

CS100 Lecture 28

Compile-time Computations and Metaprogramming

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Example: Binary literals

Binary literals

Built-in binary literals support: C++14 and C23.

```
switch (rv32inst.opcode) { // 32-bit RISC-V instruction opcode
    case 0b0110011: /* R-format */
    case 0b0010011: /* I-format (not load) */
    case 0b0000011: /* I-format: load */
    case 0b0100011: /* S-format */
    // ...
}
```

How do people write binary literals when there is no built-in support?

Runtime solution? No!

This is not satisfactory: The value is computed at run-time!

```
int dec2bin(int x) {
    int result = 0, pow_two = 1;
    while (x > 0) {
        result += (x % 10) * pow_two;
        x /= 10;
        pow_two *= 2;
    }
    return result;
}

void foo(const RV32Inst &inst) {
    const int forty_two = dec2bin(101010); // correct, but slow.
    switch (inst.opcode) {
        case dec2bin(110011): // Error! 'case' label must be compile-time constant!
            // ...
    }
}
```

Preprocessor metaprogramming solution

and ## operators: Both are used in function-like macros.

#x : stringify x .

```
#define SHOW_VALUE(x) std::cout << #x << " == " << x  
  
int ival = 42;  
SHOW_VALUE(ival); // std::cout << "ival" << " == " << ival;
```

a##b : Concatenate a and b .

```
#define DECLARE_HANDLER(name) void handler_##name(int err_code)  
  
DECLARE_HANDLER(overflow); // void handler_overflow(int err_code);
```

Preprocessor metaprogramming solution

<https://stackoverflow.com/a/68931730/8395081>

```
#define BX_0000 0
#define BX_0001 1
#define BX_0010 2
// .....
#define BX_1110 E
#define BX_1111 F

#define BIN_A(x) BX_##x

#define BIN_B(x, y) 0x##x##y
#define BIN_C(x, y) BIN_B(x, y)

#define BIN(x, y) BIN_C(BIN_A(x), BIN_A(y))

const int x = BIN(0010, 1010); // 0x##BX_0010##BX_1010 ==> 0x2a ==> 42
```

Template metaprogramming solution

```
template <unsigned N> struct Binary {  
    static const unsigned value = Binary<N / 10>::value * 2 + (N % 10);  
};  
template <> struct Binary<0u> {  
    static const unsigned value = 0;  
};  
  
void foo(const RV32Inst &inst) {  
    const auto x = Binary<101010>::value; // 42  
    switch (inst.opcode) {  
        case Binary<110011>::value: // OK.  
            // ...  
    }  
}
```

Compared to preprocessor metaprogramming, template metaprogramming is more powerful, and less error-prone.

Modern C++: constexpr function

Just mark the function `constexpr`, and the compiler will be able to execute it!

```
constexpr int dec2bin(int x) {  
    int result = 0, pow_two = 1;  
    while (x > 0) {  
        result += (x % 10) * pow_two; x /= 10; pow_two *= 2;  
    }  
    return result;  
}  
  
void foo(const RV32Inst &inst) {  
    switch (inst.opcode) {  
        case dec2bin(101010): // OK. Since 101010 is a compile-time constant,  
                               // the function is executed at compile-time and  
                               // produces a compile-time constant.  
  
        // ...  
    }  
}
```

Metaprogramming

Metaprogramming is a programming technique in which computer programs have the ability to **treat other programs as their data**.

- Read, generate, analyze or transform other programs, and even itself.

Typical problems that needs metaprogramming

Write a function that selects different behaviors **at compile-time** according to the argument?

- e.g. The `std::distance` function (in this week's recitation).

Generate some code according to the members of my class, without too much manual modification?

- e.g. Serialization: Generate `operator>>` automatically for my class that prints the members one-by-one?
- e.g. "Metaclasses": Generate the getters and setters automatically for each of my data members?

.....

Compile-time computations

How much work can be done in compile-time?

- Call to numeric functions with compile-time known arguments?
 - e.g. Can `std::acos(-1)` be computed in compile-time?
- Manipulation of compile-time known strings?
 - e.g. Preparation of compile-time known regular expressions: [CTRE](#)
- Even crazier: [Compile-time raytracer?!](#)
 - The computations are done entirely in compile-time. At run-time, the only work is to output the image.

Anything can be computed in compile-time, provided that the arguments are compile-time known!

constexpr and **constexpr**

constexpr

Constant expressions: expressions that are evaluated at compile-time.

constexpr variables:

```
constexpr double dval = 5.2;  
const int ival = 42;
```

By declaring a variable `constexpr`, we mean that its value is compile-time known, and will not change.

- A `constexpr` variable is implicitly `const`.
- It must be initialized from a constant expression. Otherwise, an compile-error.

A `const` variable initialized from a constant expression is also a constant expression.

constexpr functions

constexpr functions are **potentially** executed at compile-time:

- When the arguments are constant expressions, it is run at compile-time and produces a constant expression.
- When the arguments are not constant expressions, it is run at run-time just like a normal function.

```
constexpr int gcd(int a, int b) {  
    while (b != 0) { a = std::exchange(b, a % b); }  
    return a;  
}  
  
int main() {  
    const int x = 10, y = 16;  
    constexpr auto result = gcd(x, y); // OK. The result is a constant expression.  
    int n, m; std::cin >> n >> m;  
    std::cout << gcd(n, m) << '\n'; // OK. It is computed at run-time.  
}
```

constexpr member functions

Member functions may also be `constexpr`. This is particularly useful for some very simple classes:

```
class StringView { // The 'StringView' class in lecture 27.
    const char *mStart{nullptr};
    std::size_t mLength{0};
public:
    // constructors
    constexpr StringView(const char *cstr);
    constexpr StringView(const std::string &str);
    // length
    constexpr std::size_t size() const { return mLength; }
    constexpr bool empty() const { return mStart; }
    // searching
    constexpr std::size_t find(char c, std::size_t pos = 0) const;
    // ...
};
```


Evolution of `constexpr` functions

`constexpr` was first introduced in C++11, with many restrictions:

- A single `return` statement only. No loops or branches.
- `constexpr` member functions are implicitly `const`: They cannot modify the data members.
- `virtual` functions cannot be `constexpr`.
- Very little standard library support.
-

At that time, it was *almost* Turing-complete.

Evolution of `constexpr` functions

In C++14:

- Multiple statements, loops and branches are allowed.
- `constexpr` member functions are no longer implicitly `const`.
- `constexpr` lambdas are still not yet allowed.
- Definitely Turing-complete.

In C++17:

- Much more standard library support: A lot more functions are made `constexpr` since C++17.
- Lambdas are automatically `constexpr` when it can be.

Evolution of `constexpr` functions

C++20: A huge step!

- `constexpr` functions can perform **dynamic memory allocations**!
 - Memory allocated at compile-time must also be released at compile-time.
- **Destructors** can be `constexpr` !
- Standard library **containers** like `std::vector` , `std::string` can be `constexpr` !
- Standard library **algorithms** are `constexpr` !
- `virtual` functions can be `constexpr` !

C++20: constexpr support in the standard library

```
#include <vector>
#include <algorithm>

constexpr int find_or_42(const std::vector<int> &vec, int target) {
    auto found = std::ranges::find(vec, target); // compile-time search
    return found == vec.end() ? 42 : *found;
}

int main() {
    // 'vec' is initialized in compile-time!
    constexpr auto result_1 = find_or_42({1, 4, 2, 8, 5, 7}, 10); // 42
    constexpr auto result_2 = find_or_42({2, 3, 5, 7}, 3);         // 3
    static_assert(result_1 == 42);
    static_assert(result_2 == 3);
}
```

`constexpr` numeric functions

Since C++23, some simple numeric functions in `<cmath>`, like `abs`, `ceil`, `floor`, `trunc`, `round`, ... are `constexpr`.

Since C++26, the **power, square/cubic root, trigonometric, hyperbolic, exponential and logarithmic** functions are all `constexpr` !

constexpr functions are pure

Pure functions (mathematical functions):

- Produce the same result when given the same arguments.
- Have no side effects. They cannot modify the value of variables outside them.
- Don't change the state of the program.

`constexpr`: Immediate functions

`constexpr` generates an *immediate* function.

- Every call of an immediate function generates a constant expression that is executed at compile-time.

`constexpr`

- cannot be applied to destructors.
- has the same requirements as a `constexpr` function.

constexpr: Immediate functions

- constexpr: **potentially** executed at compile-time.
- constexpr: **must be** executed at compile-time.

```
constexpr int sqr(int n) { return n * n; }  
constexpr int r = sqr(100); // OK.  
int x = 100;           // 'x' is not a constant expression!  
int r2 = sqr(x); // Error: 'sqr' must be called with constant expressions.
```

Note: A non-constexpr variable is not treated as a constant expression, even if initialized from a constant expression.

concept and constraints

Motivating example: sorting a `std::list`.

How should we sort a `std::list` ?

```
std::list<int> l = some_list();  
std::sort(l.begin(), l.end()); // Is this correct?
```

```

In file included from b.cpp:1:
In file included from /usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/algorithm:61:
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_algo.h:1948:22: error: invalid op
erands to binary expression ('std::_List_iterator<int>' and 'std::_List_iterator<int>')
        std::_lg(__last - __first) * 2,
                        ^~~~~~
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_algo.h:4861:12: note: in instanti
ation of function template specialization 'std::_sort<std::_List_iterator<int>, __gnu_cxx::__ops::_Iter_less
_iter>' requested here
        std::_sort(__first, __last, __gnu_cxx::__ops::_iter_less_iter());
        ^
b.cpp:6:8: note: in instantiation of function template specialization 'std::sort<std::_List_iterator<int>>' r
equested here
        std::sort(l.begin(), l.end());
        ^
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_iterator.h:625:5: note: candidate
template ignored: could not match 'reverse_iterator' against '_List_iterator'
        operator-(const reverse_iterator<_IteratorL>& __x,
        ^
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_iterator.h:1800:5: note: candidat
e template ignored: could not match 'move_iterator' against '_List_iterator'
        operator-(const move_iterator<_IteratorL>& __x,
        ^
In file included from b.cpp:1:
In file included from /usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/algorithm:61:
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_algo.h:1857:18: error: invalid op
erands to binary expression ('std::_List_iterator<int>' and 'std::_List_iterator<int>')
        if (__last - __first > int(_S_threshold))
                ^~~~~~
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_algo.h:1950:9: note: in instantia
tion of function template specialization 'std::_final_insertion_sort<std::_List_iterator<int>, __gnu_cxx::__
ops::_Iter_less_iter>' requested here
        std::_final_insertion_sort(__first, __last, __comp);
        ^
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_algo.h:4861:12: note: in instanti
ation of function template specialization 'std::_sort<std::_List_iterator<int>, __gnu_cxx::__ops::_Iter_less
_iter>' requested here
        std::_sort(__first, __last, __gnu_cxx::__ops::_iter_less_iter());
        ^
b.cpp:6:8: note: in instantiation of function template specialization 'std::sort<std::_List_iterator<int>>' r
equested here
        std::sort(l.begin(), l.end());
        ^
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_iterator.h:625:5: note: candidate
template ignored: could not match 'reverse_iterator' against '_List_iterator'
        operator-(const reverse_iterator<_IteratorL>& __x,
        ^
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/stl_iterator.h:1800:5: note: candidat
e template ignored: could not match 'move_iterator' against '_List_iterator'
        operator-(const move_iterator<_IteratorL>& __x,
        ^
2 errors generated.

```

Motivating example: sorting a `std::list`.

How should we sort a `std::list` ?

```
std::list<int> l = some_list();  
std::sort(l.begin(), l.end()); // No! We should use 'l.sort()'.
```

Ooops! `std::sort` requires a pair of *RandomAccessIterators*, but `std::list<T>::iterator` is not.

- But how can I understand the output of the compiler? It is complaining about "Invalid operands to `operator-` "

Motivating example: sorting a `std::list`.

Let's look at how `std::sort` is declared:

```
template <typename Iterator, typename Pred>  
void sort(Iterator begin, Iterator end, Pred compare);
```

`Iterator` is just a type deduced from the argument without any restrictions!

- In fact, this declaration accepts *anything* we pass to it.
- Errors can only be reported inside the function body, which might be in the form of "no match for".

Constraining the template arguments

```
template <typename Iterator, typename Pred>  
void sort(Iterator begin, Iterator end, Pred compare);
```

Can we declare the function with some constraints on the type `Iterator` ?

- We need something like

```
template <RandomAccessIterator Iterator, typename Pred>  
void sort(Iterator begin, Iterator end, Pred compare);
```

concept

A `concept` is a named set of **requirements** often used to constrain the template arguments.

Examples:

```
template <typename T>
concept movable = std::is_object_v<T> &&
                  std::move_constructible<T> &&
                  std::assignable_from<T &, T> &&
                  std::swappable<T>;
```

```
template <typename T>
concept Incrementable = requires (T x) {
    { x++ } -> std::same_as<T>;
}
```

Example: Constrained algorithms

The C++20 algorithms in `std::ranges` have well-defined constraints on the arguments:

```
template <std::random_access_iterator I, std::sentinel_for<I> S,  
          typename Comp = ranges::less, class Proj = std::identity>  
    requires std::sortable<I, Comp, Proj>  
constexpr I sort(I first, S last, Comp comp = {}, Proj proj = {});  
  
template<ranges::random_access_range R, typename Comp = ranges::less,  
        class Proj = std::identity>  
    requires std::sortable<ranges::iterator_t<R>, Comp, Proj>  
constexpr ranges::borrowed_iterator_t<R>  
    sort(R&& r, Comp comp = {}, Proj proj = {});
```


Example: Constrained algorithms

This time, the compiler will produce some human-readable output on violation of the requirements:

```
std::list<int> l = some_list();  
std::ranges::sort(l);
```

```
b.cpp:6:3: error: no matching function for call to object of type 'const __sort_fn'  
  std::ranges::sort(l);  
  ~~~~~^  
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/ranges_algo.h:1794:7: note: candidate  
template ignored: constraints not satisfied [with _Range = std::list<int> &, _Comp = ranges::less, _Proj = i  
dentity]  
  operator()(_Range&& __r, _Comp __comp = {}, _Proj __proj = {}) const  
  ^  
/usr/bin/../lib/gcc/x86_64-linux-gnu/13/../../../../include/c++/13/bits/ranges_algo.h:1790:14: note: because  
'std::list<int> &' does not satisfy 'random_access_range'  
  template<random_access_range _Range,  
  ^
```

Example: Compile-time polymorphism

Run-time polymorphism:

- "Shape" is a general concept, so we define an abstract base class.

```
struct Shape {  
    virtual void draw() const = 0;  
    virtual ~Shape() = default;  
};  
struct Rectangle : Shape {  
    void draw() const override;  
};  
struct Circle : Shape {  
    void draw() const override;  
};  
void drawStuff(const Shape &s) {  
    s.draw();  
}
```

Compile-time polymorphism:

- Shape is a concept !

```
template <typename T>  
concept Shape = requires(const T x) {  
    x.draw();  
};  
struct Rectangle {  
    void draw() const; // non-virtual  
};  
struct Circle {  
    void draw() const; // non-virtual  
};  
template <Shape T>  
void drawStuff(const T &s) {  
    s.draw();  
}
```

How `concept` and `requires` benefit template code

Without the C++20 `concept` and `requires`, we need to write the requirements in a "hacky" way through **SFINAE** (Substitution Failure Is Not An Error):

```
template <typename T, typename = std::enable_if_t<std::is_integral_v<T>>>
void increment(T &x) { ++x; }
```

With C++20:

```
template <std::integral T>
void increment(T &x) { ++x; }
```

Or even simpler:

```
void increment(std::integral auto &x) { ++x; }
```

Future

Metaclasses: Generative C++