Better Numeric Types in C++

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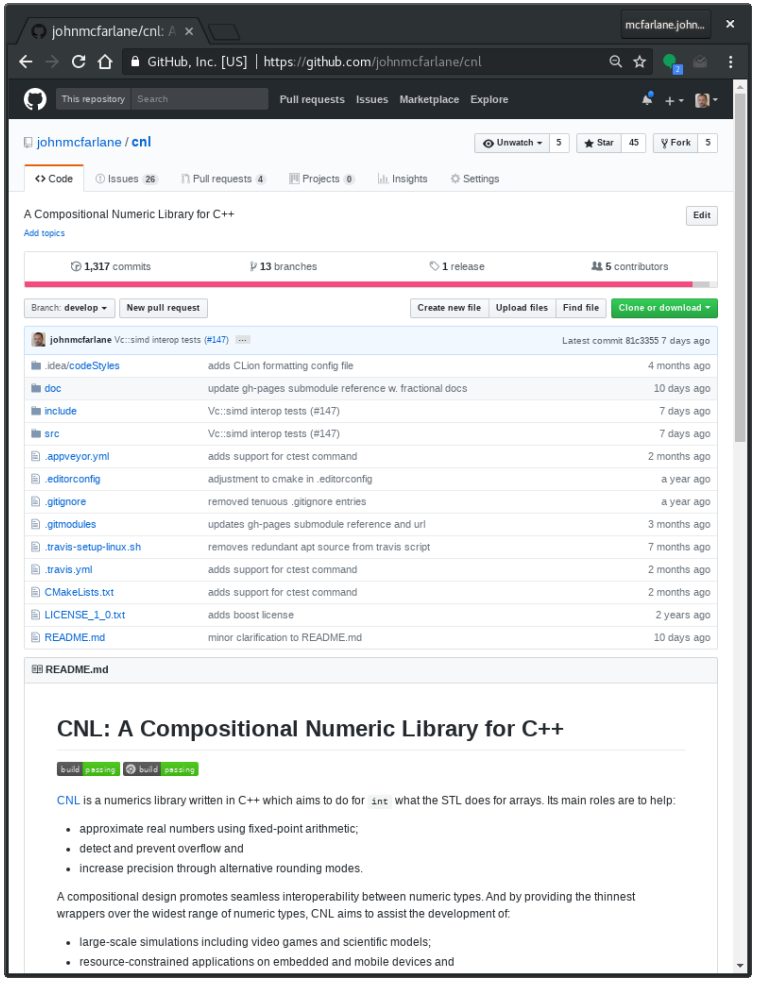
ACCU Bay Area - 2018-05-09

Background

Background



← github.com/johnmcfarlane/cnl

The Problem with Integers

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1. Fixed resolution

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1. Fixed resolution
2. Limited range

The Problem with Integers

1. Fixed resolution
2. Limited range
3. 'Interesting' arithmetic behavior

The Problem with Floating-Point

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    - ± 1.significand * 2 $^{\text{exponent}}$
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2. Occasional weirdness can surprise:
    - determinism, associativity, commutativity and ordering
3. `<cmath>` functions lack `constexpr`
4. Variable resolution
5. Costly in energy and silicon

Analysis

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- But we can do a lot better.
- so …

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- Provide zero-cost abstractions over language-level features:

```
std::array<T, N> a;  // T a[N]
std::array<T, N>::iterator i = std::begin(a); // T* i
```

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auto const& third = a[2];
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auto const& third = a[2];
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- Allow users to opt in to positive-cost functionality:

```
std::array<T, N> a;
auto const& bad_element = a.at(N);  // throws std::out_of_range!
```

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- Provide zero-cost abstractions over language-level features:

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- Allow users to opt in to positive-cost functionality:

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std::array<T, N> a;
auto const& bad_element = a.at(N);  // throws std::out_of_range!
```

- And most importantly...

Goal of CNL

"**Do for `int` what the STL did for `[]`.**"

- Compose!

```
using fs_cache = unordered_map<filesystem::path, vector<byte>>;
```

Non-Goal

"**Don't do for `int` what STL doesn't do for `[]`.**"

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"**Don't do for `int` what STL doesn't do for `[]`.**"

- Don't make the user pay for what they don't use.

Fixed-Point Arithmetic

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```
namespace cnl {

    template<typename Rep=int, int Exponent=0, int Radix=2>
    class fixed_point {
        // ...
    private:
        Rep r;
    };

}
```

Fixed-Point Arithmetic

```
namespace cnl {

    template<typename Rep=int, int Exponent=0, int Radix=2>
    class fixed_point {
        // ...
    private:
        Rep r;
    };

}
```

Example usage:

```
#include <cnl/fixed_point.h>

void f() {
    auto n = cnl::fixed_point<int, -8>{ 0.25 };
    std::cout << n * 5; // prints "1.25"
}
```

The Good

The Good

```
// what the programmer writes
bool foo(float f) {
    auto fixed = fixed_point<int, -16>{f};
    auto fixed_plus_one = fixed + 1;
    return fixed_plus_one > fixed;
}
```

The Good

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// what the compiler sees
bool foo(float) {
    return true;
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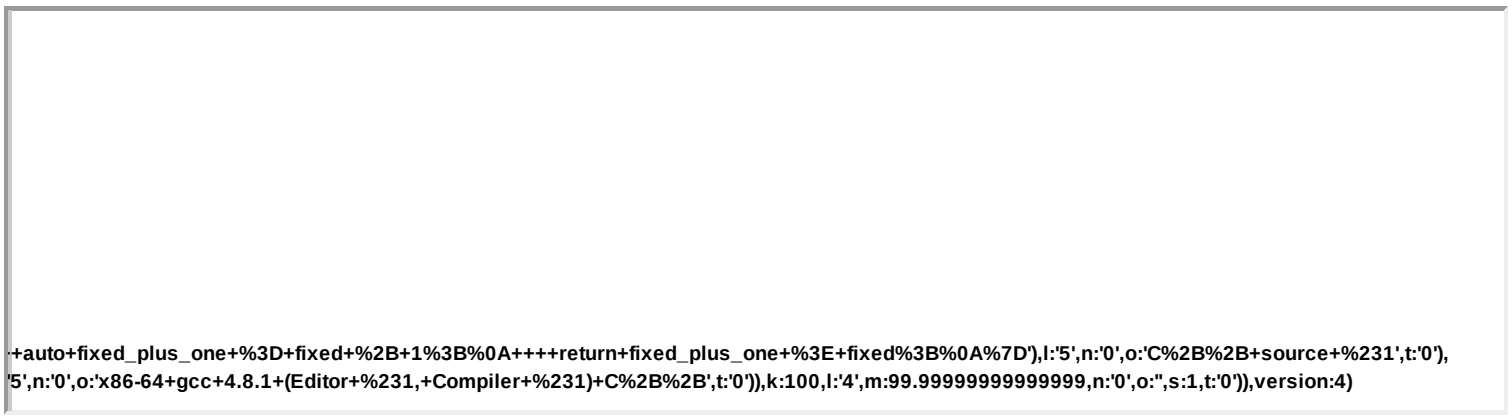
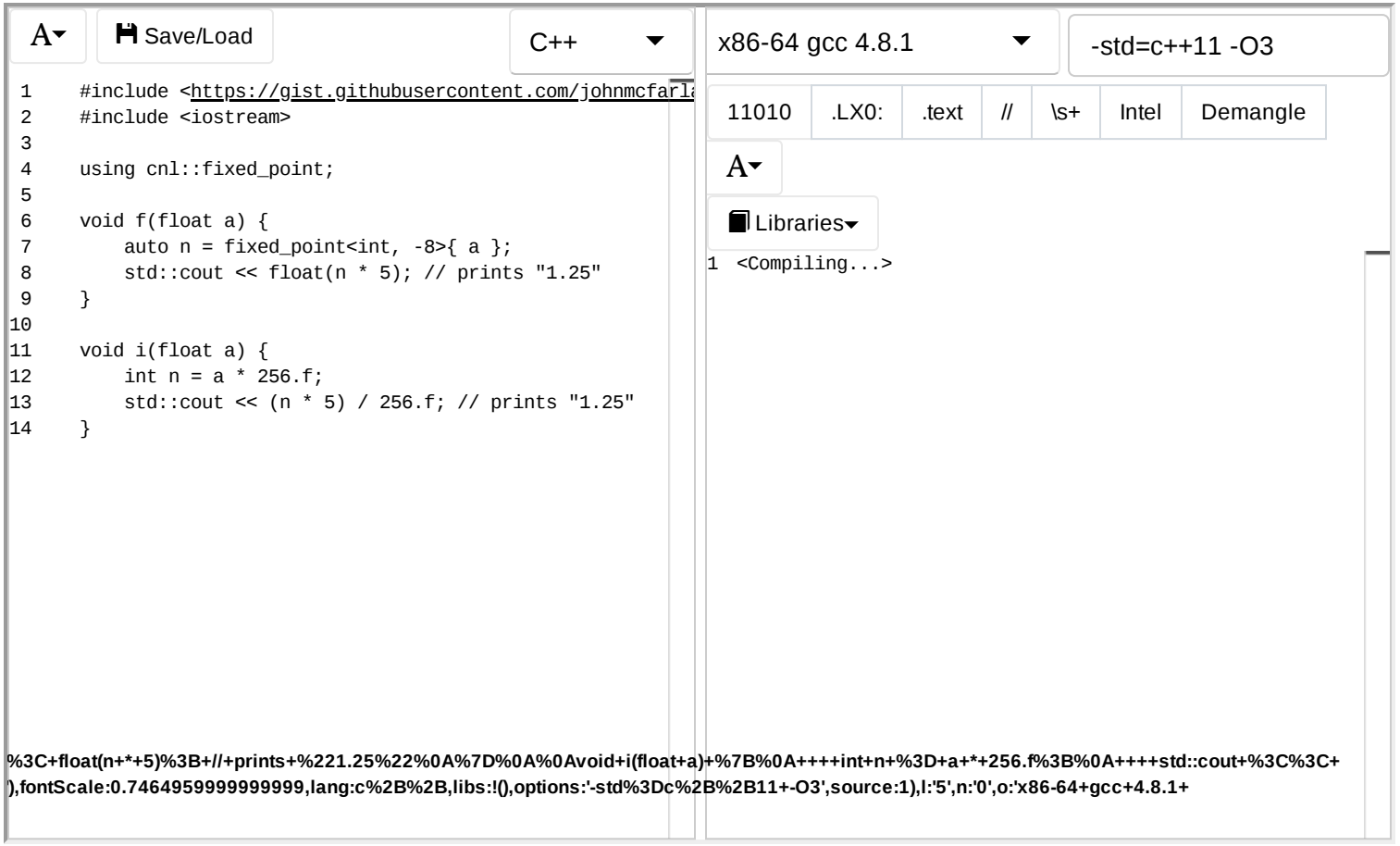


The Good


A
Save/Load
C++
x86-64 gcc 4.8.1
-std=c++11 -O3
11010
.LX0:
.text
//
\s+
Intel
Demangle
A
Libraries
1 <Compiling...>
#include <https://gist.githubusercontent.com/johnmcfarl
#include <iostream>
using cnl::fixed_point;
void f(float a) {
auto n = fixed_point<int, -8>{ a };
std::cout << float(n * 5); // prints "1.25"
}
void i(float a) {
int n = a * 256.f;
std::cout << (n * 5) / 256.f; // prints "1.25"
}
%3C+float(n+*+5)%3B+//+prints+%221.25%22%0A%7D%0A%0Avoid+i(float+a)+%7B%0A++++int+n+%3D+a+*+256.f%3B%0A++++std::cout+%3C%3C+
'),fontScale:0.7464959999999999,lang:c%2B%2B,libs:!(),options:'-std%3Dc%2B%2B11+-O3',source:1),l:'5',n:'0',o:'x86-64+gcc+4.8.1+

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```
// range exceeded! (undefined behavior)
auto a = numeric_limits<int>::max() + 1;
```

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auto a = numeric_limits<int>::max() + 1;
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```
// also undefined behavior
auto b = numeric_limits<fixed_point<int, -16>>::max() + 1;
```

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auto a = numeric_limits<int>::max() + 1;
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// also undefined behavior
auto b = numeric_limits<fixed_point<int, -16>>::max() + 1;
```

```
// compiles
static_assert(1 == 1, "this does compile");

// error: static assertion failed: this does not compile
static_assert(1 != 1, "this does not compile");

// error: left shift count >= width of type
static_assert(1 << 1000, "this does not compile");
```

The Bad

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// range exceeded! (undefined behavior)
auto a = numeric_limits<int>::max() + 1;
```

```
// also undefined behavior
auto b = numeric_limits<fixed_point<int, -16>>::max() + 1;
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static_assert(1 == 1, "this does compile");

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static_assert(1 != 1, "this does not compile");

// error: left shift count >= width of type
static_assert(1 << 1000, "this does not compile");
```

```
// compiles
static_assert(numeric_limits<fixed_point<int, -16>>::max() - 1, "this compiles");

// fatal error: static_assert expression is not an integral constant expression
static_assert(numeric_limits<fixed_point<int, -16>>::max() + 1, "this does not!");
```

The Bad

```
// compiles
static_assert(unsigned{1} < signed{-1}, "wat?");
```

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static_assert(unsigned{1} < signed{-1}, "wat?");
```

```
// compiles
static_assert(fixed_point<unsigned>{1} < fixed_point<signed>{-1}, "huh?");
```

The Bad

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// compiles
static_assert(unsigned{1} < signed{-1}, "wat?");
```

```
// compiles
static_assert(fixed_point<unsigned>{1} < fixed_point<signed>{-1}, "huh?");
```

```
// compiles (C++17)
static_assert(fixed_point{1U} < fixed_point{-1});
```

The Ugly

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```
// multiplication
auto n = cnl::fixed_point<int, -8>{1.5};
auto nn = n * n;    // type?
```

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// multiplication
auto n = cnl::fixed_point<int, -8>{1.5};
auto nn = n * n;    // type?
```

```
// (-8) + (-8) = -16
static_assert(std::is_same_v<decltype(nn), cnl::fixed_point<int, -16>>);
```

The Ugly


t%3Cint%3E(f+*+256.f)%3B%0A++++auto+nn+%3D+n+*+n%3B%0A++++return+nn+/+65536.f%3B%0A%7D'),l:'5',n:'0',o:'C%2B%2B+source+%231',t:'0'),

The Ugly

```
constexpr auto n = cnl::fixed_point<int, -8>{1.5};
constexpr auto d = cnl::fixed_point<int, -8>{2.25};
```

The Ugly

```
constexpr auto n = cnl::fixed_point<int, -8>{1.5};
constexpr auto d = cnl::fixed_point<int, -8>{2.25};
```

```
// (-8) - (-8) = 0
constexpr auto q = n / d;    // cnl::fixed_point<int, 0>;
```

The Ugly

```
constexpr auto n = cnl::fixed_point<int, -8>{1.5};
constexpr auto d = cnl::fixed_point<int, -8>{2.25};
```

```
// (-8) - (-8) = 0
constexpr auto q = n / d;    // cnl::fixed_point<int, 0>;
```

```
constexpr auto r = n % d;    // cnl::fixed_point<int, -8>;
```

The Ugly

```
constexpr auto n = cnl::fixed_point<int, -8>{1.5};
constexpr auto d = cnl::fixed_point<int, -8>{2.25};
```

```
// (-8) - (-8) = 0
constexpr auto q = n / d;    // cnl::fixed_point<int, 0>;
```

```
constexpr auto r = n % d;    // cnl::fixed_point<int, -8>;
```

```
// (-8) - (23)
constexpr auto q = cnl::divide(n, d);    // cnl::fixed_point<long, -31>;
```

How Do You Solve a Problem Like Division?

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```
5.5 * 5.5 = 30.25
55. * .55 = 30.25
5.5 * 55. = 302.5
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AAA.BBBBB * CCCCCC.DD = AAACCCCCC.BBBBBDD
```

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AAA.BBBBB * CCCCCC.DD = AAACCCCCC.BBBBBDD
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```
10 / 100 = 00.10
1 / 1000 = 0.001
```

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```
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10 / 100 = 00.10
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```

```
AAA.BBBBB / CCCCCC.DD = AAADD.BBBBBCCCCCC
```

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```
10 / 100 = 00.10
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```
AAA.BBBBB / CCCCCC.DD = AAADD.BBBBBCCCCCC
```

```
1 / 3 = 0.333333333...
```

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```
template<typename Numerator, typename Denominator>
struct fractional {
    Numerator numerator;
    Denominator denominator;
};
```

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template<typename Numerator, typename Denominator>
struct fractional {
    Numerator numerator;
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};
```

```
constexpr auto n = fixed_point<int16_t, -8>{1.5};
constexpr auto d = fixed_point<int16_t, -8>{2.25};
constexpr auto f = fractional{n, d};
constexpr auto q = fixed_point{f};  // fixed_point<int32_t, -15>{.66666667}
```

Elasticity

Elasticity

```
auto n = fixed_point<uint8_t, -8>{0.99609375};
auto nn = n * n;
```

Elasticity

```
auto n = fixed_point<uint8_t, -8>{0.99609375};
auto nn = n * n;    // fixed_point<int, -16>{0.9922027587890625};
```

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auto n = fixed_point<uint8_t, -8>{0.99609375};
auto nn = n * n;    // fixed_point<int, -16>{0.9922027587890625};
```

```
auto n = fixed_point<int, -31>{0.99609375};
auto nn = n * n;    // fixed_point<int, -62>{?!?!?!?!?!?!};
```

Elasticity

```
template<int Digits, class Narrowest = int>
class elastic_integer { WideEnoughInteger r; /* other stuff */ };
```

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class elastic_integer { WideEnoughInteger r; /* other stuff */ };
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```
#include <cnl/elastic_integer.h>
using cnl::elastic_integer;
auto e = elastic_integer<31>{0x7FFFFFFF};   // r has 31 or more digits
```

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template<int Digits, class Narrowest = int>
class elastic_integer { WideEnoughInteger r; /* other stuff */ };
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auto e = elastic_integer<31>{0x7FFFFFFF};   // r has 31 or more digits
```

```
auto ee = e * e;   // elastic_integer<62>{INT64_C(0x3FFFFFFF00000001)}
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```

```
auto ee = e * e;   // elastic_integer<62>{INT64_C(0x3FFFFFFF00000001)}
```

```
auto _2ee = ee + ee;   // elastic_integer<63>{INT64_C(0x7FFFFFFE00000002)}
```

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auto _2ee = ee + ee;   // elastic_integer<63>{INT64_C(0x7FFFFFFE00000002)}
```

```
auto fpe = fixed_point<elastic_integer<31>, -31>{0.99609375};
```

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template<int Digits, class Narrowest = int>
class elastic_integer { WideEnoughInteger r; /* other stuff */ };
```

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#include <cnl/elastic_integer.h>
using cnl::elastic_integer;
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auto _2ee = ee + ee;   // elastic_integer<63>{INT64_C(0x7FFFFFFE00000002)}
```

```
auto fpe = fixed_point<elastic_integer<31>, -31>{0.99609375};
```

```
auto sq = fpe * fpe;  // fixed_point<elastic_integer<62>, -62>{0.9922027587890625}
```

Elasticity

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template<int Digits, class Narrowest = int>
class elastic_integer { WideEnoughInteger r; /* other stuff */ };
```

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#include <cnl/elastic_integer.h>
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auto e = elastic_integer<31>{0x7FFFFFFF};   // r has 31 or more digits
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auto ee = e * e;   // elastic_integer<62>{INT64_C(0x3FFFFFFF00000001)}
```

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auto _2ee = ee + ee;   // elastic_integer<63>{INT64_C(0x7FFFFFFE00000002)}
```

```
auto fpe = fixed_point<elastic_integer<31>, -31>{0.99609375};
```

```
auto sq = fpe * fpe;  // fixed_point<elastic_integer<62>, -62>{0.9922027587890625}
```

```
auto q = fixed_point{fractional{sq, sq}};
// fixed_point<elastic_integer<124>, -62>{1}
```

Run-time Safety

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```
#include <cnl/overflow_integer.h>
using cnl::overflow_integer;
auto i = overflow_integer<uint8_t>{255};
```

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```
auto j = i + 1;
```

Run-time Safety

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#include <cnl/overflow_integer.h>
using cnl::overflow_integer;
auto i = overflow_integer<uint8_t>{255};
```

```
auto j = i + 1; // overflow_integer<int>{256}
```

Run-time Safety

```
#include <cnl/overflow_integer.h>
using cnl::overflow_integer;
auto i = overflow_integer<uint8_t>{255};
```

```
auto j = i + 1; // overflow_integer<int>{256}
```

```
overflow_integer<uint8_t> k = i + 1;  // throw std::overflow_error
```

Run-time Safety

```
#include <cnl/overflow_integer.h>
using cnl::overflow_integer;
auto i = overflow_integer<uint8_t>{255};
```

```
auto j = i + 1; // overflow_integer<int>{256}
```

```
overflow_integer<uint8_t> k = i + 1;  // throw std::overflow_error
```

```
constexpr overflow_integer<uint8_t> k = i + 1;
static_assert(cnl::_impl::identical(overflow_integer<int>{256}, k));
```

```
[ 29%] Building CXX object src/test/CMakeFiles/fp_test.dir/cppcon2017.cpp.o
/home/john/cnl/src/test/cppcon2017.cpp:151:37: fatal error: constexpr variable 'k' must be i
    constexpr overflow_integer<uint8_t> k = i + 1;
                                        ^~~~~~~~
/home/john/cnl/include/cnl/overflow.h:52:40: note: subexpression not valid in a constant exp
            return condition ? value : throw std::overflow_error("");
                                       ^
```

and so on...

Deduction and UDLs

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```
auto x = fixed_point{42UL}; // fixed_point<unsigned long, 0>{42}
```

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auto x = fixed_point{42UL}; // fixed_point<unsigned long, 0>{42}
```

```
auto y = fixed_point{128};  // fixed_point<int, 0>{128}
```

Deduction and UDLs

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auto x = fixed_point{42UL}; // fixed_point<unsigned long, 0>{42}
```

```
auto y = fixed_point{128};  // fixed_point<int, 0>{128}
```

```
using cnl::literals;
auto z = fixed_point{128_c};  // fixed_point<int, 7>{128}
```

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auto x = fixed_point{42UL}; // fixed_point<unsigned long, 0>{42}
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using cnl::literals;
auto z = fixed_point{128_c};  // fixed_point<int, 7>{128}
```

```
auto a = fixed_point{0b10000000000000000000000000000000000000000_c};
// a === fixed_point<int, 40>{0b10000000000000000000000000000000000000000L}
```

Deduction and UDLs

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auto x = fixed_point{42UL}; // fixed_point<unsigned long, 0>{42}
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```
auto a = fixed_point{0b10000000000000000000000000000000000000_c};
// a === fixed_point<int, 40>{0b10000000000000000000000000000000000000L}
```

```
auto b = fixed_point{0b11111111111111111111111111111111111111_c};
// b === fixed_point<long, 0>{0b11111111111111111111111111111111111111L}
```

Deduction and UDLs

Deduction and UDLs

```
auto c = elastic_integer{2018_c}; // elastic_integer<11>{2018}
```

Deduction and UDLs

```
auto c = elastic_integer{2018_c}; // elastic_integer<11>{2018}
```

```
auto e = 0x7f000_elastic; // fixed_point<elastic_integer<7>, 12>{0x7f000}
```

Deduction and UDLs

```
auto c = elastic_integer{2018_c}; // elastic_integer<11>{2018}
```

```
auto e = 0x7f000_elastic; // fixed_point<elastic_integer<7>, 12>{0x7f000}
```

```
auto s = e >> 1_c;  // fixed_point<elastic_integer<7>, 11>{0x3f800}
```

Interoperability - Boost.Multiprecision

```
#include <cnl/auxiliary/boost.multiprecision.h>
using namespace boost::multiprecision;

template<int NumBits, int Exponent = 0>
using mp_fixed_point = cnl::fixed_point<
        number<cpp_int_backend<NumBits, NumBits, signed_magnitude, unchecked, void
        Exponent>;
```

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Fixed-Point + Boost.Multiprecision:

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Fixed-Point + Boost.Multiprecision:

- googol (10^{100}) ✓

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using namespace boost::multiprecision;

template<int NumBits, int Exponent = 0>
using mp_fixed_point = cnl::fixed_point<
        number<cpp_int_backend<NumBits, NumBits, signed_magnitude, unchecked, void
        Exponent>;
```

Fixed-Point + Boost.Multiprecision:

- googol (10^{100}) ✓
- googolth (1 / googol) ✓

Interoperability - Boost.Multiprecision

```
#include <cnl/auxiliary/boost.multiprecision.h>
using namespace boost::multiprecision;

template<int NumBits, int Exponent = 0>
using mp_fixed_point = cnl::fixed_point<
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Fixed-Point + Boost.Multiprecision:

- googol (10^{100}) ✓
- googolth (1 / googol) ✓
- googolplex (10^{googol}) ✗

Interoperability - Boost.SIMD

```
#include <cnl/auxiliary/boost.simd.h>
using boost::simd::pack;

template<class T, std::size_t N, int Exponent>
using fixed_point_pack = fixed_point<pack<T, N>, Exponent>;
```

Interoperability - Boost.SIMD

```cpp
#include <cnl/auxiliary/boost.simd.h>
using boost::simd::pack;

template<class T, std::size_t N, int Exponent>
using fixed_point_pack = fixed_point<pack<T, N>, Exponent>;
```

```cpp
using fpp = fixed_point_pack<int, 4, -16>;
using initializer = initializer<fpp>;

auto expected = fpp{initializer{7.9375+-1, -8.+.125, 0+-5, 3.5+-3.5}};
auto augend = fpp{initializer{7.9375, -8., 0, 3.5}};
auto addend = fpp{initializer{-1, .125, -5, -3.5}};
auto sum = augend + addend;
```

Interoperability - Boost.SIMD

CNL Today and Tomorrow

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- Arbitrary width

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- Arbitrary width
- Full Support for Rounding and Overflow

```
template<class Rep = int, class RoundingTag = closest_rounding_tag>
class precise_integer;
```

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template<class Rep = int, class RoundingTag = closest_rounding_tag>
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template<class Rep = int, class RoundingTag = closest_rounding_tag>
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- Full complement of operators for `overflow_integer` and `precise_integer`
- Full complement of free functions

```
add(saturated_overflow, UINT32_C(0xFFFFFFFF), UINT32_C(0x12345678))
divide(closest_rounding_tag, 2, 3);
```

CNL Today and Tomorrow

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```
template<class Rep = int, class RoundingTag = closest_rounding_tag>
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```
add(saturated_overflow, UINT32_C(0xFFFFFFFF), UINT32_C(0x12345678))
divide(closest_rounding_tag, 2, 3);
```

- Better Literals

```
auto a = 0b1111.1111_elastic;  // fixed_point<elastic_integer<8>, -4>
```

Thank You!

Now go to GitHub and try it out! github.com/johnmcfarlane/cnl

```
git clone https://github.com/johnmcfarlane/cnl.git
```

Bonus Slides - Beyond Exponents

`std::ratio` scales things statically:

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template<int Num, int Denom = 1> class ratio;
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What if `Exponent` was replaced with a type parameter?

```
// equivalent to fixed_point<int, -8, 2>
using a = fixed_point<int, ratio<1, 256>>;
```

Bonus Slides - Beyond Exponents

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template<int Num, int Denom = 1> class ratio;
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What if `Exponent` was replaced with a type parameter?

```
// equivalent to fixed_point<int, -8, 2>
using a = fixed_point<int, ratio<1, 256>>;
```

This should be possible: simply separate `fixed_point`'s two concerns:

```
// a type which stores an integer and scales it
template<typename Rep, typename Scale>
class scaled_integer;

// a type which scales integers
template<int Exponent, int Radix> class power;
```

Bonus Slides - Beyond Exponents

Now `fixed_point` is just one of many `scaled_integer` types.

```
template<typename Rep, int Exponent, int Radix>
using fixed_point = scaled_integer<Rep, power<Exponent, Radix>>

// (Decimal fixed-point is already on the to-do list.)
template<typename Rep, int Exponent>
using decimal_fixed_point = scaled_integer<Rep, power<Exponent, 10>>
```

Bonus Slides - Beyond Exponents

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```
template<typename Rep, int Exponent, int Radix>
using fixed_point = scaled_integer<Rep, power<Exponent, Radix>>

// (Decimal fixed-point is already on the to-do list.)
template<typename Rep, int Exponent>
using decimal_fixed_point = scaled_integer<Rep, power<Exponent, 10>>
```

And a souped-up `std::ratio` is another way to scale integers.

```
template<typename Rep, int Power>
using dollar = scaled_integer<Rep, ratio<1, 100>>;

template<typename Rep, int Power>
using angle = scaled_integer<Rep, ratio<1, 360>>;

// units in the range [0, 1]
template<typename Rep>
using unit = scaled_integer<Rep, ratio<1, std::numeric_limits<Rep>::max()>>;
```

Bonus Slides - Beyond Exponents

And scaling of integers is just the beginning...

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And scaling of integers is just the beginning...

```
// type-safety prevents units from being confused
struct length_tag {};
struct time_tag {};

// individual quantities
template<typename BaseTag, int Power>
struct base_quantity;

// is quantity a scale, like exponent or std::ratio?
template<typename ... BaseQuantities>
struct quantity;

using time = quantity<base_quantity<time_tag, 1>>;
using length = quantity<base_quantity<length_tag, 1>>;

template<typename ... BaseQuantitiesA, typename ... BaseQuantitiesB>
auto operator/(quantity<BaseQuantitiesA...>, quantity<BaseQuantitiesB...>)

// quantity<base_quantity<length_tag, 1>, base_quantity<time_tag, -1>>
auto speed = length{} / time{};
```

Disclaimer: none of this compiles ... yet!

Thank You! - @JSAMcFarlane

Now go to GitHub and try it out!

```
git clone https://github.com/johnmcfarlane/cnl.git
```

slides: github.com/johnmcfarlane/presentations/tree/master/2018-05-09_ACCU_Bay_Area