constexpr: Applications

By Scott Schurr for Ripple Labs at CppCon September 2015

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constexpr Contexts

- New keyword: constexpr
- Introduced in C++11
- constexpr values:
  - Definition of an object
  - Declaration of a static data member of literal type
- constexpr computations:
  - Functions
  - Constructors

constexpr Values

```
constexpr int const_3 = 3;                    // Object definition
constexpr double half = 0.5;                  // Object definition
static_assert (half < const_3, "Yipe!");
constexpr char tile_fixative[] = "grout"; // Object definition
static_assert (tile_fixative[5] == '\0', "Yipe!");

void free_func () {
    constexpr float pi = 3.14159265;      // Object definition
    static_assert ((3.1 < pi) && (pi < 3.2), "Yipe!");
}

struct my_struct {
    // Static data member of literal type
    static constexpr char who[] = "Gabriel Dos Reis";
    static_assert (who[0] == 'G', "Yipe!");
    static constexpr const char* a = &who[1];
    static_assert (*a == 'a', "Yipe!");
};
```

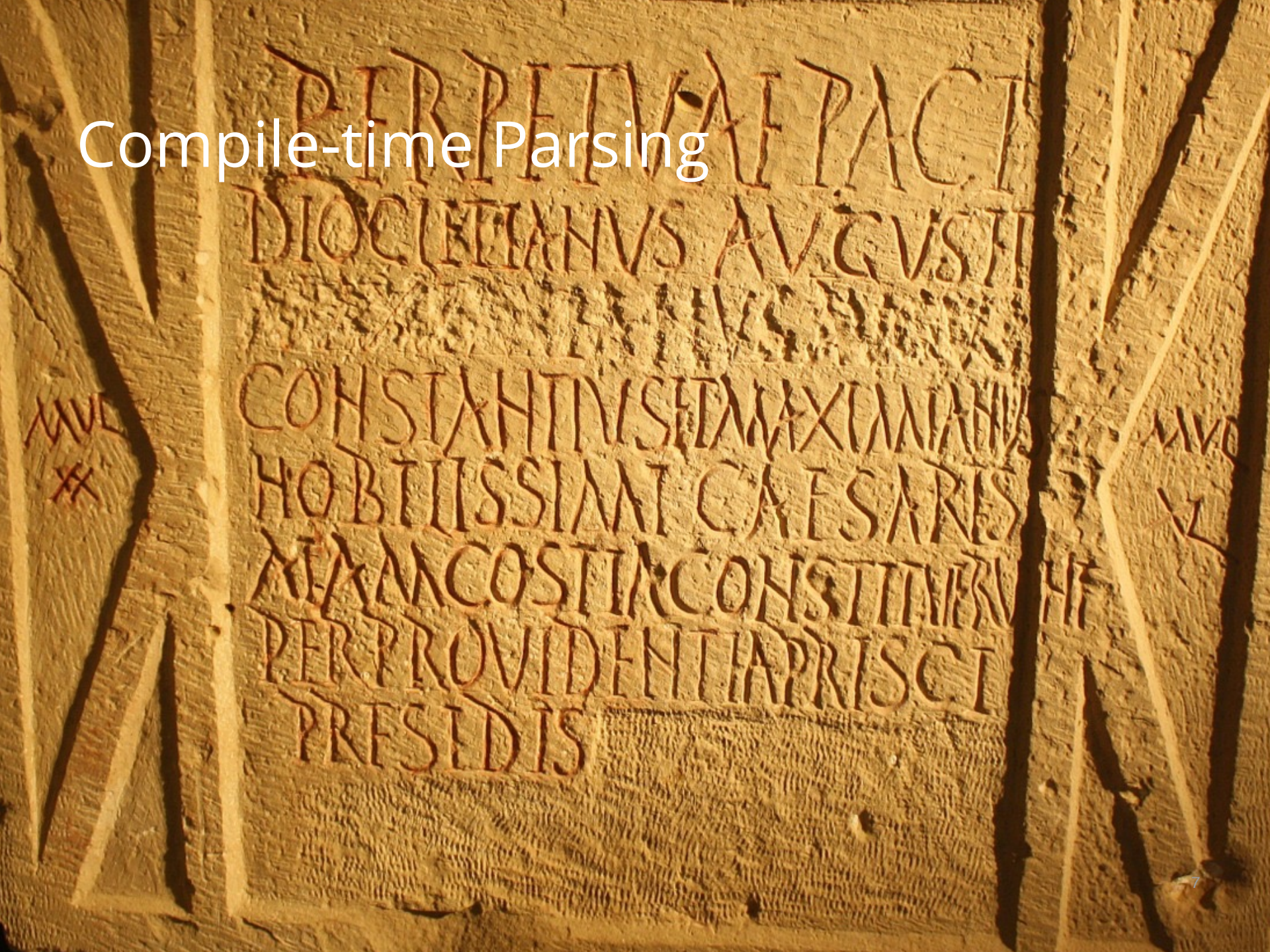
constexpr Computations

- constexpr declaration allowed on:
  - Free functions
  - Member functions
  - Constructors
- Allowed code:
  - Constrained in C++11
  - Relaxed somewhat in C++14
- constexpr constructor allows user-defined literal types

Topics

- Compile-time parsing
- Compile-time containers
- Compile-time floating point
- Future and Summary

Compile-time Parsing



C++11 binary literal

- No native binary literal in C++11
- Can we make one?

constexpr11_bin

```
template <typename T = std::uint32_t>
constexpr T constexpr11_bin(
    const char* t,
    std::size_t b = 0,       // bit count
    T x = 0)                 // accumulator
{
    return
        *t == '\0' ? x :     // end recursion
        b >= std::numeric_limits<T>::digits ?
            throw std::overflow_error("Too many bits!") :
        *t == ',' ? constexpr11_bin<T>(t+1, b,    x) :
        *t == '0' ? constexpr11_bin<T>(t+1, b+1, (x*2)+0) :
        *t == '1' ? constexpr11_bin<T>(t+1, b+1, (x*2)+1) :
        throw std::domain_error(
            "Only '0', '1', and ',' may be used");
}
```

Using constexpr11_bin

```
int main()
{
    using u8_t = std::uint8_t;

    constexpr u8_t maskA = constexpr11_bin<u8_t>("1110,0000");
    constexpr u8_t maskB = constexpr11_bin<u8_t>("0001,1000");
    constexpr u8_t maskC = constexpr11_bin<u8_t>("0000,0110");
    constexpr u8_t maskD = constexpr11_bin<u8_t>("0000,0001");

    static_assert(
        maskA + maskB + maskC + maskD == 0xFF, "Yipe!");

    constexpr double d = constexpr11_bin<double>("1000");
    static_assert(d == 8.0, "Yipe!");

    return 0;
}
```

C++14 binary literal

- Much easier to code than in C++11
- Not so useful…
  - C++14 has built-in binary literals
  - 0b1101’0011

constexpr14_bin

```
template <typename T = std::uint32_t>
constexpr T constexpr14_bin(const char* t)
{
    T x = 0;
    std::size_t b = 0;
    for (std::size_t i = 0; t[i] != '\0'; ++i) {
        if (b >= std::numeric_limits<T>::digits)
            throw std::overflow_error("Too many bits!");
        switch (t[i]) {
        case ',':                       break;
        case '0': x = (x*2);    ++b; break;
        case '1': x = (x*2)+1; ++b; break;
        default:  throw std::domain_error(
            "Only '0', '1', and ',' may be used");
        }
    }
    return x;
}
```

More constexpr Questions

- What are the limits?
- What do user errors look like?
- Do users want runtime execution?

constexpr Limits

Minimum recommended implementation quantities [Annex B]:

- Recursive constexpr function invocations: 512
- Full-expressions evaluated within a core constant expression: 1,048,576

Actual limits are up to your compiler(s)

User Errors at Compile Time

```
int main()
{
    constexpr auto mask =
        constexpr11_bin<std::uint8_t>("1110 0000");
    static_assert(mask == 0xE0, "Yipe!");
    return 0;
}
```

```
error: constexpr variable 'mask' must be initialized by a
      constant expression
 constexpr auto mask =
                ^
note: subexpression not valid in a constant expression
  throw std::domain_error(
  ^
note: in call to 'constexpr11_bin({&"1110 0000"[0],
      9}, 4, 4, 14)'
  t[i] == '0' ? constexpr11_bin<T>(t, i+1, b+1, (x*2)+0) :
                ^
```

User Errors At Runtime

```
int main()
{
    auto mask =  // <- Not constexpr!
        constexpr11_bin<std::uint8_t>("1110 0000");
    assert(mask == 0xE0);
    return 0;
}
```

```
libc++abi.dylib: terminating with uncaught exception of
type std::domain_error: Only '0', '1', and ',' may be used
Abort trap: 6
```

- Runtime exception for forgetting constexpr

Runtime Execution?

- Really handy for debugging
- In this case not so good for users
- Little reason for runtime conversion
- Which one causes a runtime error?

```
constexpr auto maskA =
     constexpr11_bin<std::uint8_t>("1110 0000");

auto maskB =
     constexpr11_bin<std::uint8_t>("0001 1111");
```

- Every invocation has error potential

Guidance

Make interfaces easy to use correctly and hard to use incorrectly.

Item 18 *Effective C++ Third Edition* by Scott Meyers

Prefer compile- and link-time errors to run-time errors.

Item 14 *C++ Coding Standards* Sutter and Alexandrescu

A Way to Force Compile-Time Only?

- Not within the standard
- But a hack that sometimes works

Unresolved Symbol In Throw

```
extern const char* compile11_bin_invoked_at_runtime;
template <typename T = std::uint32_t>
constexpr T compile11_bin(
    constexpr_txt t,
    std::size_t i = 0,      // index
    std::size_t b = 0,      // bit count
    T x = 0)                // accumulator
{
    return
        i >= t.size() ? x : // end recursion
        b >= std::numeric_limits<T>::digits ?
            throw std::overflow_error("Too many bits!") :
        t[i] == ',' ? compile11_bin<T>(t, i+1, b,    x) :
        t[i] == '0' ? compile11_bin<T>(t, i+1, b+1, (x*2)+0) :
        t[i] == '1' ? compile11_bin<T>(t, i+1, b+1, (x*2)+1) :
        throw std::domain_error( // Only '0', '1', and ','
            compile11_bin_invoked_at_runtime);
}
```

User Errors at Link-Time

```
int main()
{
    auto mask =  // <- Not constexpr!
        compile11_bin<std::uint8_t>("1110 0000");
    assert(mask == 0xE0);
    return 0;
}
```

```
Undefined symbols for architecture x86_64:
  "_compile11_bin_invoked_at_runtime", referenced from:
      unsigned char compile11_bin<unsigned char>(constexpr_txt,
unsigned long, unsigned long, unsigned char) in main11.o
ld: symbol(s) not found for architecture x86_64
clang: error: linker command failed with exit code 1 (use -v to
see invocation)
```

Why Does It Work?

The throw must not be evaluated at compile time

The throw must be included in a runtime implementation

The runtime implementation cannot link because of the unresolved extern

Is This The Best You Can Do?

- Error is ugly
- Doesn’t identify line that caused error
- May not work:

> …a function that is called in a potentially-evaluated constant expression is still odr-used, so the compiler is permitted to emit it…
>
> Richard Smith

- Any technique failure is false positive

Technique Summary

- constexpr function must have a throw
- Declare unresolved extern const char*
- Reference unresolved extern in throw

Compile-Time Parsing Summary

- Interesting technique
- Limited applicability
- But still useful
- Consider unresolved extern hack

Topics

- Compile-time parsing
- Compile-time containers
- Compile-time floating point
- Future and Summary

Compile-Time Containers

Motivation

- constexpr supports arrays
- Why bother?
  - Errors caught at compile-time
  - Improved code readability
  - Reduce executable footprint
  - Avoid global init order issues
  - Avoid initialization thread races
- Actual use cases?

First constexpr Array

```
int main()
{
    constexpr int ramp_len = 10;
    constexpr float ramp[ramp_len] {
        0.0f,0.1f,0.2f,0.3f,0.4f,0.5f,0.6f,0.7f,0.8f,0.9f
    };
    for (int ramps = 0; ramps < 10; ++ramps) {
        for (int i = 0; i <  ramp_len; ++i) {
            // Moving average filter
            float avg = ramp[i == 0 ? ramp_len - 1 : i];
            avg       += ramp[i];
            avg       += ramp[i == ramp_len - 1 ? 0 : i];
            avg       /= 3;
            std::cout << avg << std::endl;
        }
    }
    return 0;
}
```

More Interesting Array

```
constexpr float pi = pi_num<float>();
constexpr std::size_t sine_size = 10;
constexpr float sine[sine_size] {
    constexpr_sin(0.0f * 2 * pi),
    constexpr_sin(0.1f * 2 * pi),
    constexpr_sin(0.2f * 2 * pi),
    constexpr_sin(0.3f * 2 * pi),
    constexpr_sin(0.4f * 2 * pi),
    constexpr_sin(0.5f * 2 * pi),
    constexpr_sin(0.6f * 2 * pi),
    constexpr_sin(0.7f * 2 * pi),
    constexpr_sin(0.8f * 2 * pi),
    constexpr_sin(0.9f * 2 * pi),
};
```

- Self documenting
- Avoids typos

Returning a constexpr Array

```
// Can't use C++14 std::array, since element access is not
// defined as constexpr.
template <typename T, std::size_t N>
class array_result {
private:
    constexpr static std::size_t size_ = N;
    T data_[N] {};  // T default constructor essential!
public:
    constexpr std::size_t size() const { return N; }

    constexpr T& operator[](std::size_t n)
        { return data_[n]; }
    constexpr const T& operator[](std::size_t n) const
        { return data_[n]; }
    using iterator = T*;
    constexpr iterator begin() { return &data_[0]; }
    constexpr iterator end()   { return &data_[N]; }
    // ...
```

Non-const constexpr Methods

```
template <typename T, std::size_t N>
class array_result {
    // ...
    constexpr T& operator[](std::size_t n)
        { return data_[n]; }
    constexpr const T& operator[](std::size_t n) const
        { return data_[n]; }
    using iterator = T*;
    constexpr iterator begin() { return &data_[0]; }
    constexpr iterator end()   { return &data_[N]; }
    // ...
```

- Non-const methods to modify array contents
- Use before array_result is returned

generate_sine

```
template <typename T, std::size_t N>
constexpr auto generate_sine() -> array_result<T, N>
{
    array_result<T, N> ret;                          // Init ret

    constexpr T pi = pi_num<T>();
    for (int i = 0; i < N; i += 1) {
        T f = i;
        ret[i] = constexpr_sin(f * 2 * pi / N);      // Modify ret
    }
    return ret;                                      // Return ret
}
```

Try generate_sine

```
constexpr float sine_lookup (std::size_t i)
{
    constexpr auto table =
        generate_sine<float, 256>();

    if (i >= table.size()) {
        throw std::out_of_range ("Index too big.");
    }
    return table[i];
}

void try_sine_lookup ()
{
    constexpr float f1 = sine_lookup (100); // Compile time
    const float f2 = sine_lookup (100);     // May be run time
    assert (f1 == f2);
}
```

constexpr_to_upper

```
template <std::size_t N>
constexpr auto constexpr_to_upper (const char(&in)[N])
    -> array_result<char, N>
{
    array_result<char, N> out;

    for (std::size_t i = 0; in[i] != 0; ++i)
    {
        char c = in[i];
        out[i] = ((c < 'a') || ( c > 'z')) ?
            c : c - ('a' - 'A');
    }
    return out;
}
```

Test constexpr_to_upper

```
void test_constexpr_to_upper()
{
    static constexpr auto a =
        constexpr_to_upper ("Frank Lloyd Wright");
    static_assert (a.size() == 19, "Yike!");
    static_assert (a[a.size() - 2] == 'T', "Yike!");
    std::cout << &a[0] << std::endl;
}
```

```
$ ./test_to_upper
FRANK LLOYD WRIGHT
$
```

```
    .section   __TEXT,__const
__ZZ23test_constexpr_to_uppervE1a:
    .asciz "FRANK LLOYD WRIGHT"
```

So far we have...

- Computed array entries
- Generated an array
- Returned an array based on input

All at compile time

Let’s validate that a constexpr array is alphabetical

constexpr_str_less

```
constexpr bool constexpr_str_less (
    const char* lhs, const char* rhs)
{
    std::size_t i = 0;
    do
    {
        if (lhs[i] != rhs[i])
        {
            return lhs[i] < rhs[i];
        }
    } while (lhs[i++] != '\0');
    return false;
}
```

constexpr_is_alphabetical

```
constexpr bool constexpr_is_alphabetical (
    const char* const* b, const char* const* e)
{
    for (const char* const* i = b + 1; i < e; ++i)
    {
        if (constexpr_str_less(*i, *(i - 1)))
        {
            return false;
        }
    }
    return true;
}
```

Test constexpr_is_alphabetical

```
void test_is_alphabetical()
{
    constexpr std::size_t count = 4;
    constexpr const char* architects[count] =
    {
        "Daedalus",
        "Michelangelo",
        "Pei, I. M.",
        "Wright, Frank Lloyd"
    };

    static_assert (
        constexpr_is_alphabetical(
            &architects[0], &architects[count]),
            "architects not alphabetical!");
}
```

Let the Compiler Do the Sort

```
// Can't default cmp to std::less; it's not constexpr.
template <typename Itr, typename Cmp>
constexpr void constexpr_insertion_sort (Itr b, Itr e, Cmp cmp)
{
    static_assert (std::is_same <bool,
        decltype (cmp (*b, *e))>::value, "cmp not valid.");
    using T = typename std::iterator_traits<Itr>::value_type;
    if (b == e) return;
    for (Itr i = b + 1; i != e; ++i) {
        Itr j = i;
        const T temp = i[0];
        for (j = i;
            (j != b) && cmp(temp, j[-1]); --j) {
            j[0] = j[-1];
        }
        j[0] = temp;
    }
}
```

Hold It!

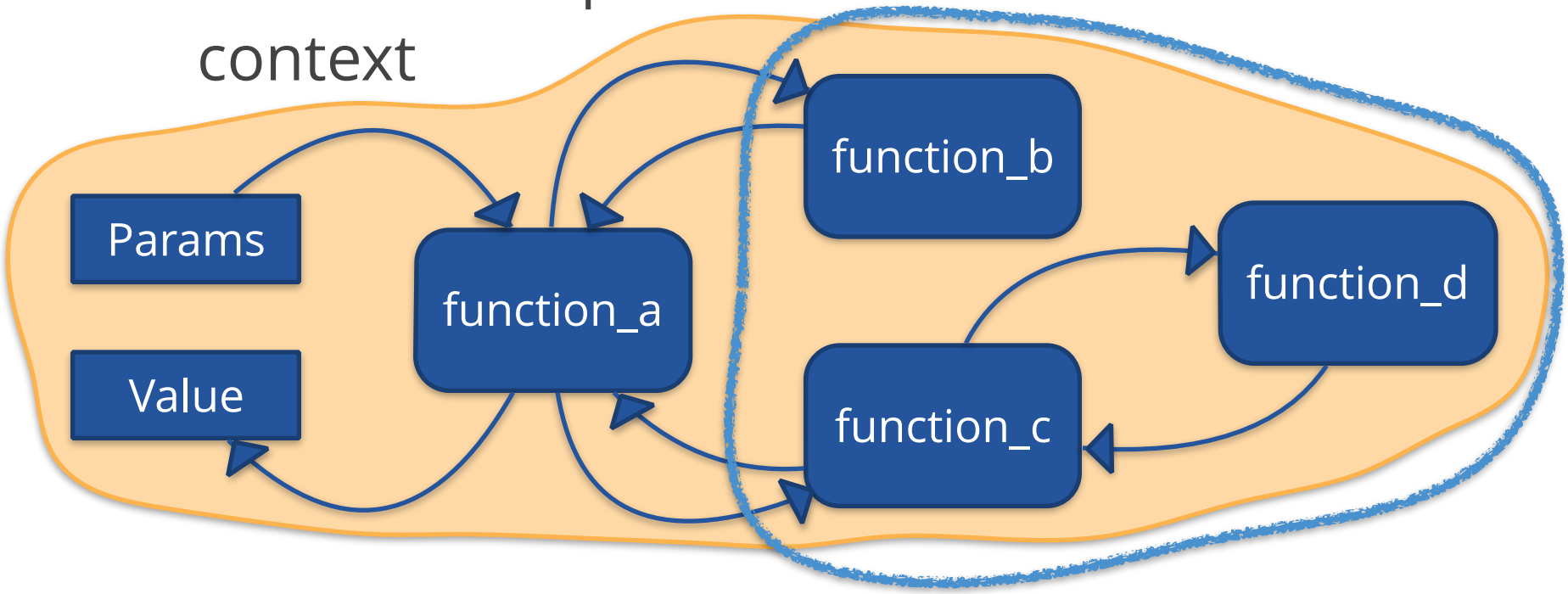
A constexpr function that returns void?

```
template <typename Itr, typename Cmp>
constexpr void
constexpr_insertion_sort (Itr b, Itr e, Cmp cmp)
{
    // ...
```

- Illegal in C++11
- Useful in C++14 if...
- Not the outermost constexpr function

C++14 constexpr Model

- C++ interpreter
- Each constexpr result has its entire context



- Inner calls can return void

constexpr_str_sort

```
template <std::size_t N>
constexpr auto constexpr_str_sort (
    const char* const(&in)[N])
        -> array_result<const char*, N>
{
    array_result<const char*, N> out;

    // Copy from in to out
    for (std::size_t i = 0; i < N; ++i) {
        out[i] = in[i];
    }

    // Sort
    constexpr_insertion_sort (
        out.data(), out.size(), constexpr_str_less);
    return out;
}
```

Test constexpr_str_sort

```
void test_str_sort()
{
    constexpr const char* architects[] =
        { "Pei", "Daedalus", "Wright", "Michelangelo" };

    constexpr auto a = constexpr_str_sort (architects);
    static_assert (a.size() == 4, "Yike!");

    for (std::size_t i = 0; i < a.size(); ++i) {
        std::cout << i << " : " << a[i] << std::endl;
    }
}

$ ./test_str_sort
0 : Daedalus
1 : Michelangelo
2 : Pei
3 : Wright
```

Validate or Sort?

Depends on your compile time

- Validation is O(n)
- A good sort is O(n log n)

Is the convenience of compile-time sort worth the compile time?

Compile-Time Associative Containers

Consider replacing associative containers with sorted vectors.

Item 23 *Effective STL* by Scott Meyers

Um, or sorted arrays...

Anon

Add More Iterators to array_result<>

```
template <typename T, std::size_t N>
class array_result {

    // ...
    using const_iterator = const T*;
    constexpr const_iterator
    begin() const { return &data_[0]; }

    constexpr const_iterator
    cbegin() const { return &data_[0]; }

    constexpr const_iterator
    end() const { return &data_[N]; }

    constexpr const_iterator
    cend() const { return &data_[N]; }
};
```

std::equal_range() With array_result<>

```
void test_str_sort_find()
{
    // Construct sorted array "a" at compile time.
    constexpr const char* architects[] =
        { "Pei", "Daedalus", "Wright", "Michelangelo" };
    constexpr auto a = constexpr_str_sort (architects);
    static_assert (a.size() == 4, "Yike!");

    // Search sorted array at run time.
    auto range = std::equal_range(
        a.begin(), a.end(), "Pei", constexpr_str_less);

    assert ((range.first + 1) == range.second);  // Found Pei
    assert (range.first - a.begin() == 2);       // Index 2
    assert (strcmp (*range.first, "Pei") == 0);  // It's Pei
}
```

constexpr Unordered Containers?

- A much bigger stretch
  - Potential hash collisions require an unknown number of buckets
- But values known at compile time

- Consider a minimal perfect hash

hash_and_str

```
// Can't use std::pair because the assignment
// operator is not constexpr.
struct hash_and_str
{
    std::uint32_t hash;
    const char* str;

    static constexpr bool
    less (const hash_and_str& lhs, const hash_and_str& rhs) {
        return lhs.hash < rhs.hash;
    }
};
```

Fill In the Hash Container

```
using hash_fn_t = std::uint32_t (*)(const char*);

template <std::size_t N>
constexpr auto constexpr_str_hash (
    const char* const(&in)[N], hash_fn_t hash_fn)
    -> array_result<hash_and_str, N>
{
    array_result<hash_and_str, N> out;

    // Copy from in to out.  Compute hash.
    for (std::size_t i = 0; i < N; ++i) {
        out[i].hash = hash_fn (in[i]);
        out[i].str  = in[i];
    }
    // ...
```

Sort and Verify the Hash

```
    // ...
    // Sort.  Can't use a lambda.  No lambdas in constexpr.
    constexpr_insertion_sort (
        out.begin(), out.end(), hash_and_str::less);

   // Verify hash is perfect and minimal.
    const std::uint32_t base = (N == 0 ? 0 : out[0].hash);
    for (std::size_t i = 0; i < N; ++i) {
        if (out[i].hash != (i + base)) {
            throw std::invalid_argument(
                "Hash is not minimal and perfect.");
        }
    }
    return out;
}
```

Perfect Minimal Hash Function

```
// Minimal perfect hash found manually.
constexpr std::uint32_t architects_hash (const char* in)
{
    std::uint32_t h = 2166136261;
    for (std::size_t i = 0; in[i] != '\0'; ++i)
    {
        h = (h * 16777619) ^ in[i];
    }
    h = h & 0x03;
    return h;
}
```

Adapted from http://www.eternallyconfuzzled.com/tuts/algorithms/jsw_tut_hashing.aspx

Testing constexpr_str_hash

```
void test_str_hash()
{
    constexpr const char* architects[] =
        { "Pei", "Daedalus", "Wright", "Michelangelo" };

    constexpr auto a =
        constexpr_str_hash (architects, architects_hash);

    for (std::size_t i= 0; i < a.size(); ++i) {
        std::cout << a[i].hash
            << " : " << a[i].str << std::endl;
    }
}
$ ./test_str_hash
0 : Daedalus
1 : Pei
2 : Wright
3 : Michelangelo
```

constexpr Container Downsides

- Container is immutable
- Call site must know container size
  - Usually from template parameter
- Watch evaluated expression limit
- May not contain std::string
  - std::string requires allocator
  - std::string_ref may help

constexpr Container Summary

- constexpr containers can…
  - Be validated at compile time
  - Prevent initialization race conditions
  - Reduce code footprint
- C++14 makes it somewhat natural
- Lack of std::string support is awkward
- Accidental use at runtime can be bad
  - Consider unresolved extern hack

Topics

- Compile-time parsing
- Compile-time containers
- Compile-time floating point
- Future and Summary

Compile-Time Floating Point

Motivation

- constexpr supports floating point
- Why bother?
  - Errors caught at compile-time
  - Reduce executable footprint
  - Improve runtime execution speed
- Actual use cases?

Use Case: Biquad Coefficients

- Biquad is a common DSP filter
- Two parts:
  1. Coefficients
     - Determine filter response
     - Typically hard to compute
     - Constant for a given response
  2. Recursive computation
     - Provides filter output
     - Typically fast to compute
     - Executes once per sample

Buckle Up!

I wanted a real example

We need some infrastructure

Coefficient computing using constexpr

What We're Computing...

```
enum class BiquadType : unsigned char {
    lowpass = 0,
    highpass,
    bandpass,
    notch,
    peak,
    lowshelf,
    highshelf
};
template <typename T>
struct Coeffs {
    T a0 = 0;
    T a1 = 0;
    T a2 = 0;
    T b1 = 0;
    T b2 = 0;
};
```

BiquadCoeffs

```
template <typename T = double> // T <- storage type
class BiquadCoeffs
{
public:
    template <typename U>
    constexpr BiquadCoeffs(
        BiquadType type, U fc, U q, U peakGainDB)
    : type_(type)
    , coeffs_(computeCoeffs<T>(type, fc, q, peakGainDB))
    { }
private:
    template <typename U> friend class Biquad;
    constexpr T process(T in, T& z1, T& z2) const;
private:
    BiquadType type_;
    Coeffs<T> coeffs_;
};
```

computeCoeffs

```
template <typename T, typename U> // T <- storage type
constexpr Coeffs<T> computeCoeffs (
    BiquadType type, U fc, U q, U peakGainDB)
{
    using W = typename std::common_type<T, U>::type;
    if ((fc < 0) || (fc >= 0.5f )) {
        throw std::domain_error(
            "fc must be less than the Nyquist frequency.");
    }

    Coeffs<T> coeffs;
    W norm = 0;
    const W v = constexpr_pow<W>(
        10, constexpr_abs<W>(peakGainDB) / 20);
    const W k = constexpr_tan<W>(pi_num<W>() * fc);
    switch (type) {
    ...
```

Coefficients by Type

```
case BiquadType::lowpass:
    norm = 1 / (1 + k / q + k * k);
    coeffs.a0 = static_cast<T>(k * k * norm);
    coeffs.a1 = static_cast<T>(2 * coeffs.a0);
    coeffs.a2 = coeffs.a0;
    coeffs.b1 = static_cast<T>(2 * (k * k - 1) * norm);
    coeffs.b2 = static_cast<T>((1 - k / q + k * k) * norm);
    break;

case BiquadType::highpass:
    norm = 1 / (1 + k / q + k * k);
    coeffs.a0 = static_cast<T>(1 * norm);
    coeffs.a1 = static_cast<T>(-2 * coeffs.a0);
    coeffs.a2 = coeffs.a0;
    coeffs.b1 = static_cast<T>(2 * (k * k - 1) * norm);
    coeffs.b2 = static_cast<T>((1 - k / q + k * k) * norm);
    break;
...
```

Functions Created / Used

- `T pi_num<T> ()`
- `T constexpr_abs<T> (U x)`
- `T constexpr_pow<T> (U base, V exp)`
  - `T eulers_num<T> ()`
  - `T constexpr_log<T> (U x)`
  - `T constexpr_exp<T> (U x)`
  - `pair<T> constexpr_modf<T> (U x)`
- `T constexpr_tan<T> (U x)`
  - `T constexpr_sin<T> (U x)`
  - `T constexpr_cos<T> (U x)`

Using the Coefficients

```
template <typename T>
constexpr T
BiquadCoeffs<T>::process(T in, T& z1, T& z2) const
{
    T out = in * coeffs_.a0 + z1;
    z1 = in * coeffs_.a1 + z2 - coeffs_.b1 * out;
    z2 = in * coeffs_.a2 - coeffs_.b2 * out;
    return out;
}
```

- This is the runtime computation:
  - Adds
  - Subtracts
  - Multiplies

Biquad (not constexpr) Wraps It

```
template <typename T>
class Biquad {
public:
    explicit Biquad(BiquadCoeffs<T> const& coeffs)
    : coeffs_(coeffs)
    , z1_(0)
    , z2_(0) { }

    inline T process(T in) {
        return coeffs_.process(in, z1_, z2_);
    }

private:
    BiquadCoeffs<T> coeffs_;
    T z1_, z2_; // Hold changing recursion values
};
```

Using Biquad

```
void test_biquad()
{
    constexpr BiquadCoeffs<float> coeffs_l
        (BiquadType::lowpass, 0.05, 0.707, 0.0);
    Biquad<float> lowpass (coeffs_l);
    constexpr std::size_t ramp_size = 10;
    constexpr float ramp[ramp_size] {
        0.0f,0.2f,0.4f,0.6f,0.8f,1.0f,1.2f,1.4f,1.6f,1.8f
    };
    constexpr int sample_count = 101;
    float samples[sample_count];
    std::size_t i = 0;
    for (int j = 0; j < sample_count; ++j) {
        if (i >= ramp_size) {
            i = 0;
        }
        samples[j] = lowpass.process(ramp[i++]);
    }
}
```

constexpr BiquadCoeffs Benefits

Declare constexpr BiquadCoeffs

Assembly file 144 lines

Forget constexpr on BiquadCoeffs

Assembly file 2017 lines

Lots of additional machine instructions

Constrained platforms take heed!

Consider the unresolved symbol hack

constexpr Float Timing

constexpr_pow() at compile-time

vs

std::pow()

vs

constexpr_pow() at runtime

Timing Code 1

```
constexpr int repetitions = 10'000'000;

void compile_time()
{
    using namespace std::chrono;
    constexpr double two = 2.0;
    volatile static double sink;
    const auto start_t = high_resolution_clock::now();
    for (int i = 0; i < repetitions; ++i) {
        constexpr double sqrt2 = constexpr_pow (two, 0.5);
        sink = sqrt2;
    }
    const auto end_t = high_resolution_clock::now();
    auto elapsed = end_t - start_t;
    std::cout << "constexpr_pow at compile time: "
        << duration_cast<nanoseconds>(elapsed).count()
        << " ns" << std::endl;
}
```

Timing Code 2

```
constexpr int repetitions = 10'000'000;

void run_time()
{
    using namespace std::chrono;
    volatile double two = 2.0;
    volatile static double sink;
    const auto start_t = high_resolution_clock::now();
    for (int i = 0; i < repetitions; ++i) {
        double sqrt2 = std::pow (two, 0.5);
        sink = sqrt2;
    }
    const auto end_t = high_resolution_clock::now();
    auto elapsed = end_t - start_t;
    std::cout << "std::pow:                    "
        << duration_cast<nanoseconds>(elapsed).count()
        << " ns" << std::endl;
}
```

Timing Code 3

```
constexpr int repetitions = 10’000’000;

void constexpr_run_time()
{
    using namespace std::chrono;
    volatile  double two = 2.0;
    volatile static double sink;
    const auto start_t = high_resolution_clock::now();
    for (int i = 0; i < repetitions; ++i) {
        double sqrt2 = constexpr_pow (two, 0.5);
        sink = sqrt2;
    }
    const auto end_t = high_resolution_clock::now();
    auto elapsed = end_t - start_t;
    std::cout << "constexpr_pow at runtime:   "
        << duration_cast<nanoseconds>(elapsed).count()
        << " ns" << std::endl;
}
```

Timing Results: Intel i5 2.4 GHz

clang++ -std=c++1y -O3

```
constexpr_pow at compile time: 3828350 ns
std::pow:                     78555220 ns
constexpr_pow at runtime:   1772557008 ns
```

Normalized…

```
constexpr_pow at compile time:   1
std::pow:                       20
constexpr_pow at runtime:      463
```

Why the Time Differences?

- Compile time has no runtime cost
- pow() uses intrinsics on Intel machine
- constexpr_pow() can’t use intrinsics

Consider the unresolved symbol hack

Numeric Errors at Compile Time

```
void sqrt_neg2_compile_time ()
{
    constexpr double neg_sqrt2 = constexpr_pow (-2.0, 0.5);
    static_assert (neg_sqrt2 != 0, "Yipe!");
}
```

```
main.cpp:63:22: error: constexpr variable 'neg_sqrt2' must be
      initialized by a constant expression
    constexpr double neg_sqrt2 = constexpr_pow (-2.0, 0.5);
                     ^           ~~~~~~~~~~~~~~~~~~~~~~~~~~
./../constexpr_float/constexpr_log.h:21:9: note: subexpression
      not valid in a constant expression
        throw std::domain_error (
        ^
./../constexpr_float/constexpr_pow.h:28:23: note: in call to
      'constexpr_log(-2.000000e+00)'
    const W ln_base = constexpr_log<W> (base);
```

Numeric Errors at Runtime?

```
void sqrt_neg2_run_time ()
{
    const double neg_sqrt2 = std::pow (-2.0, 0.5);
    assert (!std::isnan (neg_sqrt2));
}
```

```
Assertion failed: (!std::isnan (neg_sqrt2)),
function sqrt_neg2_run_time, file main.cpp, line 73.
Abort trap: 6
```

std::pow() doesn't throw

- Sets errno — not allowed in constexpr
- Returns NaN

Floating Point Compiler Magic?

Could the compiler provide a constexpr value at compile time and an intrinsic at runtime?

Not without changing the interface of:

- functions that set errno
- functions that return a value through an output parameter

Math With Non-constexpr Interfaces

`sin(x)`	`cosh(x)`	`floor(x)`
`cos(x)`	`tanh(x)`	`fabs(x)`
`tan(x)`	`exp(x)`	`ldexp(x,n)`
`asin(x)`	`log(x)`	`frexp(x,*e)`
`acos(x)`	`log10(x)`	`mod(f,*ip)`
`atan(x)`	`pow(x,y)`	`fmod(x,y)`
`atan2(y,x)`	`sqrt(x)`	
`sinh(x)`	`ceil(x)`	

No Peeking at Float Internals!

```
void float_bits_ptr ()
{
    static constexpr float f1 {1.0f};
    constexpr const unsigned char* raw =
        reinterpret_cast<const unsigned char*>(&f1);
}
```

```
error: constexpr variable 'raw' must be initialized by a
      constant expression
    constexpr const unsigned char* raw =
                                   ^
note: reinterpret_cast is not allowed in a constant expression
        reinterpret_cast<const unsigned char*>(&f1);
        ^
1 error generated.
```

No Peeking at Float Internals!

```
void float_bits_union ()
{
    union f_to_i {
        float f32;
        unsigned char raw[sizeof (float)];
        constexpr f_to_i (float f) : f32(f) { }
    };
    constexpr f_to_i u (1.0f);
    static_assert (u.raw[0] != 0, "Yipe!");
}
```

```
error: static_assert expression is not an integral constant
      expression
    static_assert (u.raw[0] != 0, "Yipe!");
                   ^~~~~~~~~~~~~
note: read of member 'raw' of union with active member 'f32' is
      not allowed in a constant expression
1 error generated.
```

Compile-Time Floating Point Summary

- constexpr floating point can…
  - Identify errors at compile time
  - Improve runtime speed
  - Reduce code footprint
  - Omit entire libraries from runtime
- C++14 makes it very natural
- Little standard library support so far
- Accidental use at runtime can be bad
  - Consider unresolved extern hack

Topics

- Compile-time parsing
- Compile-time containers
- Compile-time floating point
- Future and Summary

Future and Summary

Future

Expect to see lots more constexpr in the standard library

There’s work on constexpr lambdas

Summary

Good for:

- Errors caught at compile-time
- Improved code readability
- Reduce executable footprint
- Avoid global init order issues
- Avoid initialization thread races

Accidental use of constexpr code at runtime can slow execution

- Consider unresolved extern hack

C++ at compile time?

Absolutely!

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- cppreference.com: constexpr_txt

http://en.cppreference.com/w/cpp/language/constexpr

- Nigel Redmon: Biquad code

http://www.earlevel.com/main/2012/11/26/biquad-c-source-code/

- All errors belong to Scott Schurr

Questions?

Thanks for attending