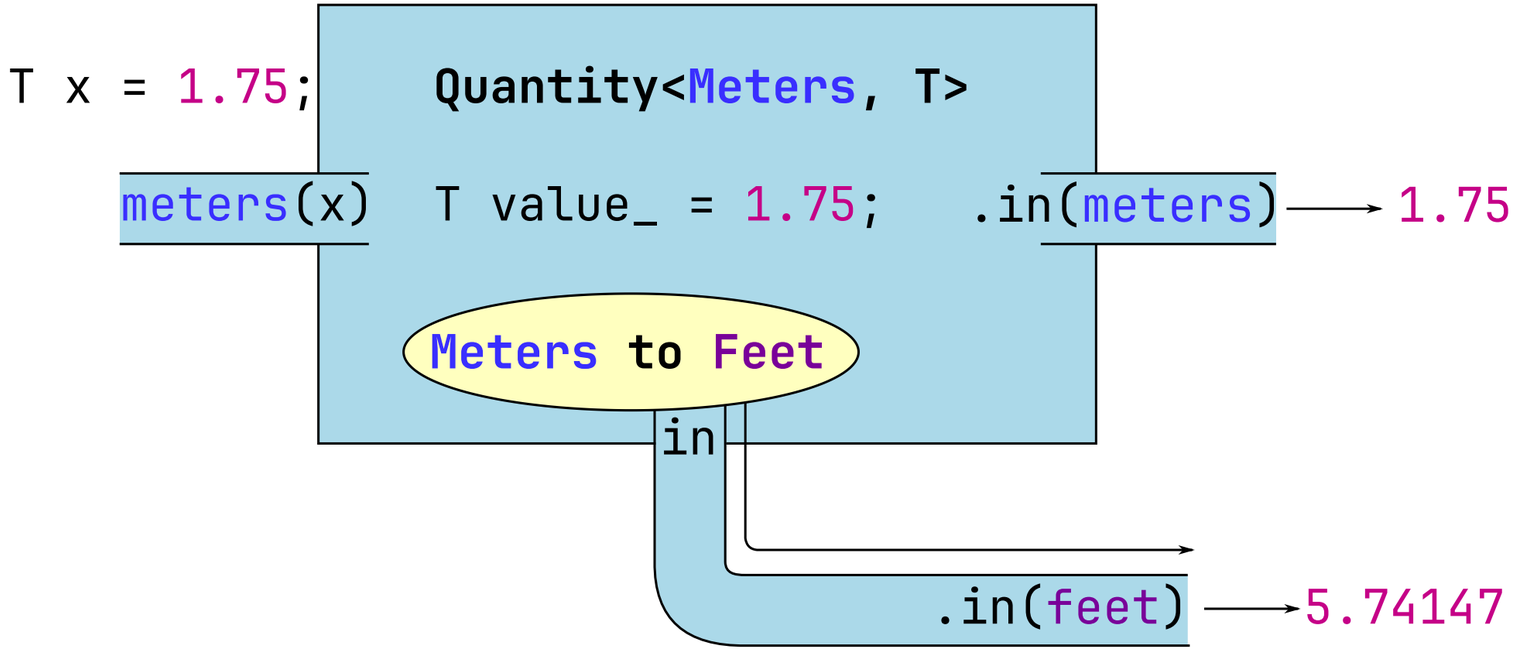

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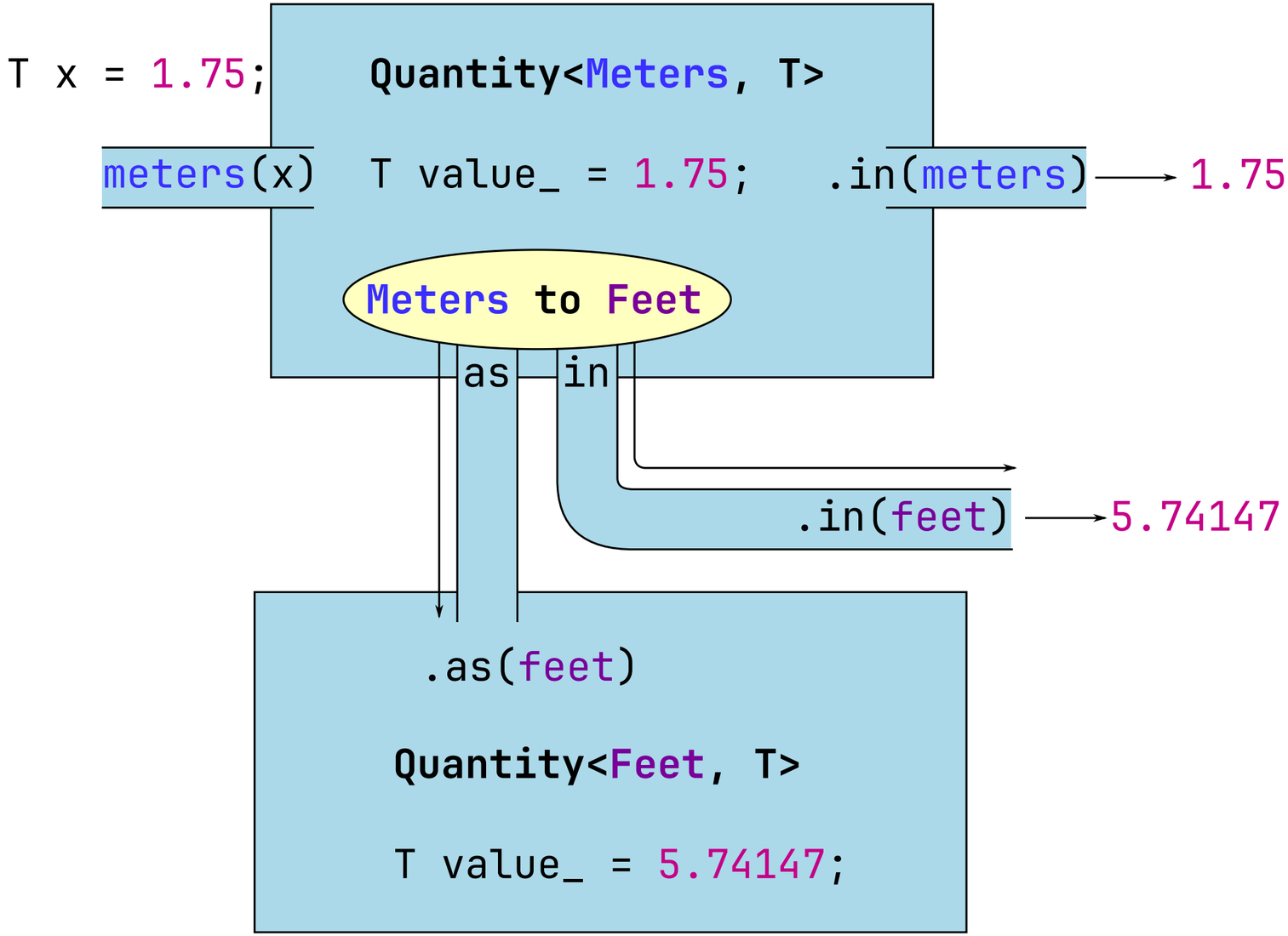

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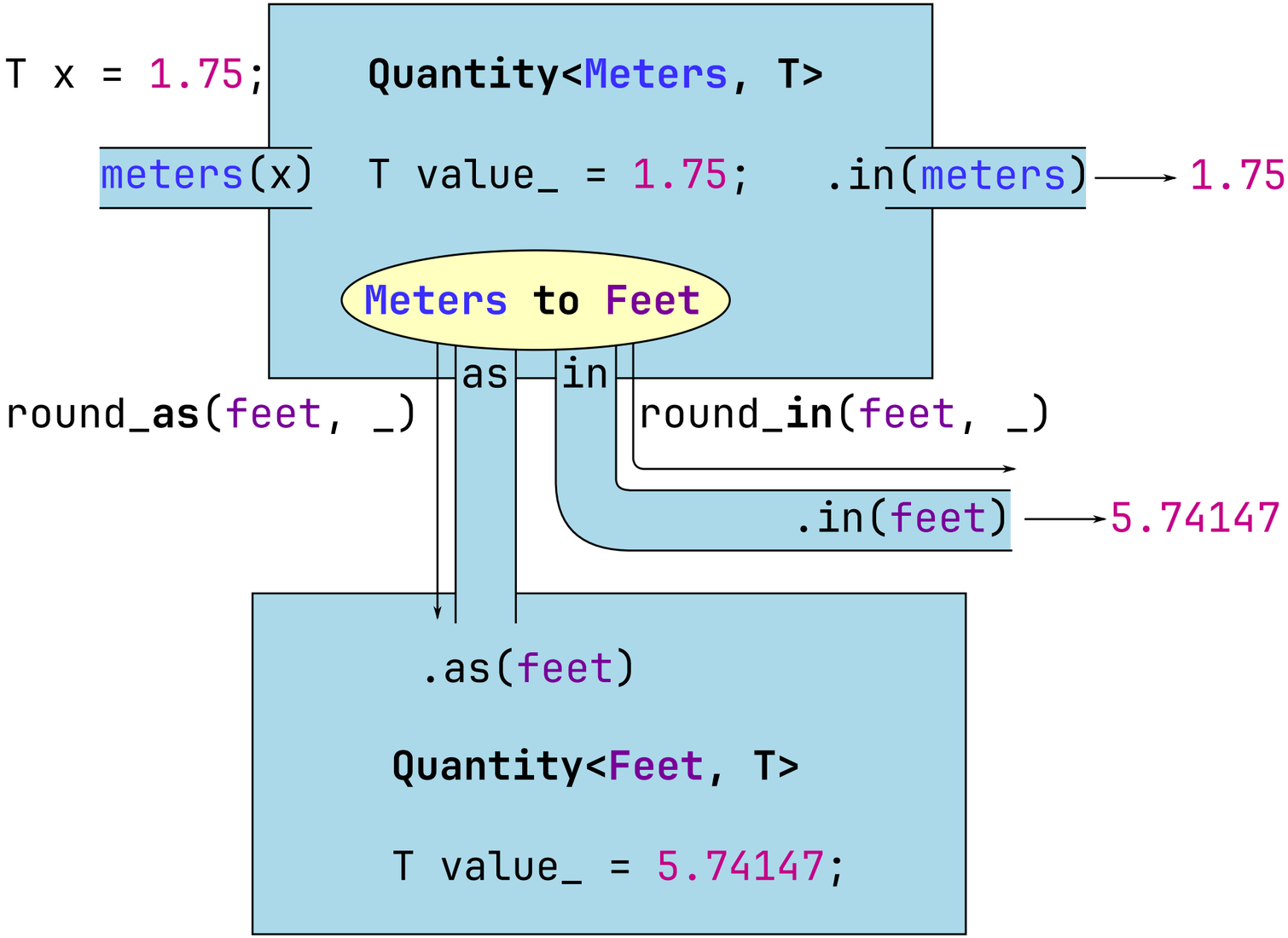

Au: learning more

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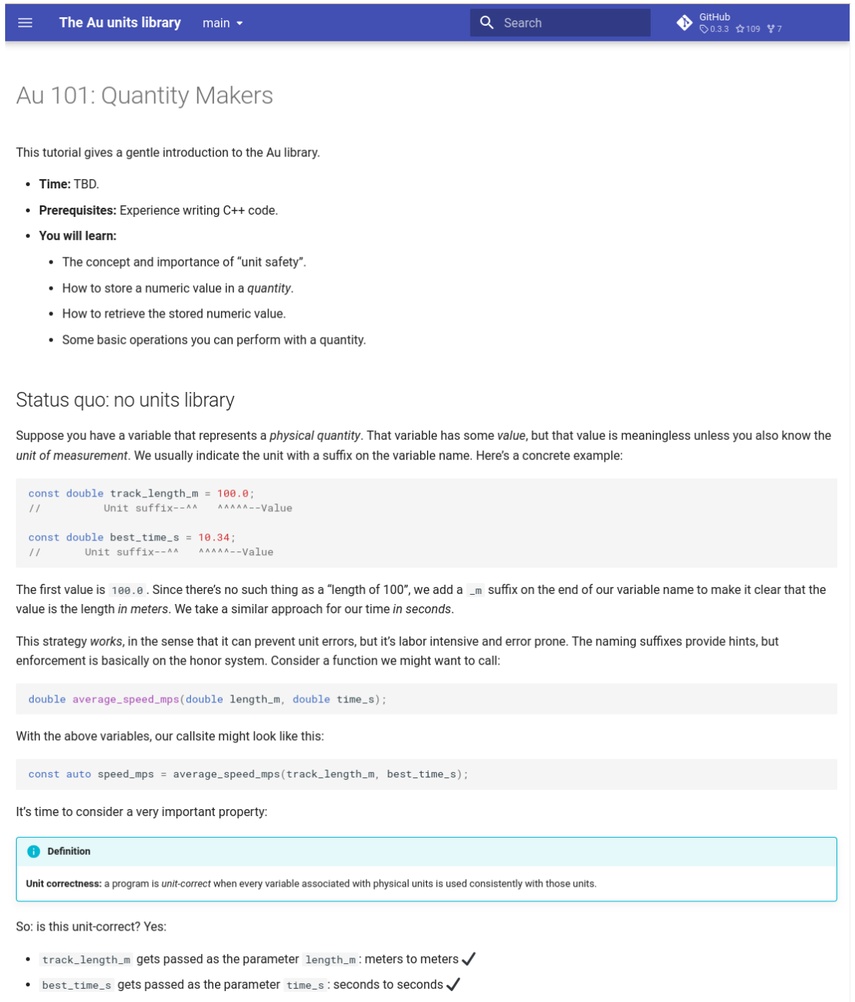


The Au units library main Search GitHub 0.3.3 109 7

Au 101: Quantity Makers

This tutorial gives a gentle introduction to the Au library.

- **Time:** TBD.
- **Prerequisites:** Experience writing C++ code.
- **You will learn:**
  - The concept and importance of "unit safety".
  - How to store a numeric value in a *quantity*.
  - How to retrieve the stored numeric value.
  - Some basic operations you can perform with a quantity.

Status quo: no units library

Suppose you have a variable that represents a *physical quantity*. That variable has some *value*, but that value is meaningless unless you also know the *unit of measurement*. We usually indicate the unit with a suffix on the variable name. Here's a concrete example:

```
const double track_length_m = 100.0;
//          Unit suffix--^^   ^^^^^--Value

const double best_time_s = 10.34;
//       Unit suffix--^^   ^^^^^--Value
```

The first value is `100.0`. Since there's no such thing as a "length of 100", we add a `_m` suffix on the end of our variable name to make it clear that the value is the length *in meters*. We take a similar approach for our time *in seconds*.

This strategy *works*, in the sense that it can prevent unit errors, but it's labor intensive and error prone. The naming suffixes provide hints, but enforcement is basically on the honor system. Consider a function we might want to call:

```
double average_speed_mps(double length_m, double time_s);
```

With the above variables, our callsite might look like this:

```
const auto speed_mps = average_speed_mps(track_length_m, best_time_s);
```

It's time to consider a very important property:

Definition

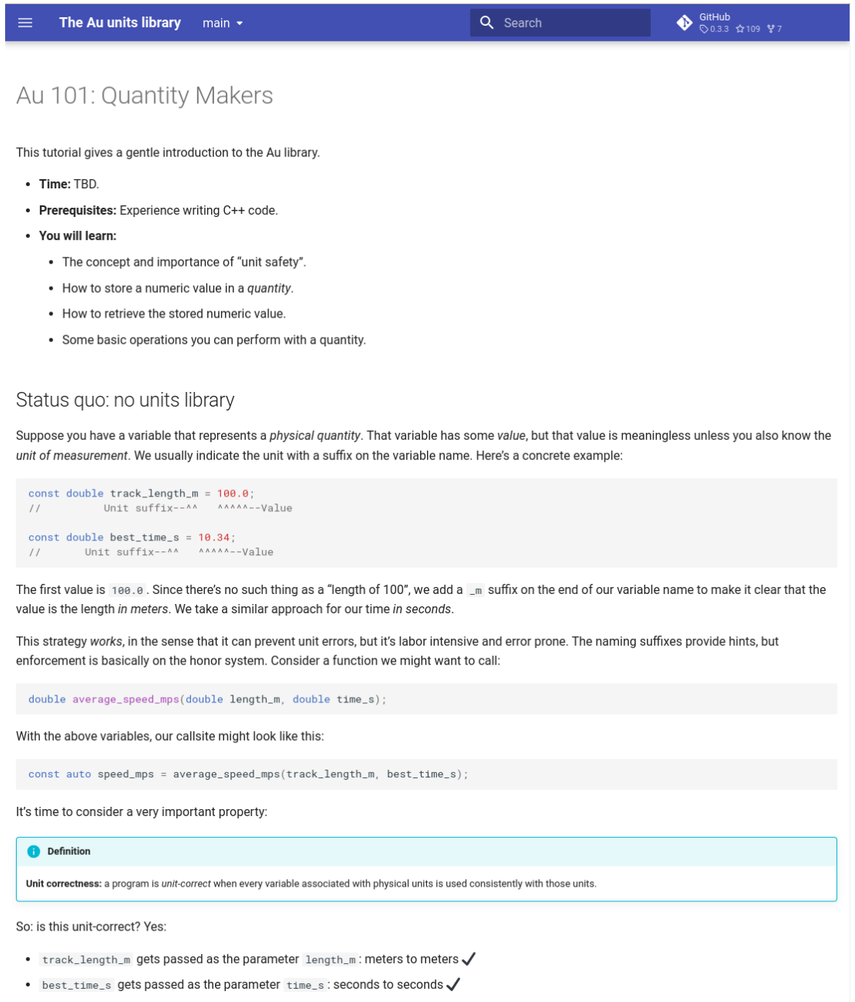
Unit correctness: a program is *unit-correct* when every variable associated with physical units is used consistently with those units.

So: is this unit-correct? Yes:

- `track_length_m` gets passed as the parameter `length_m`: meters to meters ✓
- `best_time_s` gets passed as the parameter `time_s`: seconds to seconds ✓

https://aurora-opensource.github.io/au/main/**tutorial/**

Au: learning more



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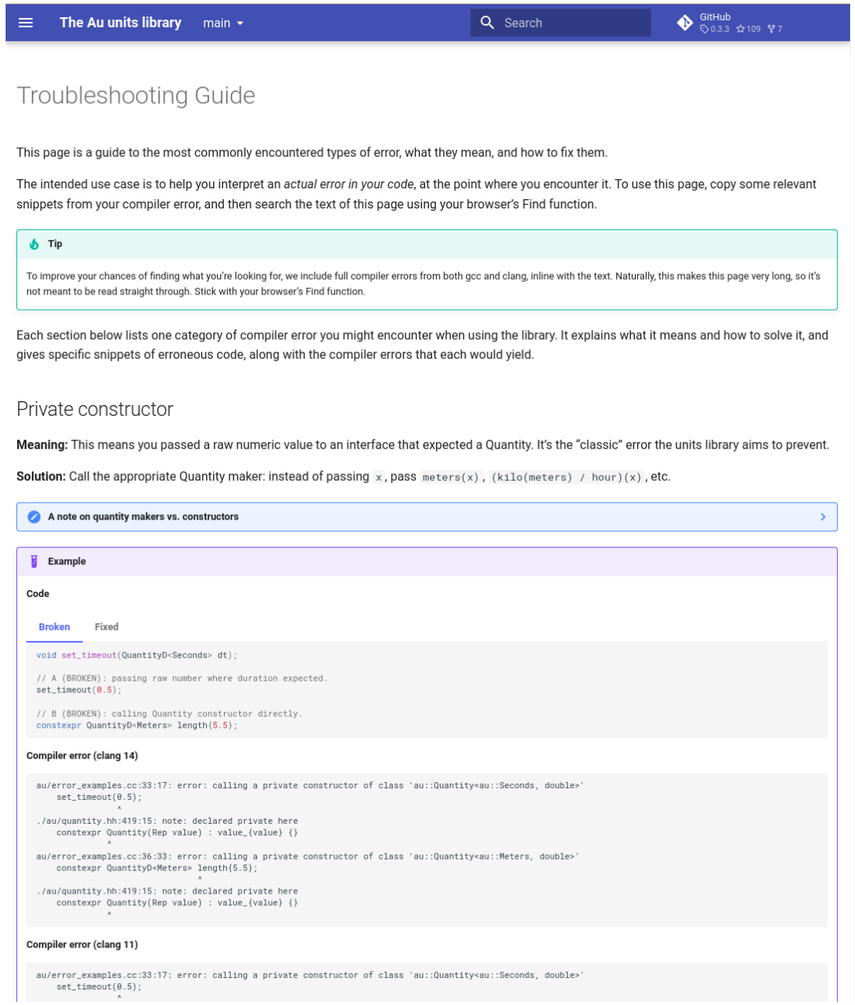


https://aurora-opensource.github.io/au/main/**troubleshooting/**

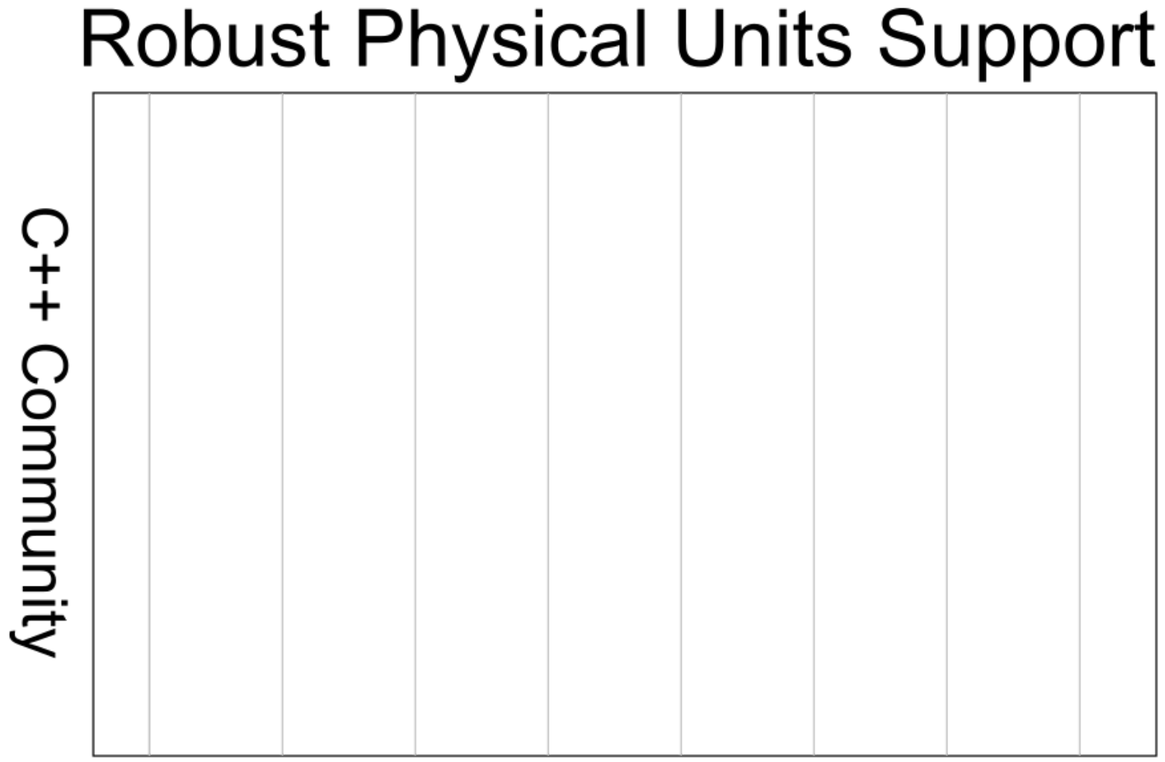
C++ Units: the goal

All of the people, all of the time

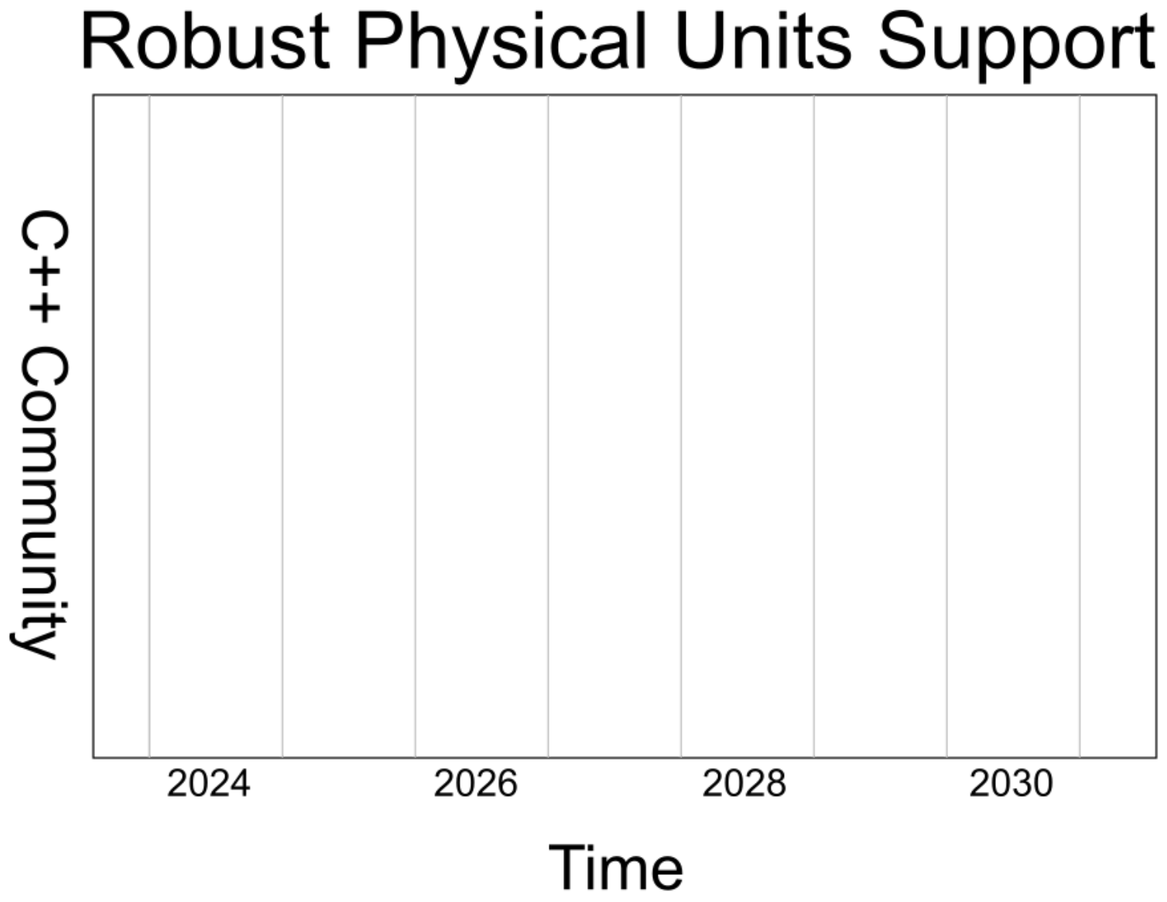
All of the people, all of the time

Robust Physical Units Support

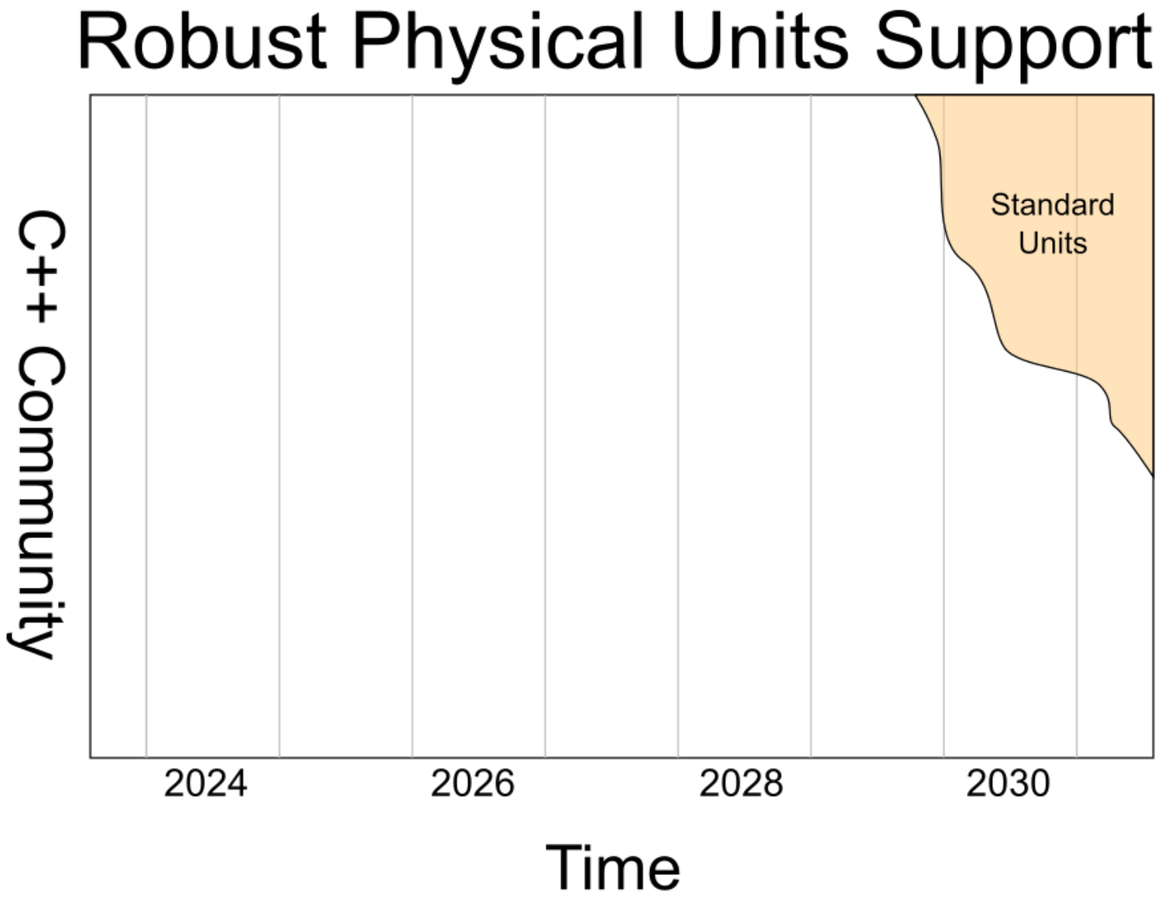
All of the people, all of the time



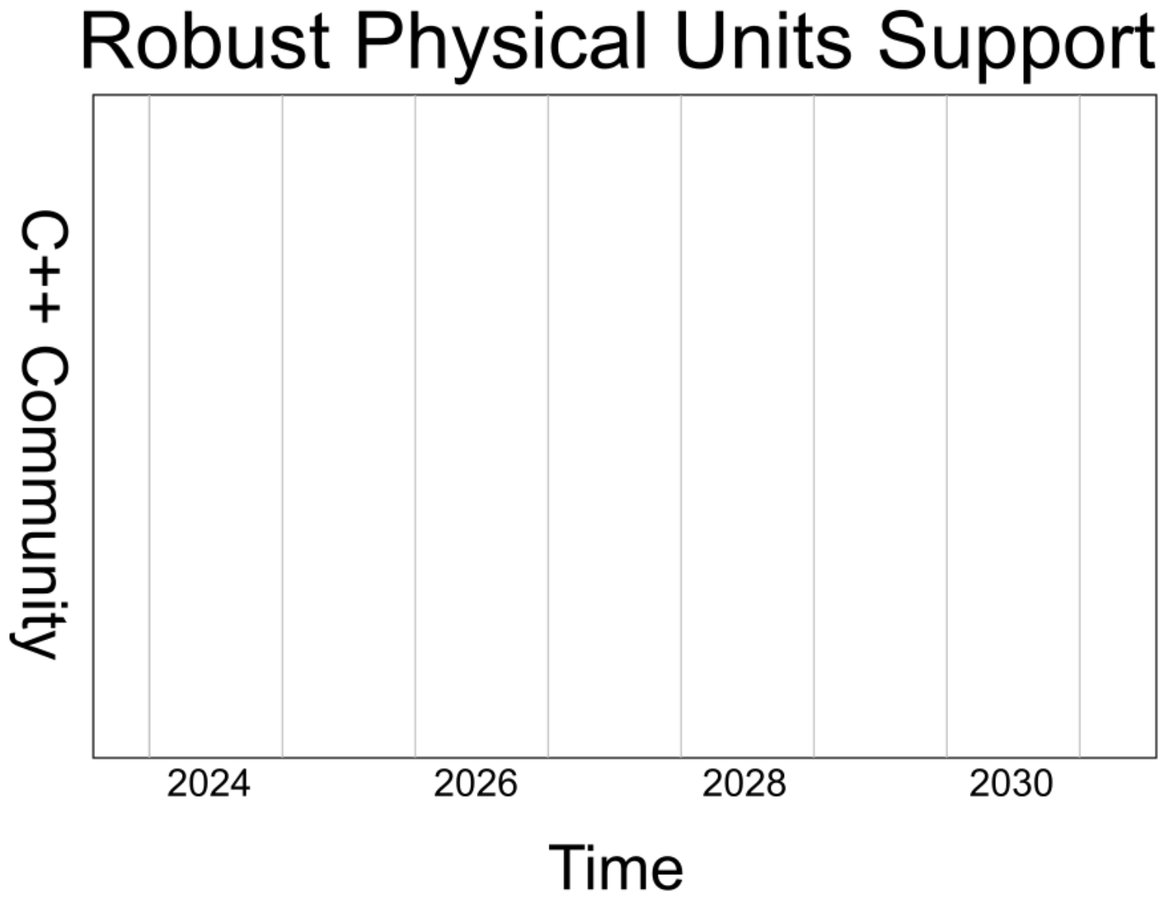
All of the people, all of the time



Standard units library?



The C++ Units Library Ecosystem



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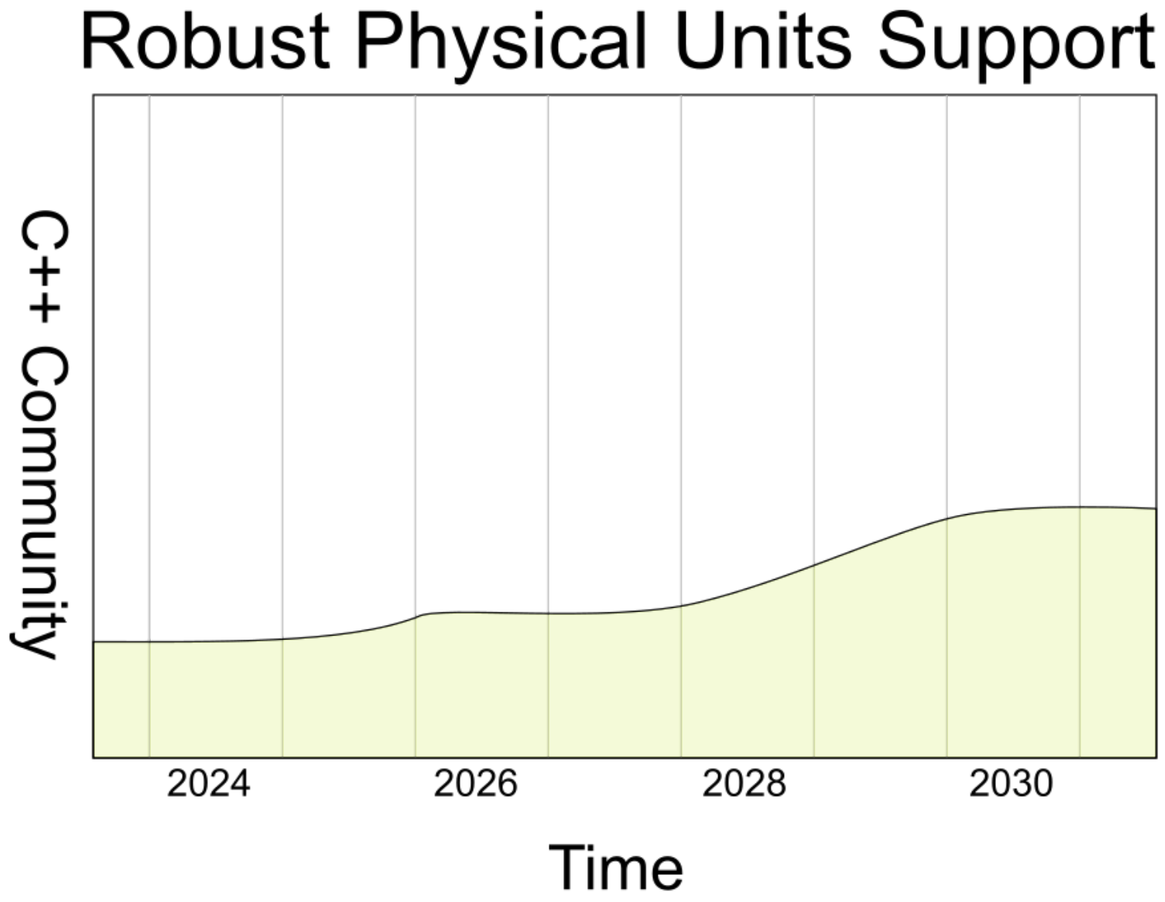

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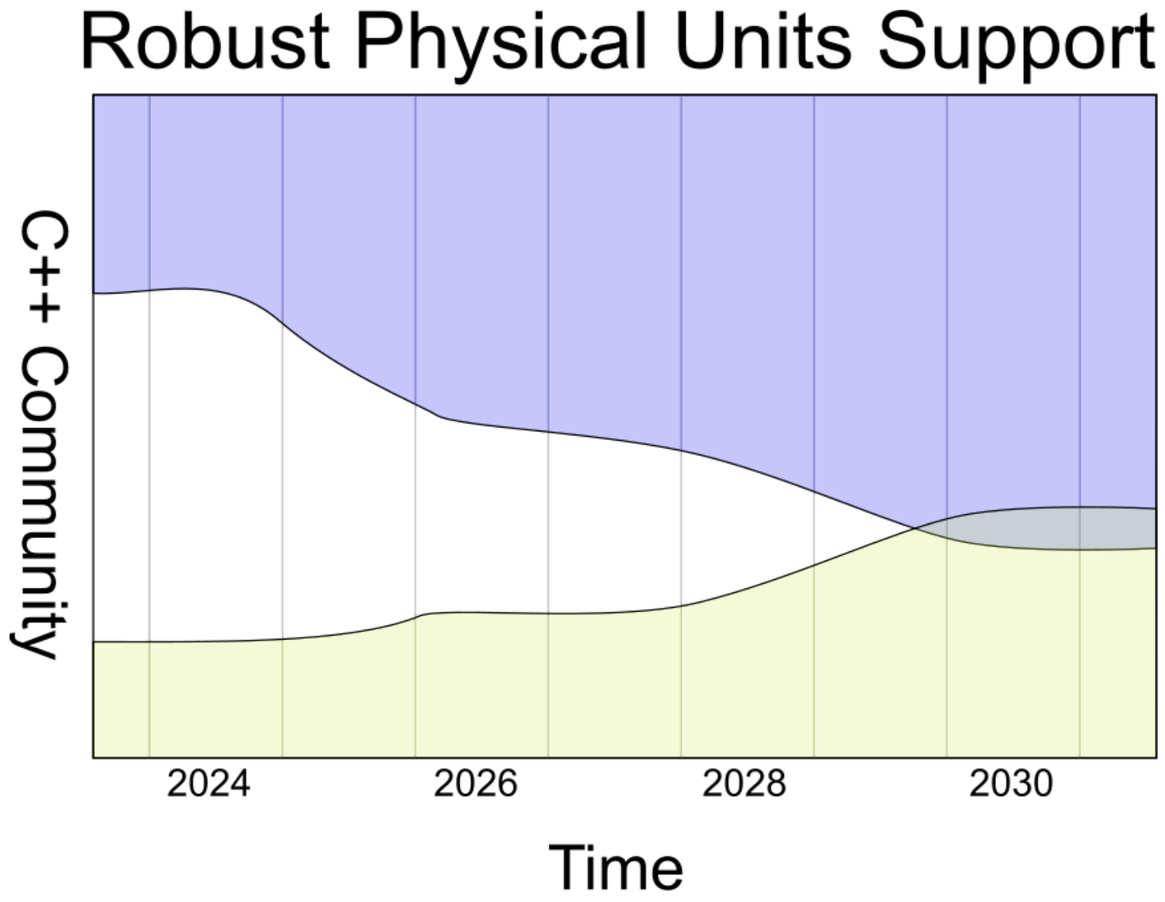

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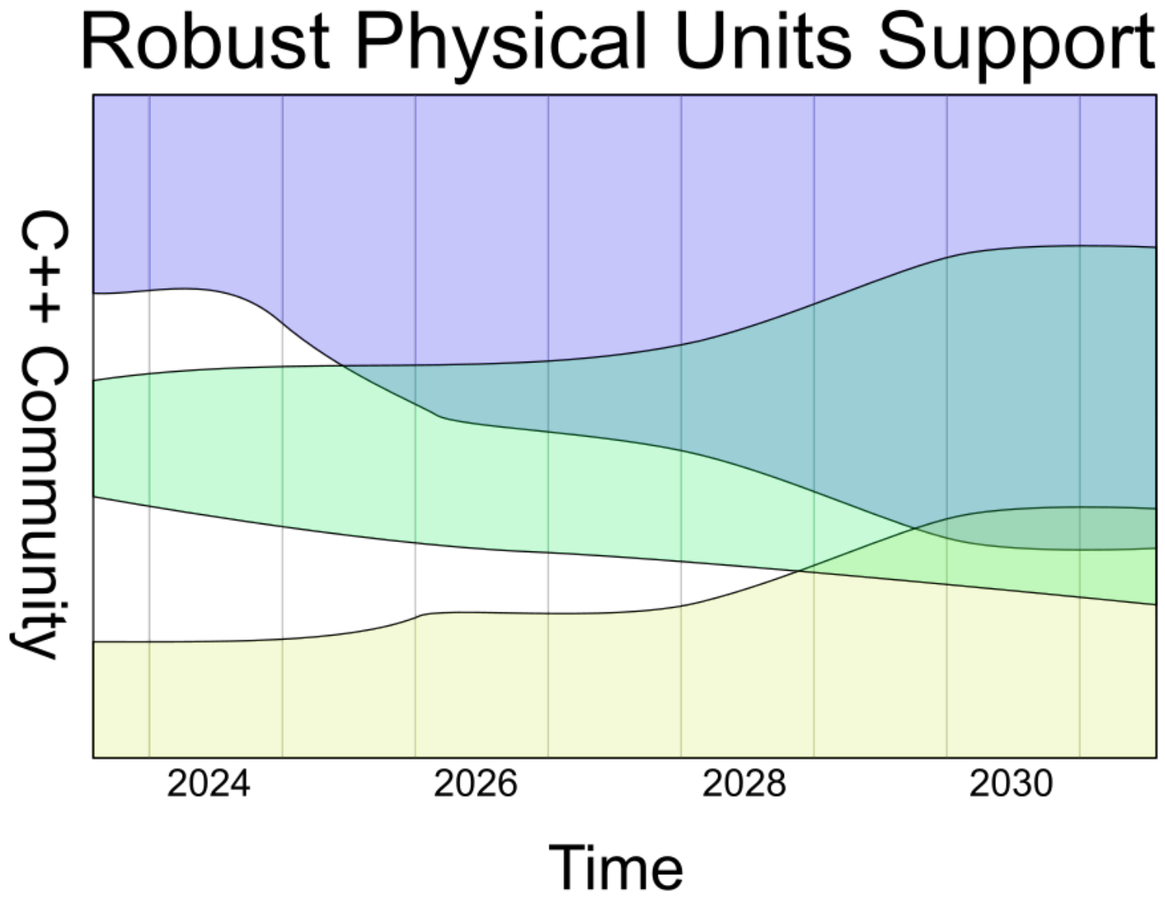

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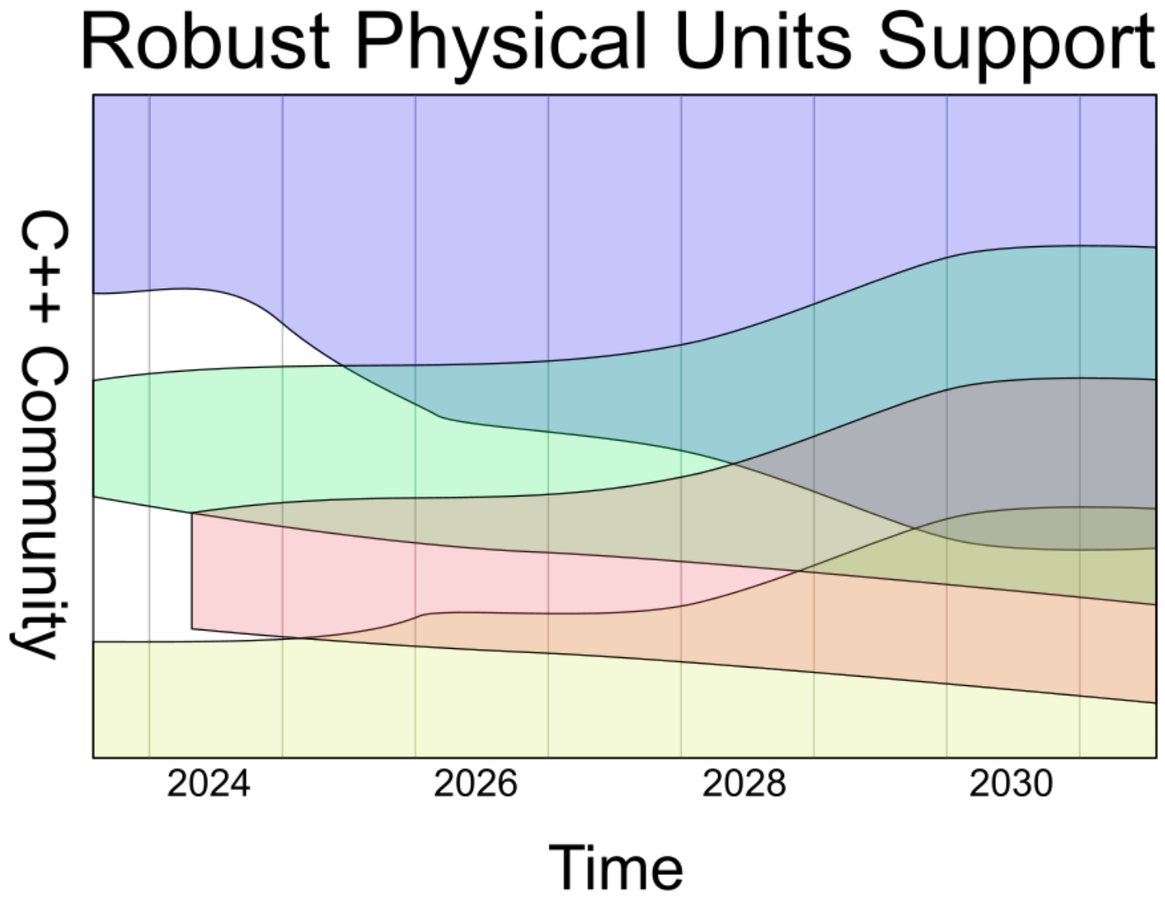

Choosing
a Units Library

Framework for Choosing

Framework for Choosing

1. **Can you get it** in your project?

Framework for Choosing

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2. What does it **cost**, in terms of **developer experience**?

Framework for Choosing

1. **Can you get it** in your project?
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3. What "units library specific" features does it have?

Full comparison

https://aurora-opensource.github.io/au/main/**alternatives/**

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1. Can you get it?

	Boost	nholthaus	bernedom/SI	mp-units	Au
C++ Version Compatibility	C++98	C++14	C++17	C++20	C++14
Ease of Acquisition	Part of boost	Single, self-contained header	Available on conan	Available on conan and vcpkg	Supports single-header delivery, with features: ✓ Easy to customize units and I/O support ✓ Version-stamped for full reproducibility

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Compilation Speed	(Not assessed)	Very slow, but can be *greatly* improved by removing I/O support and most units	(Not assessed)	(Not assessed)	Possibly "best", but will need to assess all libraries on the same code
Compiler Error Readability	Infamously challenging	Positional dimensions	Alias for unit template	✓ Pioneered strong typedefs for units ✓ Expression templates produce very readable errors	✓ Strong unit typenames appear in errors ✓ Short namespace minimizes clutter ✓ Detailed troubleshooting guide

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3. "Units library specific" features:

Au and alternatives

Libraries considered

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Libraries considered

Library Name	GitHub repo
bc C++ L	
nholt	
	

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a) C++ standard compatibility

C++ Version	Example features
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C++17	Fold expressions `constexpr` if
C++14	More permissive `constexpr` `auto` return type
C++11	Primitive `constexpr` Variadic templates `static_assert`
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Legend: “C++ version is (fully / partially / not-at-all) supported in project.”

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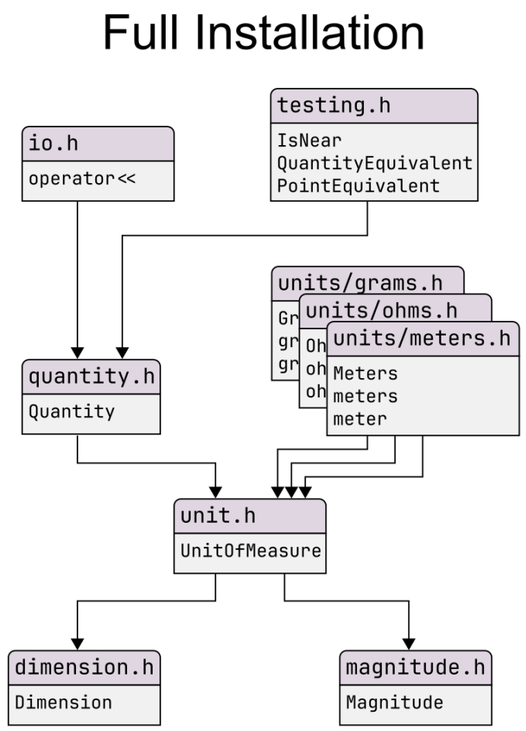
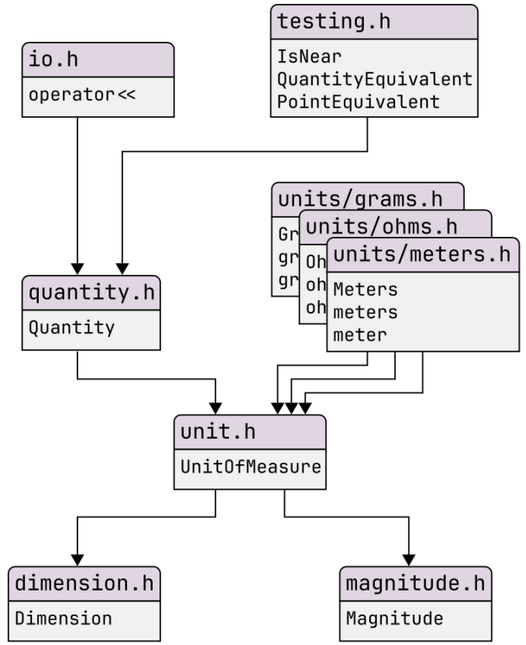
b) Delivery mechanism

1. Can you get it?
b) Delivery mechanism

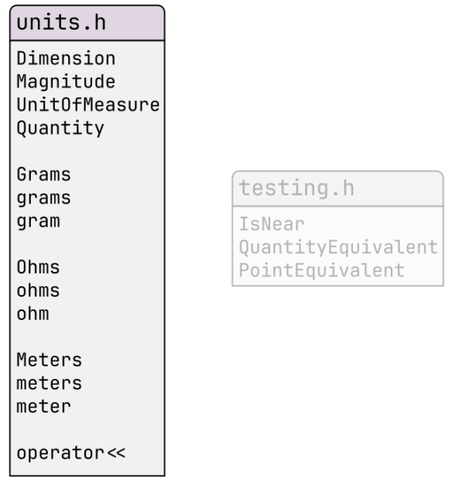


1. Can you get it?
b) Delivery mechanism

Full Installation

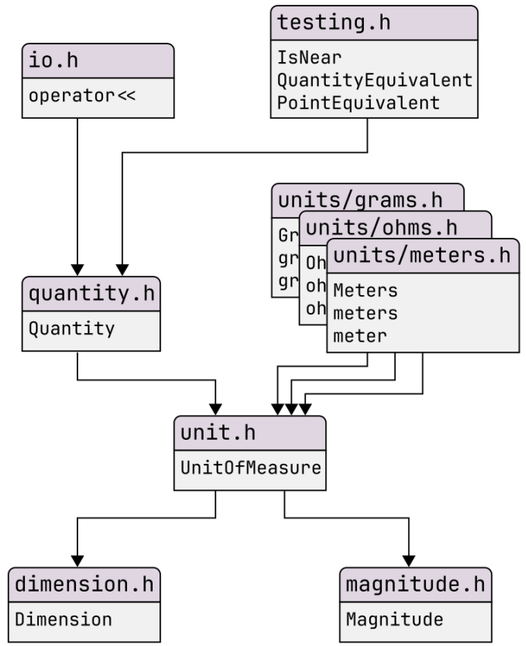


Single File



1. Can you get it?
b) Delivery mechanism

Full Installation



boost C++ LIBRARIES

mp-units

Single File

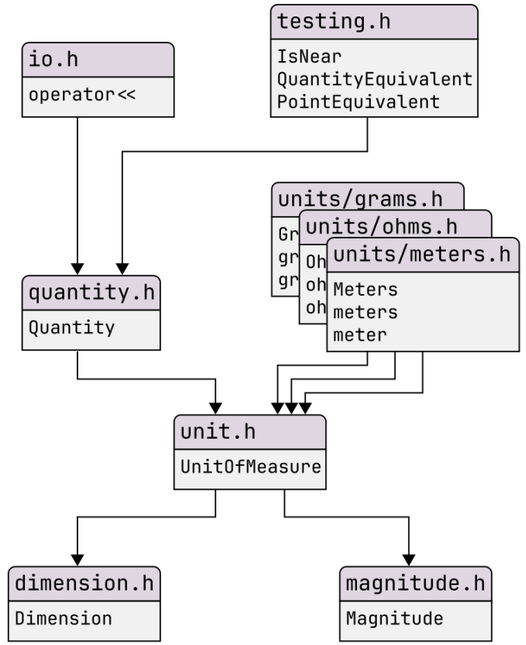
```
units.h
Dimension
Magnitude
UnitOfMeasure
Quantity

Grams
grams
gram

Ohms
ohms
ohm

Meters
meters
meter

operator<<
```

```
testing.h
IsNear
QuantityEquivalent
PointEquivalent
```

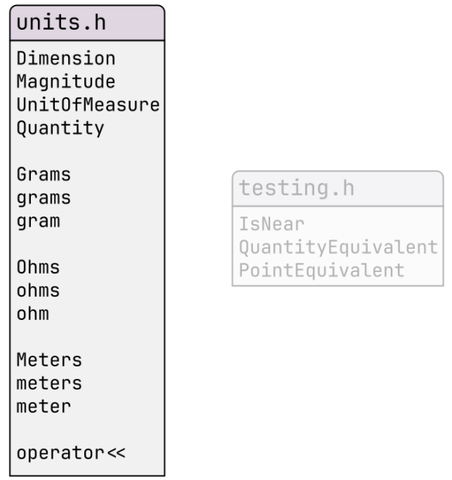
nholthaus

1. Can you get it?
b) Delivery mechanism

Full Installation



Single File



boost C++ LIBRARIES

mp-units

nholthaus

1. Can you get it?
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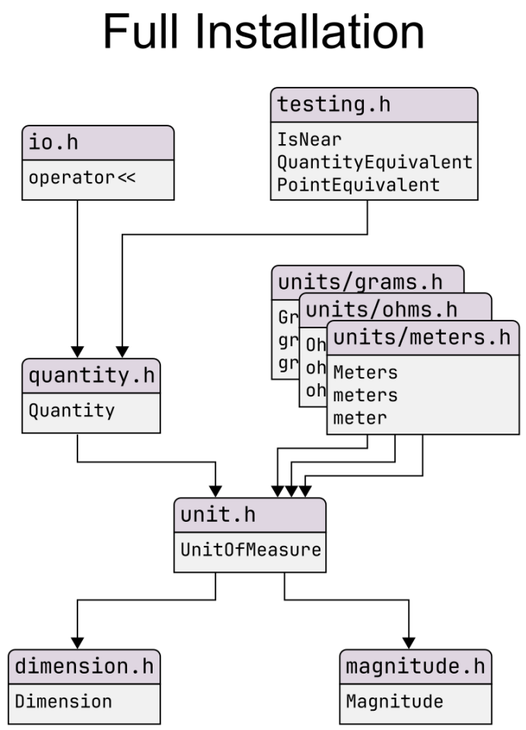


```
// Version identifier: 0.3.3
// <iostream> support: INCLUDED
// List of included units:
//   amperes
//   bits
//   candelas
//   grams
//   kelvins
//   meters
//   moles
//   radians
//   seconds
//   unos
```

boost C++ LIBRARIES

mp-units

nholthaus

2. DevEx cost? a) Compile times

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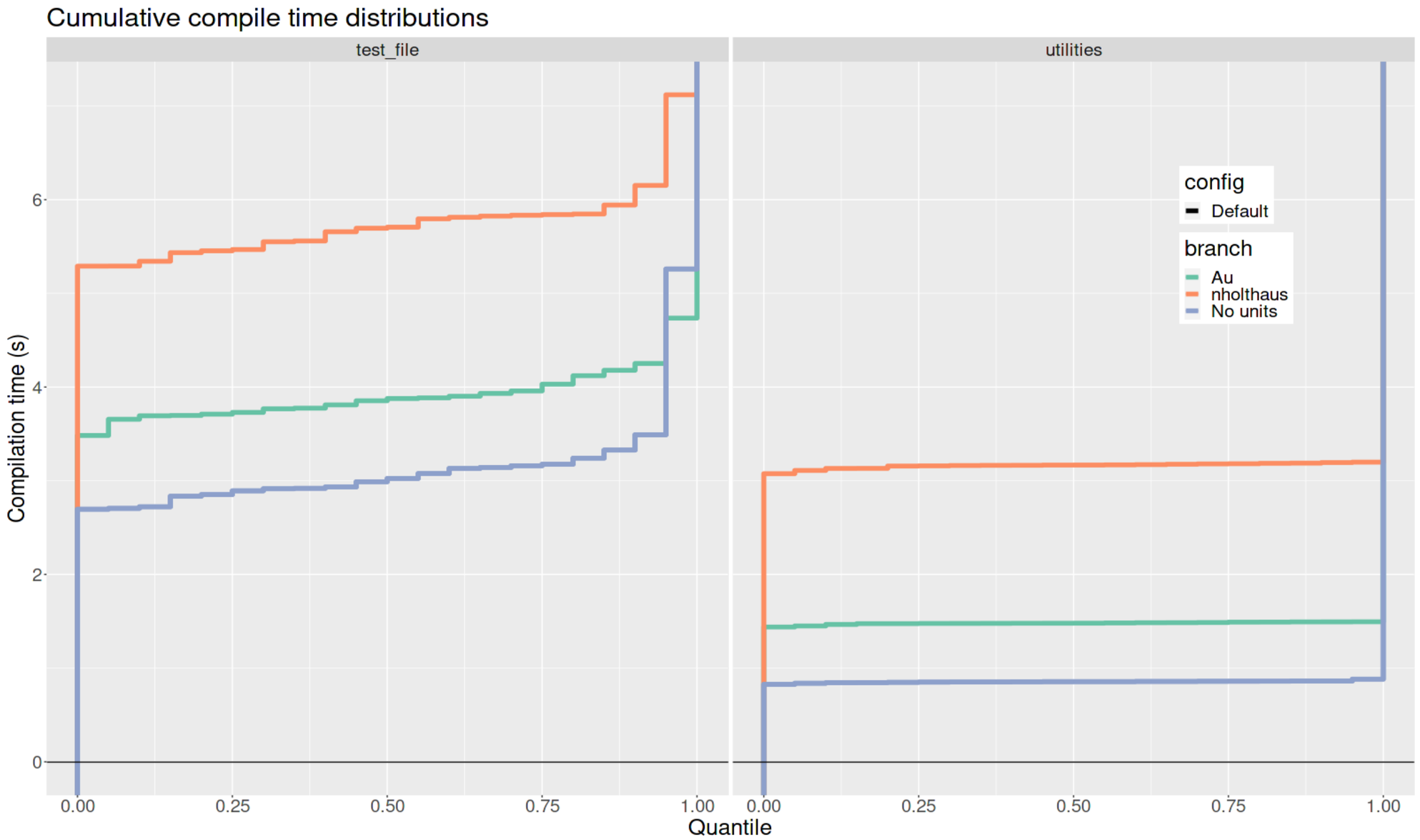
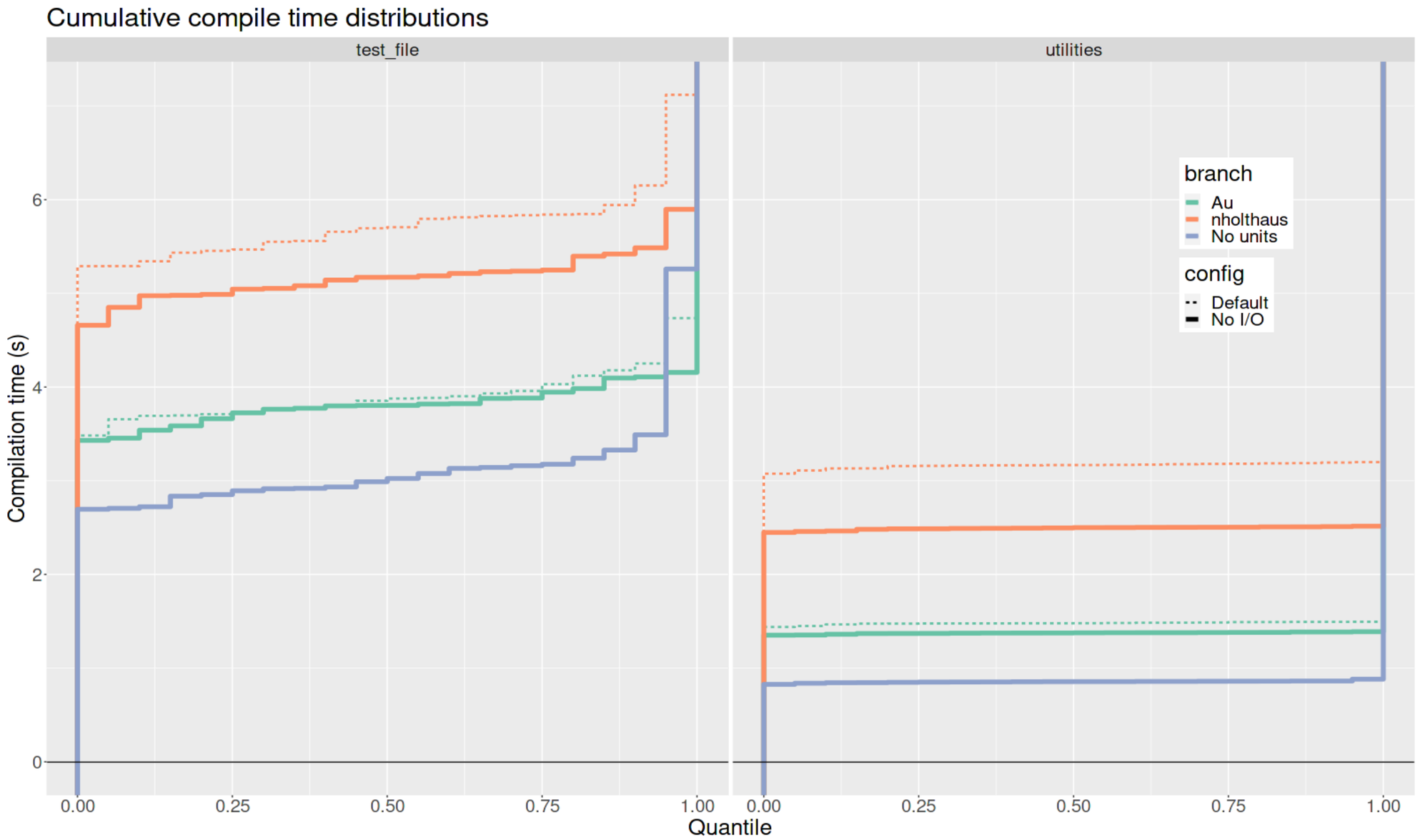


2. DevEx cost? a) Compile times



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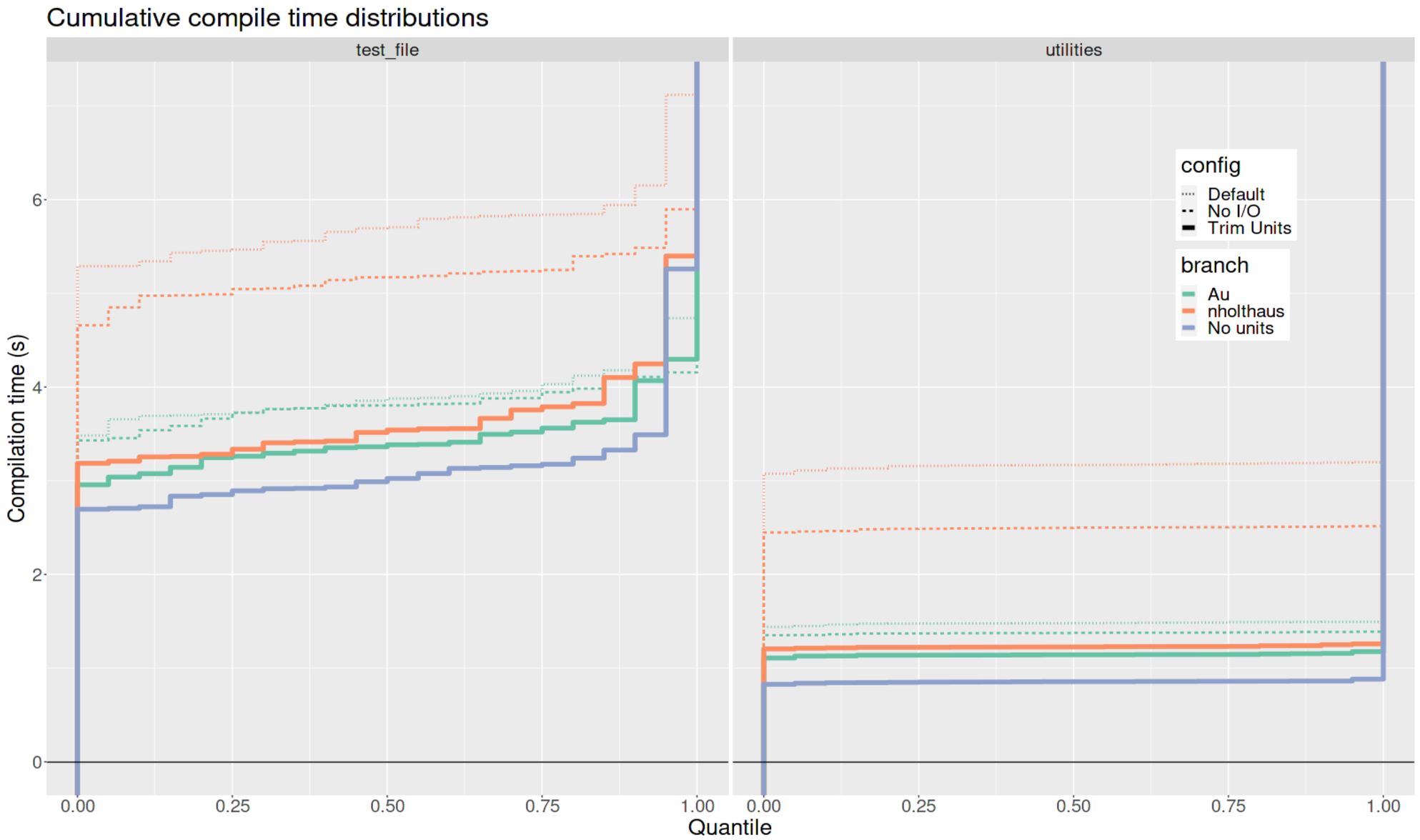

2. DevEx cost? b) Compiler errors

2. DevEx cost? b) Compiler errors

Code:

```
boost::units::quantity<boost::units::si::velocity> v =
  (5 * boost::units::si::meters) * (1.0 * boost::units::si::seconds);
```

Error:

```
x86-64 gcc 7.1

<Compilation failed>

<source>: In function 'int main(int, char**)':
<source>:9:38: error: conversion from
'boost::units::multiply_typeof_helper<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,
```

2. DevEx cost? b) Compiler errors

`nholthaus`

Code:

```
units::velocity::meters_per_second_t v =
  units::length::meter_t{5.0} * units::time::second_t{1.0};
```

Error:

```
x86-64 gcc 7.1

<Compilation failed>

In file included from <source>:3:0:
/app/raw.githubusercontent.com/nholthaus/units/master/include/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]':
/app/raw.githubusercontent.com/nholthaus/units/master/include/units.h:1976:41:
required from 'constexpr units::unit_t<Units, T, NonLinearScale>::unit_t(const
```

2. DevEx cost? b) Compiler errors

`mp-units`

Code:

```
quantity<si::metre / si::second> v1 = (5.0 * m) * (1.0 * s);
```

Error:

```
x86-64 gcc 13.1

<Compilation failed>

<source>: In function 'int main()':
<source>:8:49: error: conversion from 'quantity<mp_units::derived_unit<
mp_units::si::metre, mp_units::si::second>(), [...]>'
to non-scalar type 'quantity<mp_units::derived_unit<
mp_units::si::metre, mp_units::per<mp_units::si::second> >(),[...]>' requested
    8 |   quantity<si::metre / si::second> v1 = (5 * m) * (1. * s);
      |                                         ~~~~~~~~^~~~~~~~~~
Compiler returned: 1
```

2. DevEx cost? b) Compiler errors

Code:

```
Quantity<decltype(Meters{} / Seconds{}), double> v = meters(5.0) * seconds(1.0);
```

Error:

```
x86-64 gcc 7.1

<Compilation failed>

<source>: In function 'int main(int, char**)':
<source>:9:70: error: conversion from
'au::Quantity<au::UnitProduct<au::Meters, au::Seconds>, double>' to non-scalar type
'au::Quantity<au::UnitProduct<au::Meters, au::Pow<au::Seconds, -1> >, double>'
requested
   Quantity<decltype(Meters{} / Seconds{}), double> v = meters(5.0) * seconds(1.0);
                                                        ~~~~~~~~~~~~~^~~~~~~~~~~~~~
Compiler returned: 1
```

Au: core features

Unit safety

*A program is "unit safe" when the correct handling of physical units can be verified in **each individual line**, by **inspection**, in **isolation**.*

Unit safety

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```
1 auto height = meters(1.87);
2 //              ^^^^^^
3
4
5
6
7
8
9
```

Unit safety

*A program is "unit safe" when the correct handling of physical units can be verified in **each individual line**, by **inspection**, in **isolation**.*

```
1 auto height = meters(1.87);
2 //              ^^^^^^
3
4 QuantityD<Joules> potential_energy = m * g * height;
5
6
7
8
9
```

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*A program is "unit safe" when the correct handling of physical units can be verified in **each individual line**, by **inspection**, in **isolation**.*

```
1 auto height = meters(1.87);
2 //              ^^^^^^
3
4 QuantityD<Joules> potential_energy = m * g * height;
5
6 const bool can_fit = (height < clearance);
7
8
9
```

Unit safety

*A program is "unit safe" when the correct handling of physical units can be verified in **each individual line**, by **inspection**, in **isolation**.*

```
auto height = meters(1.87);
//            ^^^^^^
QuantityD<Joules> potential_energy = m * g * height;

const bool can_fit = (height < clearance);

proto.set_height_m(height.in(meters));
//                 ^           ^^^^^^
```

Same program, only safer

Same program, only safer

(No units library)

```
int degrees_per_second_from_rpm(int rpm) {
  return rpm * 6; // Magic number!
}
```

Same program, only safer

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```
int degrees_per_second_from_rpm(int rpm) {
  return rpm * 6; // Magic number!
}
```

nholthaus

```
int degrees_per_second_from_rpm(int rpm) {
  return degrees_per_second_t{revolutions_per_minute_t{rpm}}.to<int>();
}
```

Same program, only safer

(No units library)

```
int degrees_per_second_from_rpm(int rpm) {
  return rpm * 6; // Magic number!
}
```

nholthaus

```
int degrees_per_second_from_rpm(int rpm) {
  return degrees_per_second_t{revolutions_per_minute_t{rpm}}.to<int>();
}
```


```
int degrees_per_second_from_rpm(int rpm) {
  return (revolutions / minute)(rpm).in(degrees / second);
}
```

Same program, only safer

(No units library)

```
int degrees_per_second_from_rpm(int rpm) {
  return rpm * 6; // Magic number!
}
```

```
no_units::degrees_per_second_from_rpm(int):
        lea     eax, [rdi+rdi*2]
        add     eax, eax
        ret
```

nholthaus

```
int degrees_per_second_from_rpm(int rpm) {
  return degrees_per_second_t{revolutions_per_minute_t{rpm}}.to<int>();
}
```

```
nholthaus::degrees_per_second_from_rpm(int):
        pxor    xmm0, xmm0
        cvtsi2sd        xmm0, edi
        mulsd   xmm0, QWORD PTR .LC0[rip]
        cvttsd2si       eax, xmm0
        ret
```


```
int degrees_per_second_from_rpm(int rpm) {
  return (revolutions / minute)(rpm).in(degrees / second);
}
```

```
with_au::degrees_per_second_from_rpm(int):
        lea     eax, [rdi+rdi*2]
        add     eax, eax
        ret
```

Same program, only safer

(No units library)

```
int degrees_per_second_from_rpm(int rpm) {
  return rpm * 6; // Magic number!
}
```

```
no_units::degrees_per_second_from_rpm(int):
        sll     $2,$4,1
        addu    $2,$2,$4
        jr      $31
        sll     $2,$2,1
```

nholthaus

```
int degrees_per_second_from_rpm(int rpm) {
  return degrees_per_second_t{revolutions_per_minute_t{rpm}}.to<int>();
}
```

```
nholthaus::degrees_per_second_from_rpm(int):
        addiu   $sp,$sp,-32
        sw      $31,28($sp)
        jal     __floatsidf
        nop

        lui     $4,%hi($LC0)
        lw      $7,%lo($LC0+4)($4)
        lw      $6,%lo($LC0)($4)
        move    $5,$3
        move    $4,$2
        jal     __muldf3
        nop

        move    $5,$3
        move    $4,$2
        jal     __fixdfsi
        nop

        lw      $31,28($sp)
        nop
        jr      $31
        addiu   $sp,$sp,32
```


```
int degrees_per_second_from_rpm(int rpm) {
  return (revolutions / minute)(rpm).in(degrees / second);
}
```

```
with_au::degrees_per_second_from_rpm(int):
        sll     $2,$4,1
        addu    $2,$2,$4
        jr      $31
        sll     $2,$2,1
```

Conversion safety

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3
4
5
6
7
8
9
```

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3 auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms
4
5
6
7
8
9
```

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3 auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms
4
5 // Does not compile!
6 // auto dt_min = std::chrono::minutes{dt_s};
7
8
9
```

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3 auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms
4
5 // Does not compile!
6 // auto dt_min = std::chrono::minutes{dt_s};
7
8 using chrono_minutes_double = std::chrono::duration<double, std::ratio<60>>;
9
```

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3 auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms
4
5 // Does not compile!
6 // auto dt_min = std::chrono::minutes{dt_s};
7
8 using chrono_minutes_double = std::chrono::duration<double, std::ratio<60>>;
9 auto dt_min = chrono_minutes_double{dt_s}; // 0.5 min
```

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3 auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms
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7
8 using chrono_minutes_double = std::chrono::duration<double, std::ratio<60>>;
9 auto dt_min = chrono_minutes_double{dt_s}; // 0.5 min
```

```
using nanos_u32 = std::chrono::duration<uint32_t, std::nano>;
const auto five_sec = nanos_u32{std::chrono::seconds{5}}; // 0.705'032'704 s (!)
```

Conversion safety

```
1 auto dt_s = std::chrono::seconds{30};
2
3 auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms
4
5 // Does not compile!
6 // auto dt_min = std::chrono::minutes{dt_s};
7
8 using chrono_minutes_double = std::chrono::duration<double, std::ratio<60>>;
9 auto dt_min = chrono_minutes_double{dt_s}; // 0.5 min
```

```
using nanos_u32 = std::chrono::duration<uint32_t, std::nano>;
const auto five_sec = nanos_u32{std::chrono::seconds{5}}; // 0.705'032'704 s (!)
```


```
QuantityU32<Nano<Seconds>> dt = seconds(5);
```

Conversion safety

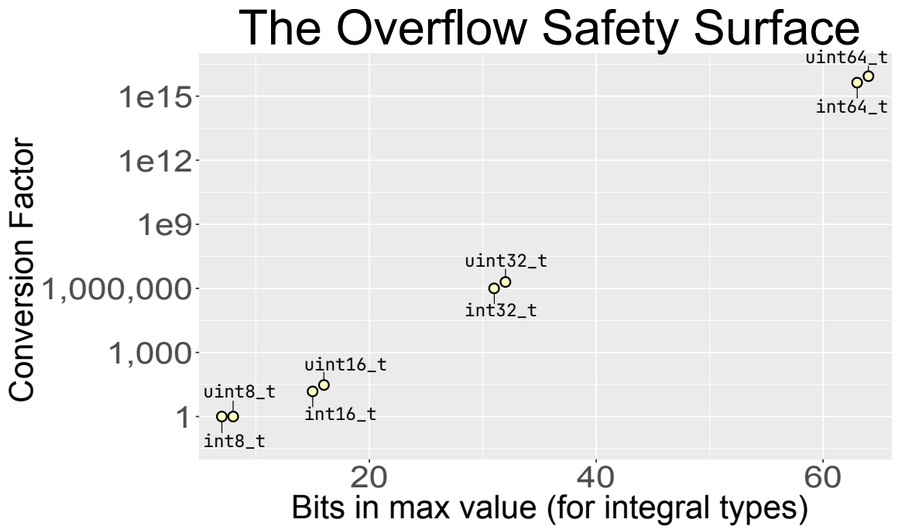
```cpp
auto dt_s = std::chrono::seconds{30};

auto dt_ms = std::chrono::milliseconds{dt_s}; // 30'000 ms

// Does not compile!
// auto dt_min = std::chrono::minutes{dt_s};

using chrono_minutes_double = std::chrono::duration<double, std::ratio<60>>;
auto dt_min = chrono_minutes_double{dt_s}; // 0.5 min
```

```cpp
using nanos_u32 = std::chrono::duration<uint32_t, std::nano>;
const auto five_sec = nanos_u32{std::chrono::seconds{5}}; // 0.705'032'704 s (!)
```

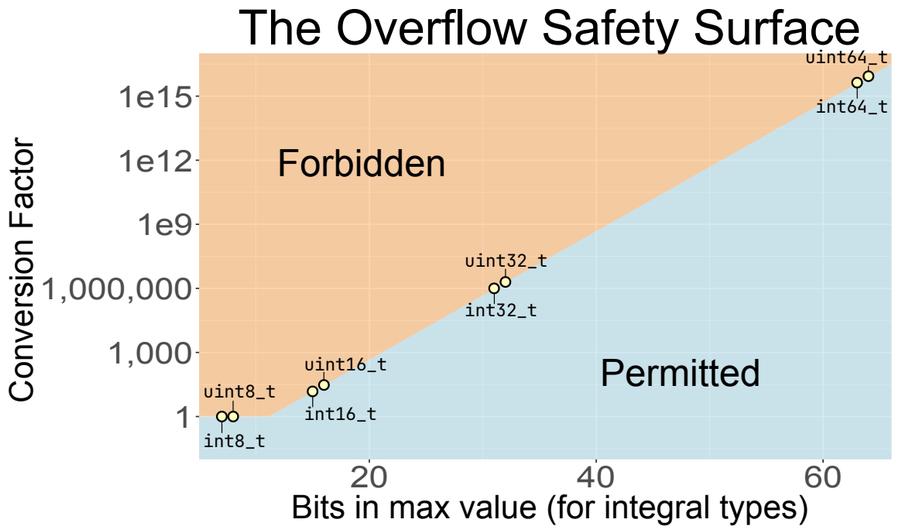

```cpp
QuantityU32<Nano<Seconds>> dt = seconds(5);
```

```
error: conversion from 'Quantity<au::Seconds,int>' to non-scalar type
'Quantity<au::Nano<au::Seconds>,unsigned int>' requested
```

The “Safety Surface”



The “Safety Surface”



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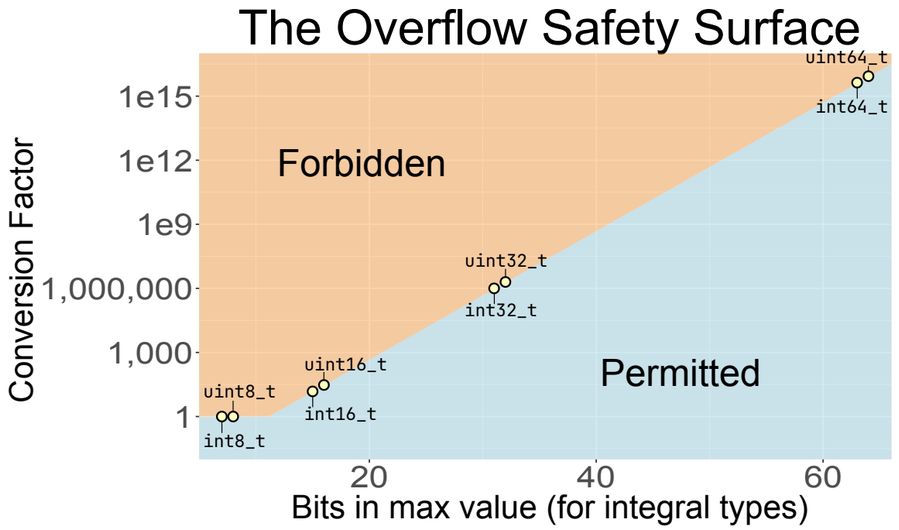

Protection	boost C++ LIBRARIES	nholthaus		mp-units	Au AURORA UNITS LIBRARY
Truncation	✔️	❌	❌	✔️	✔️
Overflow	❌	❌	❌	❌	✔️

Vector space magnitudes

https://aurora-opensource.github.io/au/main/**discussion/implementation/vector_space/#magnitude**

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Requirement: *magnitudes* must do everything *units* can do!

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- …are *closed* under **products** and **rational powers**.

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`std::ratio`: $\frac{N}{D}$ **Vector space magnitudes:** $\prod_i b_i^{p_i}$

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$$\left(\frac{\text{AU}}{\text{m}}\right) \qquad M = \frac{149\,597\,870\,700}{1} \qquad M = 2^2 \cdot 3^1 \cdot 5^2 \cdot 73^1 \cdot 877^1 \cdot 7789^1$$

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$\left(\frac{\text{AU}}{\text{m}}\right)^2$ $M =$ 🚫 $M = 2^4 \cdot 3^2 \cdot 5^4 \cdot 73^2 \cdot 877^2 \cdot 7789^2$

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$\left(\frac{\text{AU}}{\text{m}}\right)^2$ $M =$ 🚫 $M = 2^4 \cdot 3^2 \cdot 5^4 \cdot 73^2 \cdot 877^2 \cdot 7789^2$

$\sqrt{2}$	$M =$ 🚫	$2\frac{1}{2}$

Vector space magnitudes

https://aurora-opensource.github.io/au/main/**discussion/implementation/vector_space/#magnitude**

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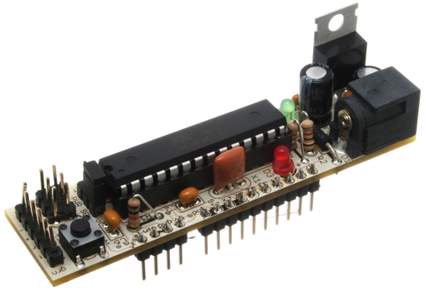
$\left(\frac{\text{AU}}{\text{m}}\right)^2$ $M =$ 🚫 $M = 2^4 \cdot 3^2 \cdot 5^4 \cdot 73^2 \cdot 877^2 \cdot 7789^2$

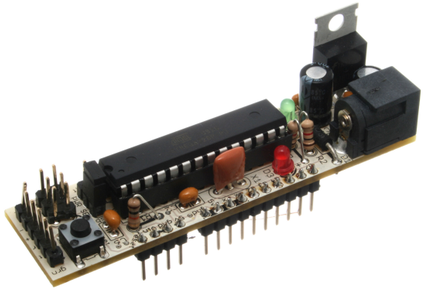
$\sqrt{2}$	$M =$ 	$2^{\frac{1}{2}}$
$\frac{\text{deg}}{\text{rad}}$	$M =$ 	$M = 2^{-2} \cdot 3^{-2} \cdot \pi^{1} \cdot 5^{-1} \left(= \frac{\pi}{180} \right)$

Embedded friendliness



By oomlout (Flickr), CC BY-SA 2.0 DEED, https://commons.wikimedia.org/wiki/File:ADAF-03-BRD_(14336910552).jpg

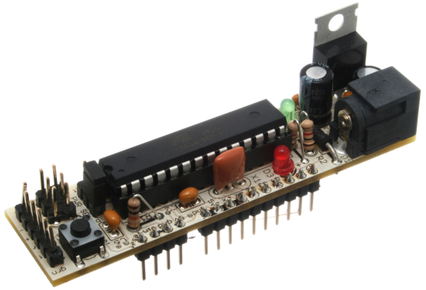
Embedded friendliness



Tired:

Wired:

Embedded friendliness



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- `double`, `float`

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- `int64_t`, `uint32_t`, …

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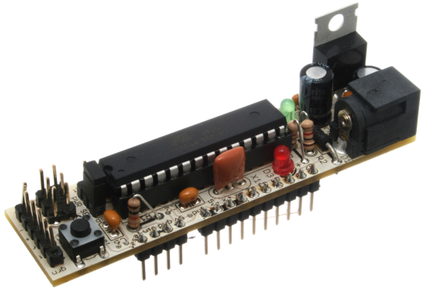

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- `double`, `float`
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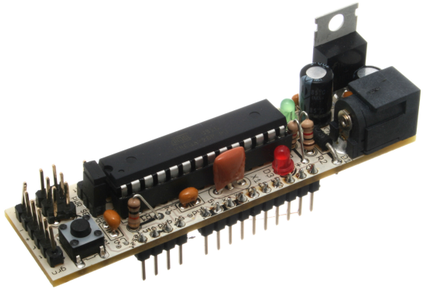

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Tired:

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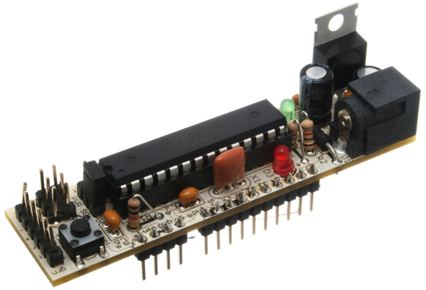
```
const auto &label = unit_label(Meters{} * Kilo<Grams>{} / squared(Seconds{}));
```

Embedded friendliness



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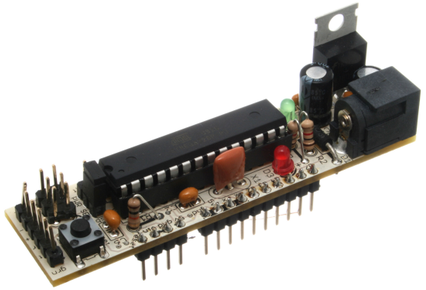
Tired:

Wired:

```
const auto &label = unit_label(Meters{} * Kilo<Grams>{} / squared(Seconds{}));

static_assert(std::is_same<decltype(label), const char(&)[15]>::value, "");
//                                          ^^^^^^^^^^^^^^^^^
```

Embedded friendliness



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printf("Label of length %d is: [%s]\n", sizeof(label), label);
//                                      ^^^^^^^^^^^^^
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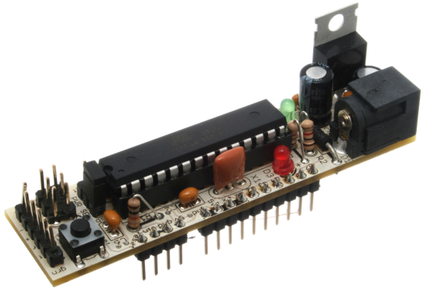
Embedded friendliness



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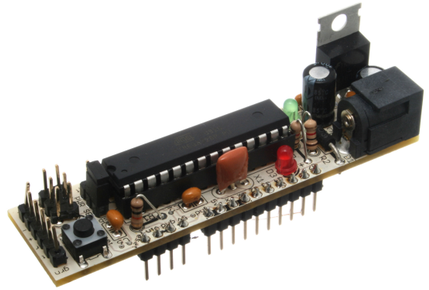
//                                          ^^^^^^^^^^^^^^^^^^

printf("Label of length %d is: [%s]\n", sizeof(label), label);
//                                      ^^^^^^^^^^^^^
```

```
Label of length 15 is: [(m * kg) / s^2]
```

Embedded friendliness



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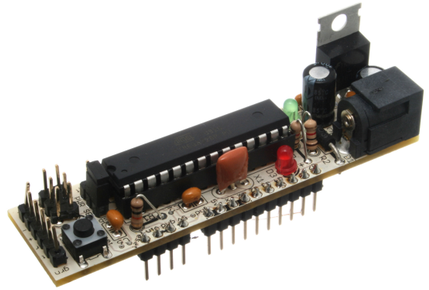

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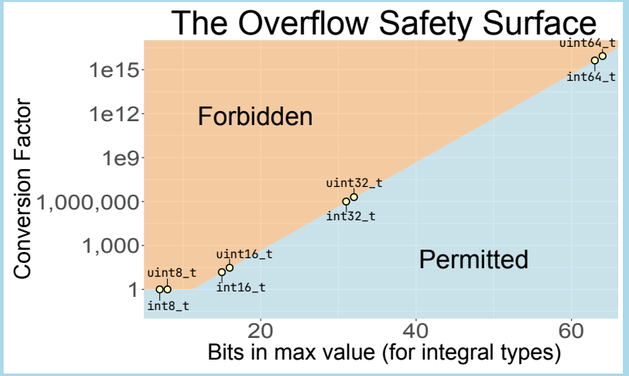

Composability

Code:

Output:

Composability

Code:

```
std::cout << meters(10) << std::endl;
```

Output:

```
10 m
```

Composability

Code:

```
std::cout << meters(10) << std::endl;
std::cout << (meters / second)(20) << std::endl;
```

Output:

```
10 m
20 m / s
```

Composability

Code:

```
std::cout << meters(10) << std::endl;
std::cout << (meters / second)(20) << std::endl;
std::cout << (kilo(meters) / hour)(30) << std::endl;
```

Output:

```
10 m
20 m / s
30 km / h
```

Composability

Code:

```
std::cout << meters(10) << std::endl;
std::cout << (meters / second)(20) << std::endl;
std::cout << (kilo(meters) / hour)(30) << std::endl;
std::cout << (meters / squared(second))(40) << std::endl;
```

Output:

```
10 m
20 m / s
30 km / h
40 m / s^2
```

Unit-aware inverses

https://aurora-opensource.github.io/au/main/**reference/math/#inverse-functions**

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$$T = 1/f = 0.0025\,\mathrm{s}$$

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Solve for (units of) 1...

$$1 = Tf$$

$$= (2\,500\,[\mu\mathrm{s}])(400[\mathrm{Hz}])$$

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$$\begin{aligned} 1 &= Tf \\ &= (2\,500\,[\mu\mathrm{s}])(400[\mathrm{Hz}]) \\ &= 1\,000\,000[\mu\mathrm{s}\cdot\mathrm{Hz}] \end{aligned}$$

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$$f = 400\,\text{Hz}$$

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Solve for (units of) 1...

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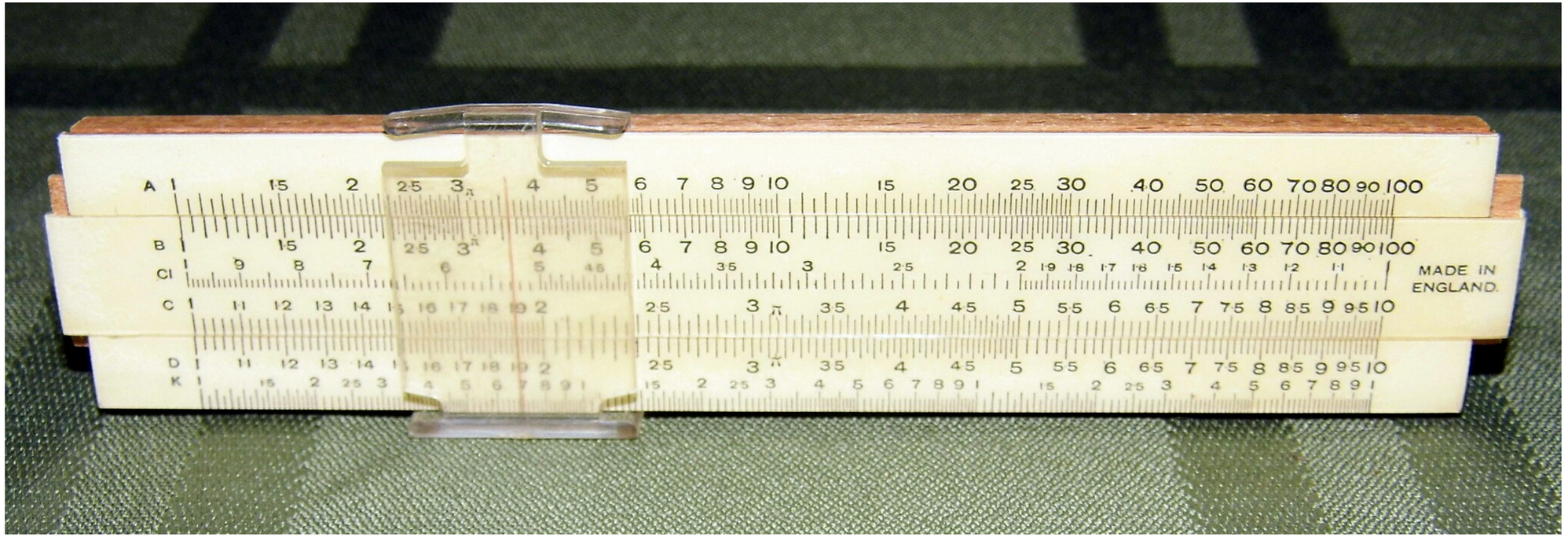
```
inverse_as(micro(seconds), hertz(400));  // micro(seconds)(2'500)
```

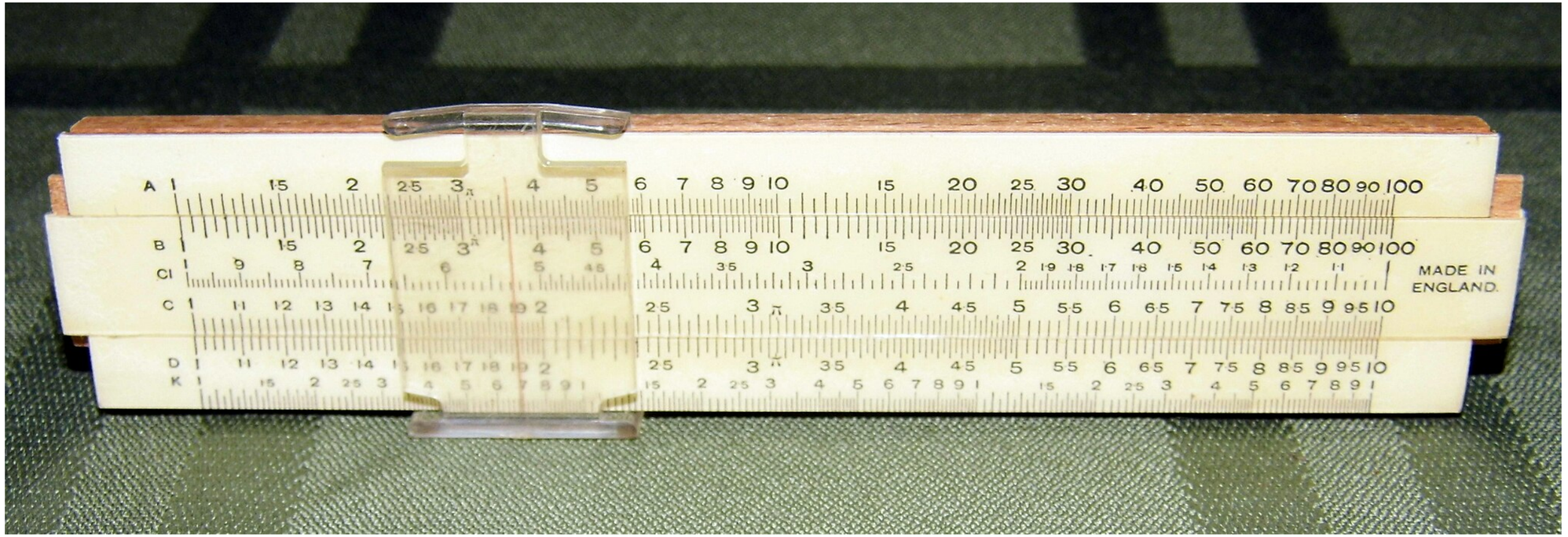
Au: missing features

Decibels



By Joe Haupt, CC BY-SA 2.0 DEED, https://commons.wikimedia.org/wiki/File:Vintage_Small_Slide_Rule,_4.75_Inches_in_Length,_Made_in_England_(9610232930).jpg

Decibels



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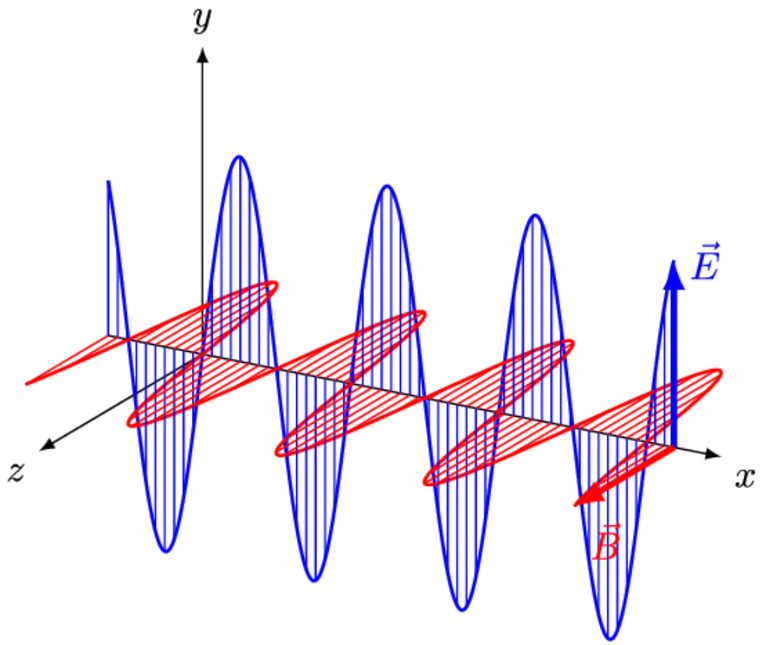
“Power” quantity:

“Root power” quantity:

$$L = 10\log_{10}\left(\frac{X}{X_0}\right)\text{dB}$$

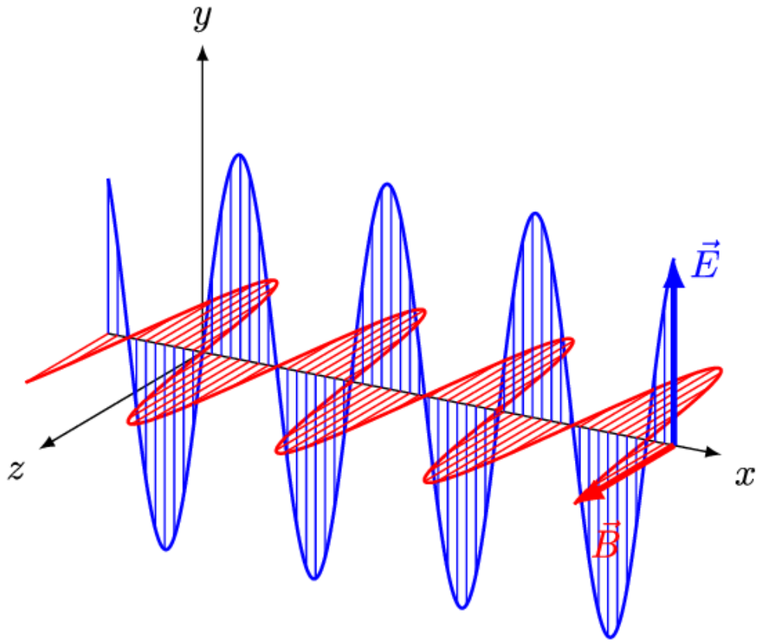
$$L = 20\log_{10}\left(\frac{X}{X_0}\right)\text{dB}$$

Explicit systems of quantities



By And1mu - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Plane_electromagnetic_wave.svg

Explicit systems of quantities



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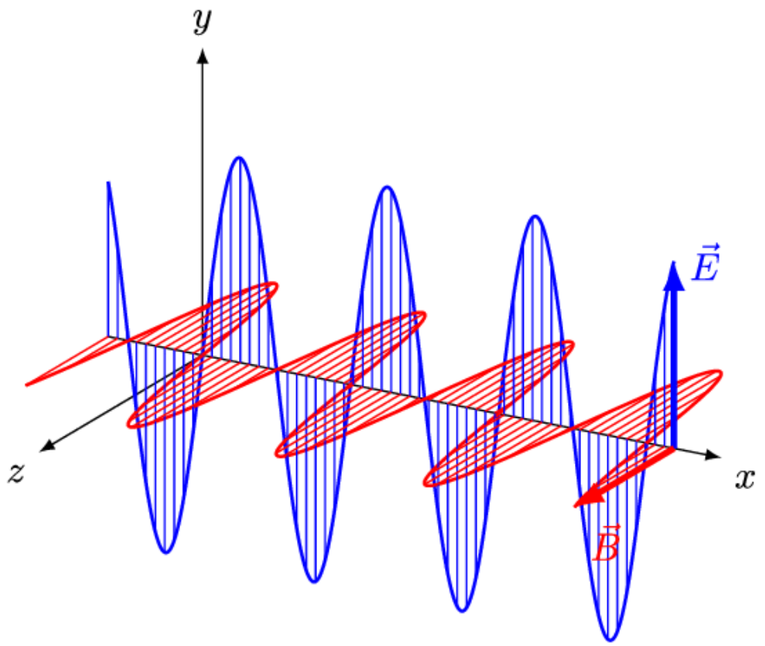
SI Units:

$$E = cB$$

Explicit systems of quantities



By And1mu - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Plane_electromagnetic_wave.svg

SI Units:

$$E = cB$$

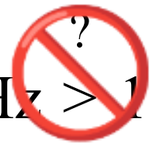
Gaussian Units:

$$E = B$$

Quantity “kind”

$$1\,\mathrm{Hz} \overset{?}{>} 1\,\mathrm{Bq}$$

Quantity “kind”



1 Hz > 1 Bq

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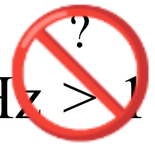

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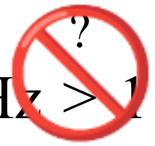
```
constexpr bool b = (hertz(1) > becquerel(1));  // Not meaningful, but compiles
```

Quantity “kind”



```
constexpr bool b = (hertz(1) > becquerel(1));  // Not meaningful, but compiles
```

mp-units

```
const bool b = (1 * si::hertz) > (1 * si::becquerel);
```

```
<source>:15:30: error: no match for 'operator>' (operand types are
'mp_units::quantity<mp_units::si::hertz(), int>' and
'mp_units::quantity<mp_units::si::becquerel(), int>')
   15 |   const bool b = (1 * si::hertz) > (1 * si::becquerel);
      |                   ~~~~~~~~~~~~~~ ^ ~~~~~~~~~~~~~~~~~~
      |                      |                  |
      |                      |            quantity<mp_units::si::becquerel(),[...]>
      |                    quantity<mp_units::si::hertz(),[...]>
```

Aside: mistakes in the real world

Tier	
e.g.	
Real World Errors	

Aside: mistakes in the real world

Tier Wrong dimension

---

e.g.

```
dist_m = time_s;
```

Real World Errors

Aside: mistakes in the real world

Tier	Wrong dimension	Right dimension, Wrong magnitude
e.g.	`dist_m = time_s;`	`dist_m = dist_cm;`
Real World Errors		

Aside: mistakes in the real world

Tier	Wrong dimension	Right dimension, Wrong magnitude	Right dimension, Right magnitude, Wrong "kind"
e.g.	`dist_m = time_s;`	`dist_m = dist_cm;`	`freq_hz = act_bq`
Real World Errors			

Aside: mistakes in the real world

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Real World Errors			

Quantity errors from P2981:

Mars Climate | Columbus | Vasa | Gimli glider | Black Sabbath | Korean Air 6316 | Moorpark Zoo | Space Mountain | Wild rice | Med dose

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Quantity errors from P2981:

Unit symbol APIs (e.g., literals)

Functions	UDLs
`meters(3.0)`	`3.0_m`

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`meters(3.0f)`	`???`
`meters(dist_m)`	`???`

Unit symbol APIs (e.g., literals)

Functions	UDLs	Unit Symbols
`meters(3.0)`	`3.0_m`	`3.0 * m`
`(meters / second)(8.0)`	`8.0_mps  // New manual definition 😞`	`8.0 * m / s`
`meters(3.0f)`	`???`	`3.0f * m`
`meters(dist_m)`	`???`	`dist_m * m`

Inter-library interactions

Feature inspirations

`nholthaus`

`mp-units`

Directly Shared

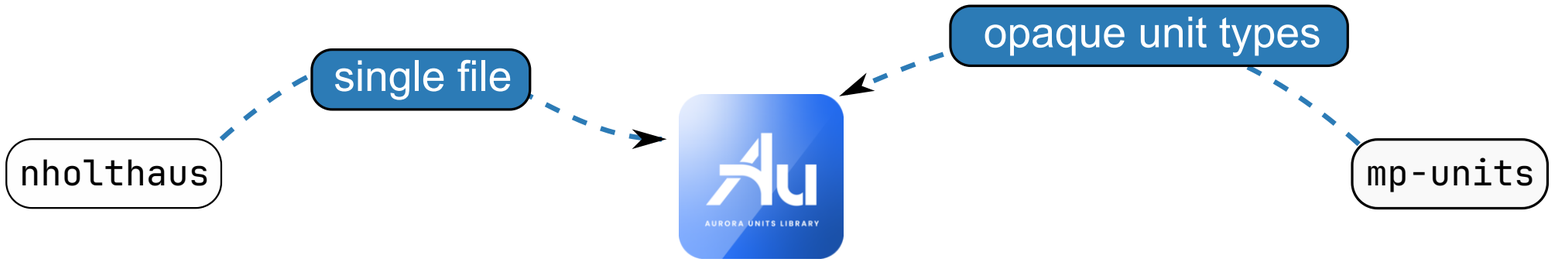
Inspired

Feature inspirations

Directly Shared

Inspired

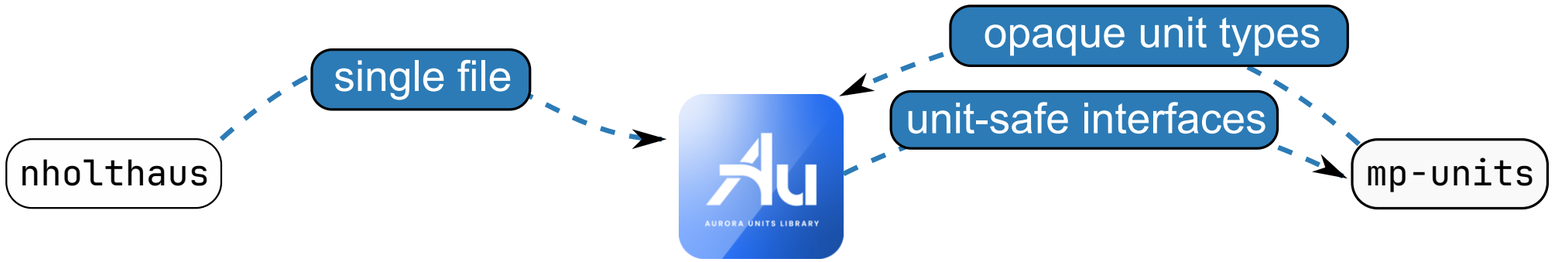
Feature inspirations



Directly Shared

Inspired

Feature inspirations



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Feature inspirations

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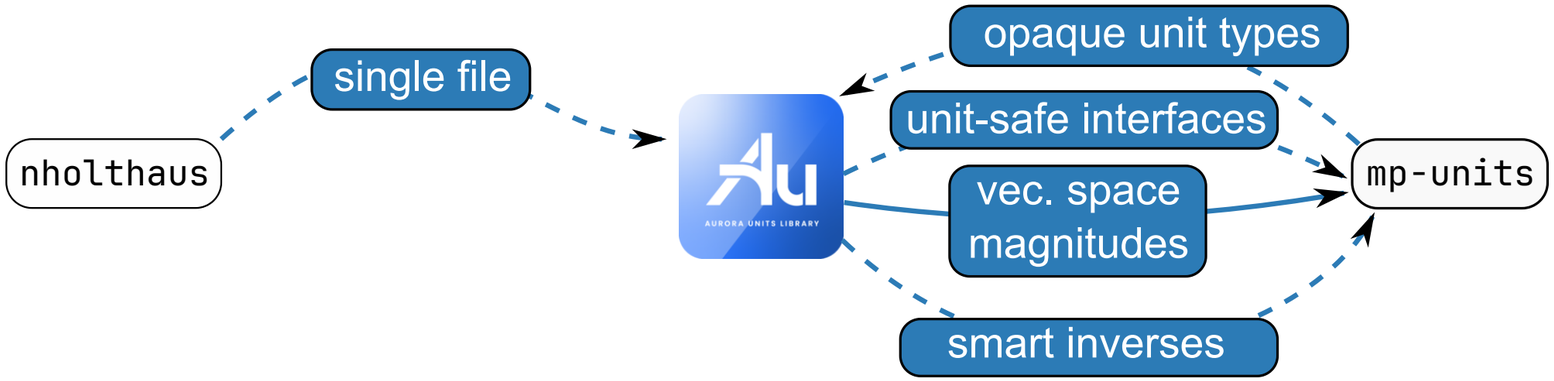
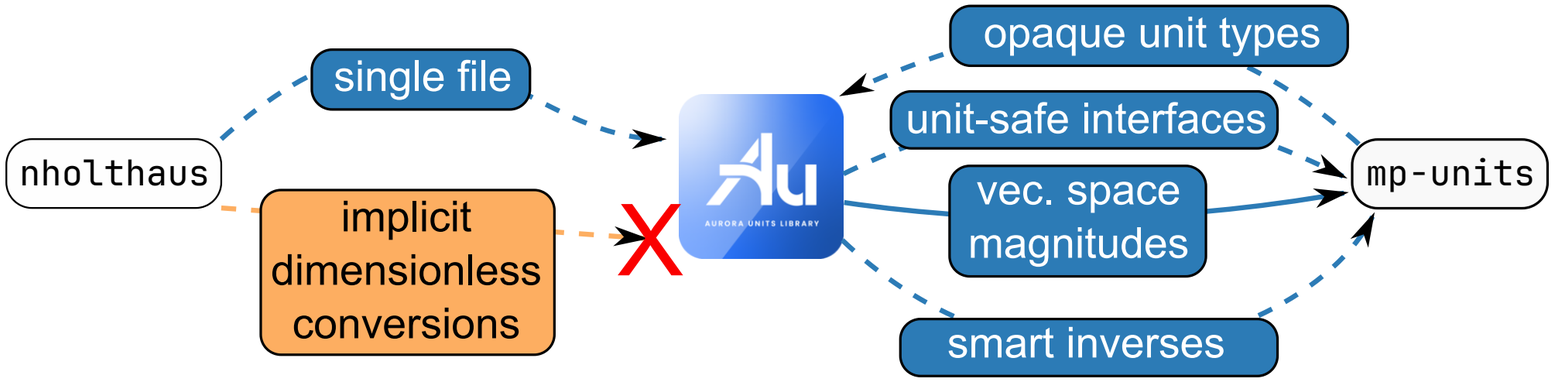


Directly Shared

Inspired

Feature inspirations

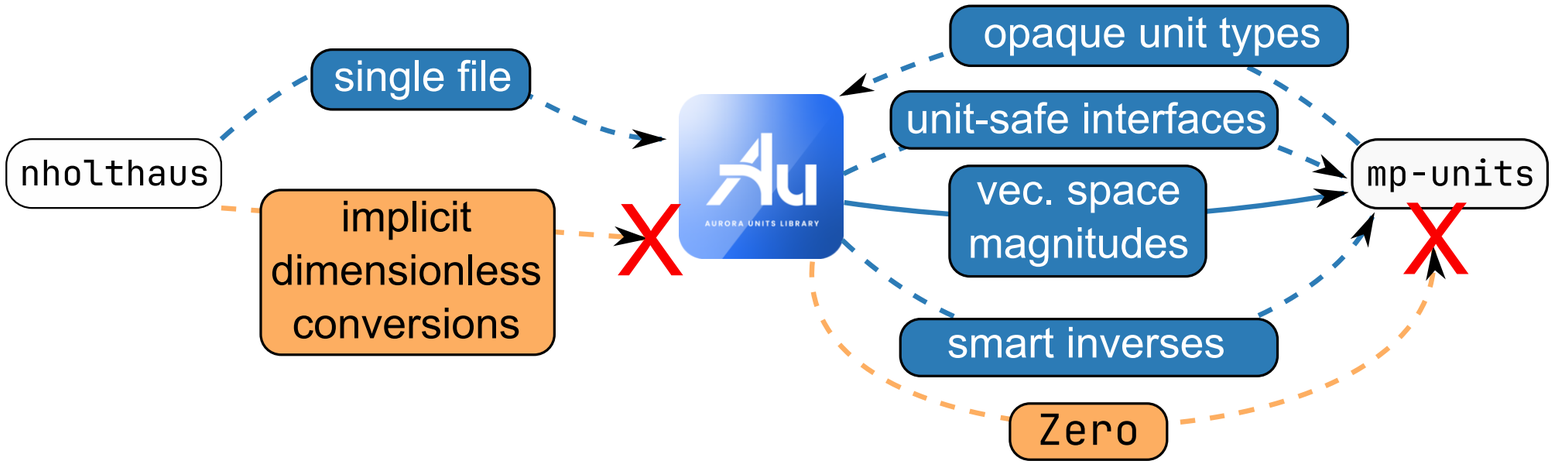


Directly Shared

Inspired

"Negatively" Inspired

Feature inspirations



Corresponding quantity mechanism

https://aurora-opensource.github.io/au/main/**howto/interop/**

```
struct MyMeters {
  uint32_t val;
};
```

```
class Quantity<Meters, uint32_t> {
  uint32_t value_;
};
```

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```cpp
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```cpp
class Quantity<Meters, uint32_t> {
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};
```

```cpp
namespace au {
template<>
struct CorrespondingQuantity<MyMeters> {



};
} // namespace au
```

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```cpp
struct MyMeters {
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class Quantity<Meters, uint32_t> {
  uint32_t value_;
};
```

```cpp
namespace au {
template<>
struct CorrespondingQuantity<MyMeters> {
    using Unit = Meters;









};
} // namespace au
```

Corresponding quantity mechanism

https://aurora-opensource.github.io/au/main/**howto/interop/**

```
struct MyMeters {
  uint32_t val;
};
```

<=>

```
class Quantity<Meters, uint32_t> {
  uint32_t value_;
};
```

```
1  namespace au {
2  template<>
3  struct CorrespondingQuantity<MyMeters> {
4      using Unit = Meters;
5      using Rep = uint32_t;
6
7
8
9
10
11
12
13
14 };
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Cross-library interop

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Initialization:

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3
4
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3 Quantity<Meters, uint32_t>         q1 = x;  //==> meters(3)
4 Quantity<Milli<Meters>, uint32_t> q2 = x;  //==> milli(meters)(3'000)
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Cross-library interop

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API passing:

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API passing:

```
// Legacy interfaces:
MyMeters measure_length(const Object& o);
void evaluate(const MyMeters& m);
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API passing:

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```
// Client code:
MyMeters m = measure_length(my_object);
evaluate(m);
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```

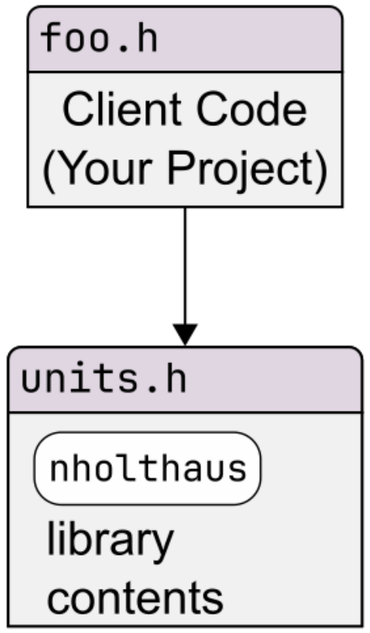
API passing:

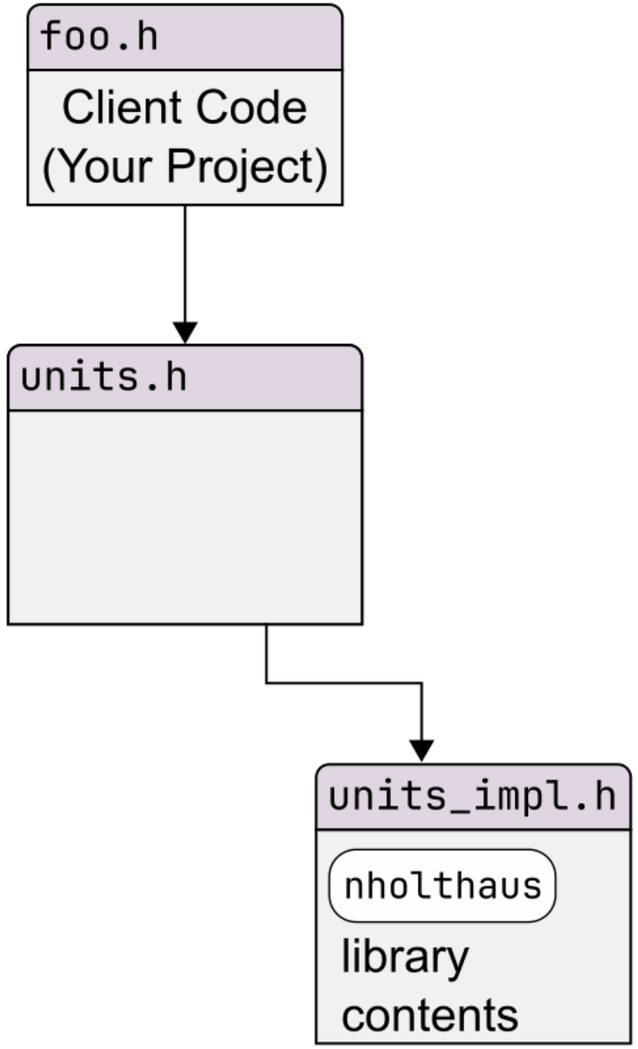
```
// After refactoring:
Quantity<Meters, uint32_t> measure_length(const Object& o);
void evaluate(const Quantity<Meters, uint32_t>& m);
```

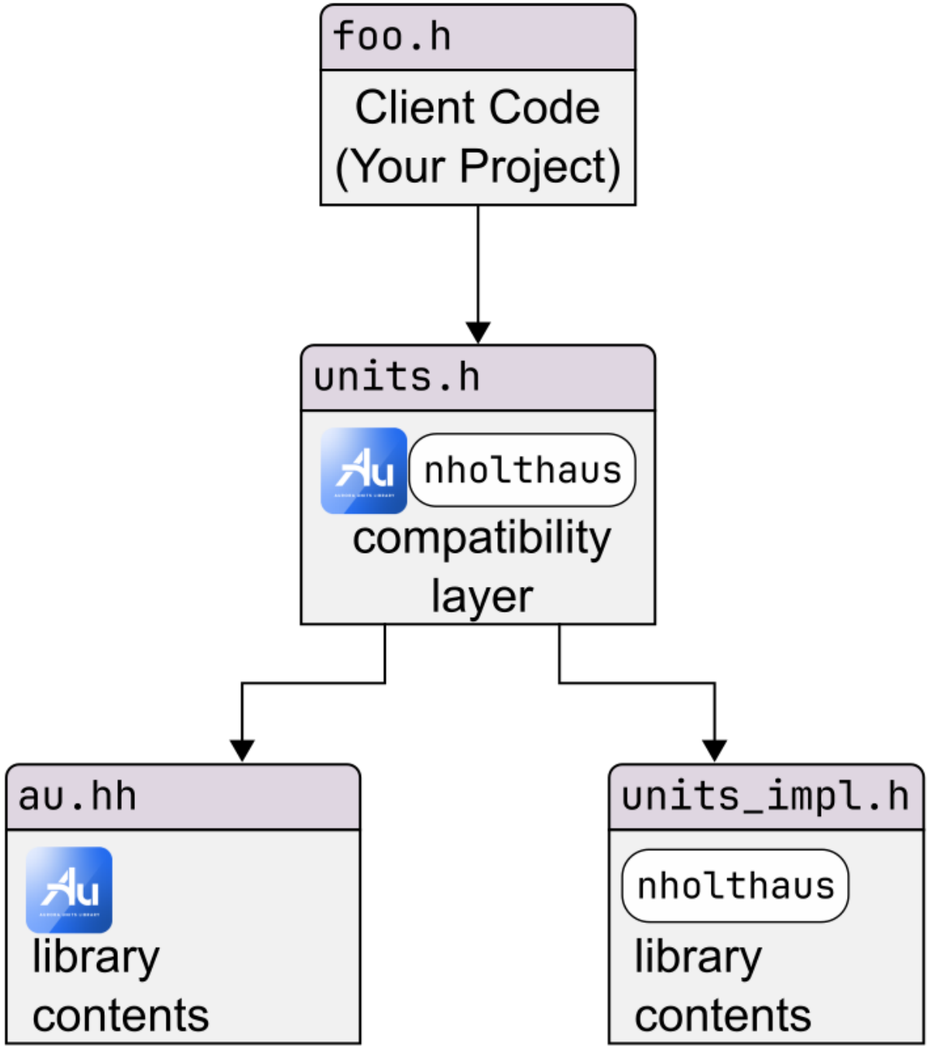
```
// Client code:
MyMeters m = measure_length(my_object);
evaluate(m);
```

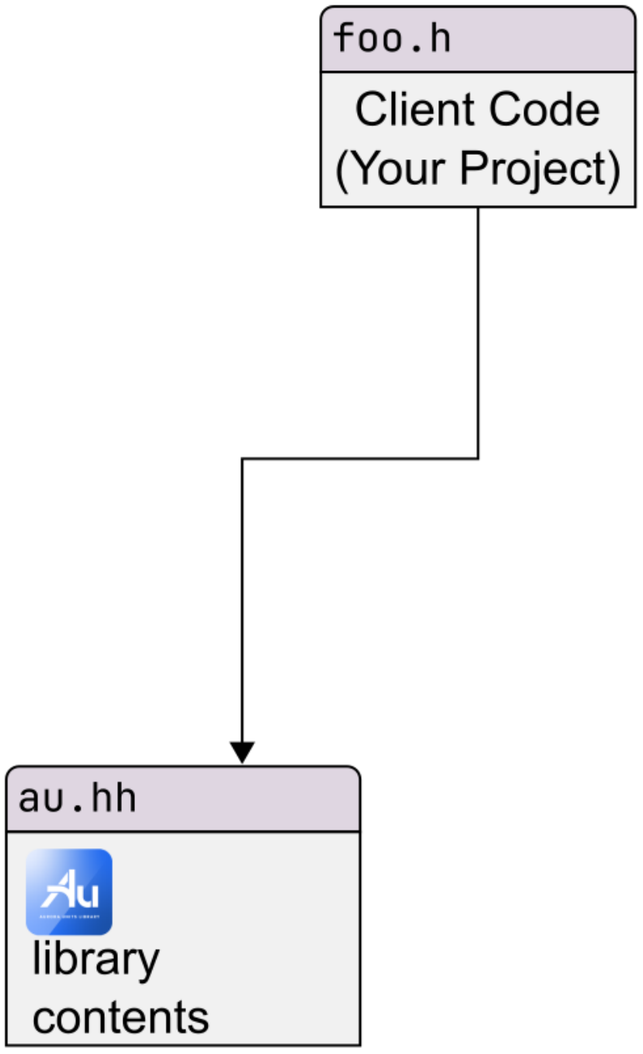
nholthaus compatibility layer

https://aurora-opensource.github.io/au/main/**howto/interop/nholthaus/**


foo.h
Client Code
(Your Project)
units.h
nholthaus
library
contents


foo.h
Client Code
(Your Project)
units.h
units_impl.h
nholthaus
library
contents


foo.h
Client Code
(Your Project)
units.h
nholthaus
compatibility
layer
au.hh
library
contents
units_impl.h
nholthaus
library
contents


foo.h
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aurora-opensource/au