CONSTEXPR 从 11 到 20

constexpr auto 😀

template metaprogramming is dead
long live constexpr

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自我介绍

- 96年出生，18年毕业于合肥工业大学本科
- 高级工程师
- 知乎 《魅力C++》 专栏作者
- 兴趣： CS, OO, FP, Design, Coding, Writing
- Skills: C/C++/Rust, Haskell/Scheme, Bash/Python/Javascript/PHP

议程

- 编译时计算（元编程）
- 演进历史
- constexpr vs 模板元
- 深入constexpr
- 应用
- 展望未来
- 结论

编译时计算（元编程）

- 零成本抽象
- 编译时多态 (eg. Policy Class, Tag Dispatcher, CRTP)
- 值计算
- 类型计算(Type Traits)
- 类型安全 (eg. 单位运算, Phantom Types)
- 内部领域特定语言(EDSL)

编译时计算（元编程）& 风格

- 模板元编程
- Constexpr all the things!
- 两者结合

演进历史

模板元编程

- 1986 C++引入模板
- C++98 模板实例化
- C++11 模板类别名、可变模板参数、static_assert、decltype、type_traits
- C++14 decltype(auto)、integer_sequence
- C++17 类模板参数推导CTAD、auto非类型参数、void_t
- C++20 概念Concept、放宽非类型参数

constexpr

- C++11 引入constexpr简单函数
- C++14 放开constexpr约束, 模板变量
- C++17 if constexpr、constexpr lambda、折叠表达式
- C++20 constexpr容器、constexpr new、constexpr析构函数、constexpr虚函数、consteval/constinit、lambda模板参数
- constexpr STL algorithms

constexpr vs 模板元编程

BrainFuck语言

- 图灵完备
- 8种操作符
- DSL

brainfuck-visualizer

>	++ptr;
<	--ptr;
+	++*ptr;
-	--*ptr;
.	putchar(*ptr);
,	*ptr = getchar();
[	while (*ptr) {
]	}

BrainFuck: Hello world

```
puts( R"(
    >++++++++[<+++++++++>-]<.             ; H   (8*9     = 72)
    >>++++++++++[<++++++++++>-]<+.        ; e   (10*10+1 = 101)
    >>+++++++++[<++++++++++++>-]<.        ; l   (9*12    = 108)
    >>+++++++++[<++++++++++++>-]<.        ; l   (9*12    = 108)
    >>++++++++++[<+++++++++++>-]<+.       ; o   (10*11+1 = 111)
    >>++++[<++++++++>-]<.                 ; ' ' (4*8     = 32)
    >>+++++++++++[<++++++++>-]<-.         ; W   (11*8-1  = 87)
    >>++++++++++[<+++++++++++>-]<+.       ; o   (10*11+1 = 111)
    >>++++++++++[<++++++++++++>-]<------. ; r   (10*12-6 = 114)
    >>+++++++++[<++++++++++++>-]<.        ; l   (9*12    = 108)
    >>++++++++++[<++++++++++>-]<.         ; d   (10*10   = 100)
    >>++++++[<++++++>-]<---.              ; !   (6*6-3   = 33)
)"_brain_fuck );
```

BrainFuck编译器：模板元解法

基础元数据结构

```cpp
template<char c>
using Cell = std::integral_constant<char, c>;

template<size_t P = 0, bool INLOOP = false, typename ...CELLs>
struct Machine {
    using type = Machine<P, INLOOP, CELLs...>;
    constexpr static bool InLoop = INLOOP;
};
```

BrainFuck编译器：模板元解法

相关操作

```
namespace MachineTrait {
    template<size_t N>
    struct InitMachine: Concat_t<Machine<0, 0, Cell<0>>, typename InitMachine<N-1>::type> {};
    template<> struct InitMachine<0>: Machine<0, 0, Cell<0>> {};

    template<typename MACHINE> struct Inc;
    template<typename MACHINE> using Inc_t = typename Inc<MACHINE>::type;
    template<size_t PC, bool INLOOP, typename C, typename... CELLs>
    struct Inc<Machine<PC, INLOOP, C, CELLs...>>:
        Concat_t<Machine<PC, INLOOP, C>, Inc_t<Machine<PC - 1, INLOOP, CELLs...>>> {};
    template<bool INLOOP, typename C, typename... CELLs>
    struct Inc<Machine<0, INLOOP, C, CELLs...>>:
        Machine<0, INLOOP, Cell< C::value + 1 >, CELLs...> {};

    template<typename MACHINE>
    struct Left;
    template<typename MACHINE>
    using Left_t = typename Left<MACHINE>::type;
    template<size_t PC, bool INLOOP, typename... CELLs>
    struct Left<Machine<PC, INLOOP, CELLs...>>:
        Machine< PC-1, INLOOP, CELLs...> {};
};
```

BrainFuck编译器：模板元解法

解析BrainFuck代码：基本操作

```
template<typename MACHINE, bool skip, char ...cs>
struct BrainFuck: MACHINE {};
template<typename MACHINE, bool skip, char ...cs>
using BrainFuck_t = typename BrainFuck<MACHINE, skip, cs...>::type;

template<typename MACHINE, char ...cs>
struct BrainFuck<MACHINE, false, '+', cs...>:
    BrainFuck_t<MachineTrait::Inc_t<MACHINE>, false, cs...> {};

template<typename MACHINE, char ...cs>
struct BrainFuck<MACHINE, false, '-', cs...>:
    BrainFuck_t<MachineTrait::Dec_t<MACHINE>, false, cs...> {};

template<typename MACHINE, char ...cs>
struct BrainFuck<MACHINE, false, '<', cs...>:
    BrainFuck_t<MachineTrait::Left_t<MACHINE>, false, cs...> {};

template<typename MACHINE, char ...cs>
struct BrainFuck<MACHINE, false, '>', cs...>:
    BrainFuck_t<MachineTrait::Right_t<MACHINE>, false, cs...> {};
```

BrainFuck编译器：模板元解法

解析BrainFuck代码：循环 & 分支

```
template<typename MACHINE, char ...cs>
struct BrainFuck<MACHINE, false, '[', cs...> {
    using EnableLoopedMachine = MachineTrait::EnableLoop_t<MACHINE>;

    template<typename IN, bool = MachineTrait::IsZero_t<IN>::value>
    struct Select: BrainFuck_t<IN, true, cs...> {}; // skip
    template<typename IN> // loop
    struct Select<IN, false>: BrainFuck_t<IN, false, cs...> {};

    using Result = typename Select<EnableLoopedMachine>::type;

    template<typename IN, bool = (! MachineTrait::IsZero_t<IN>::value && IN::InLoop)>
    struct Loop: IN {};    // skip
    template<typename IN> // continue
    struct Loop<IN, true>: BrainFuck_t<IN, false, '[', cs...> {};

    using type = typename Loop<Result>::type;
};
```

BrainFuck编译器：模板元解法

保存结果

```
template<size_t PC, bool INLOOP, typename ...CELLs>
inline const auto ToStr(Machine<PC, INLOOP, CELLs...>) {
    constexpr const static char str[] = { CELLs::value ...  };
    return str;
}

template<typename T, T... cs>
constexpr auto operator ""_brain_fuck() {
    using Machine = MachineTrait::InitMachine_t<15>;
    using Result = BrainFuck_t<Machine, false, cs...>;

    return ToStr(Result{});
};
```

BrainFuck编译器：模板元解法

完整代码：https://godbolt.org/z/GTKxhc

生成代码

```
main:
        subq    $8, %rsp
        movl    $MachineTrait::ToStr<...>(Machine<...>)::str, %edi
        call    puts
        xorl    %eax, %eax
        addq    $8, %rsp
        ret
MachineTrait::ToStr<...>(Machine<...>)::str:
        .string "Hello World!"
        .string ""
        .string ""
        .string ""
```

BrainFuck编译器：constexpr解法

基础数据结构

```
template<size_t N>
class Stream {
public:
    constexpr void push(char c) { data_[idx_++] = c; }
    constexpr operator const char*() const { return data_; }
    constexpr size_t size() { return idx_; }
private:
    size_t idx_{};
    char data_[N]{};
};
```

BrainFuck编译器：constexpr解法

递归下降解析器

```
template<typename STREAM>
constexpr auto parse(const char* input, bool skip, char* cells,
        size_t& pc, STREAM&& output) -> size_t {
    const char* c = input;
    while(*c) {
        switch(*c) {
            case '+': if (!skip) ++cells[pc];            break;
            case '-': if (!skip) --cells[pc];            break;
            case '.': if (!skip) output.push(cells[pc]); break;
            case '>': if (!skip) ++pc;                   break;
            case '<': if (!skip) --pc;                   break;
            case '[': {
                while (!skip && cells[pc] != 0)
                    parse(c + 1, false, cells, pc, std::forward<STREAM>(output));
                c += parse(c + 1, true, cells, pc, std::forward<STREAM>(output)) + 1;
            } break;
            case ']': return c - input;
            default: break;
        }
        ++c;
    }
    return c - input;
}
```

BrainFuck编译器：constexpr解法

整合一起：

```
constexpr size_t CELL_SIZE = 16;
template<typename STREAM>
constexpr auto parse(const char* input, STREAM&& output) -> STREAM&& {
    char cells[CELL_SIZE]{};
    size_t pc{};
    parse(input, false, cells, pc, output);
    return std::forward<STREAM>(output);
}

template<size_t OUTPUT_SIZE = 15>
constexpr auto brain_fuck(const char* input) {
    return parse(input, Stream<OUTPUT_SIZE>{});
}
```

BrainFuck编译器：constexpr解法

完整代码：https://godbolt.org/z/EYn7PG

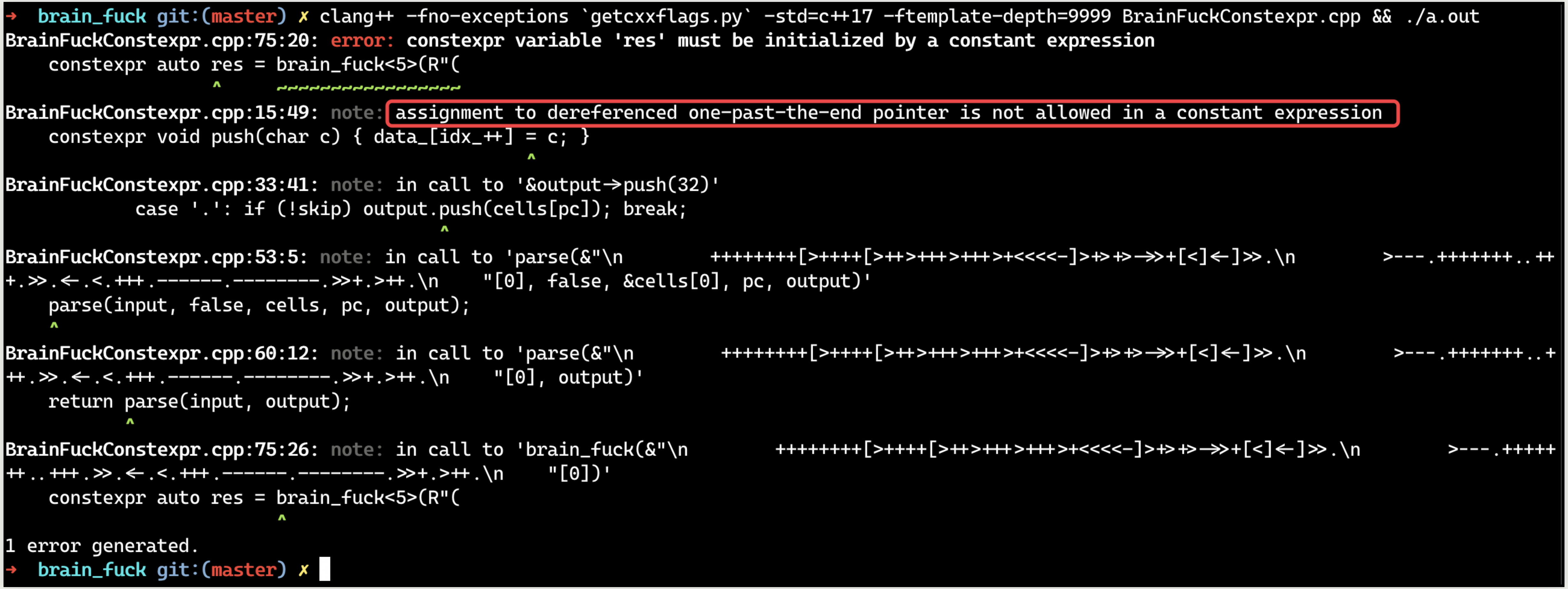
编译、运行时使用：

```
// compile time
constexpr auto res = brain_fuck(R"(
    ++++++++[>++++[>++>+++>+++>+<<<<-]>+>+>->>+[<]<-]>>.
    >---.+++++++..+++.>>.<-.<.+++.------.--------.>>+.>++.
)");
puts(res);

// runtime
if (argc > 1) puts(brain_fuck(argv[1]));
```

BrainFuck编译器：constexpr解法

```
template<size_t OUTPUT_SIZE = 15>
constexpr auto brain_fuck(const char* input);
```

❓若OUTPUT_SIZE过小，会怎么样



```
➜  brain_fuck git:(master) ✗ clang++ -fno-exceptions `getcxxflags.py` -std=c++17 -ftemplate-depth=9999 BrainFuckConstexpr.cpp && ./a.out
BrainFuckConstexpr.cpp:75:20: error: constexpr variable 'res' must be initialized by a constant expression
    constexpr auto res = brain_fuck<5>(R"(
                   ^     ~~~~~~~~~~~~~~~~~
BrainFuckConstexpr.cpp:15:49: note: assignment to dereferenced one-past-the-end pointer is not allowed in a constant expression
    constexpr void push(char c) { data_[idx_++] = c; }
                                                ^
BrainFuckConstexpr.cpp:33:41: note: in call to '&output->push(32)'
            case '.': if (!skip) output.push(cells[pc]); break;
                                        ^
BrainFuckConstexpr.cpp:53:5: note: in call to 'parse(&"\n        ++++++++[>++++[>++>+++>+++>+<<<<-]>+>+>->>+[<]<-]>>.\n        >---.+++++++..++
+.>>.<-.<.+++.------.--------.>>+.>++.\n    "[0], false, &cells[0], pc, output)'
    parse(input, false, cells, pc, output);
    ^
BrainFuckConstexpr.cpp:60:12: note: in call to 'parse(&"\n        ++++++++[>++++[>++>+++>+++>+<<<<-]>+>+>->>+[<]<-]>>.\n        >---.+++++++..+
++.>>.<-.<.+++.------.--------.>>+.>++.\n    "[0], output)'
    return parse(input, output);
           ^
BrainFuckConstexpr.cpp:75:26: note: in call to 'brain_fuck(&"\n        ++++++++[>++++[>++>+++>+++>+<<<<-]>+>+>->>+[<]<-]>>.\n        >---.+++++
++..+++.>>.<-.<.+++.------.--------.>>+.>++.\n    "[0])'
    constexpr auto res = brain_fuck<5>(R"(
                         ^
1 error generated.
➜  brain_fuck git:(master) ✗ 
```

💡编译报错，**不允许内存越界ub**

BrainFuck编译器：constexpr解法

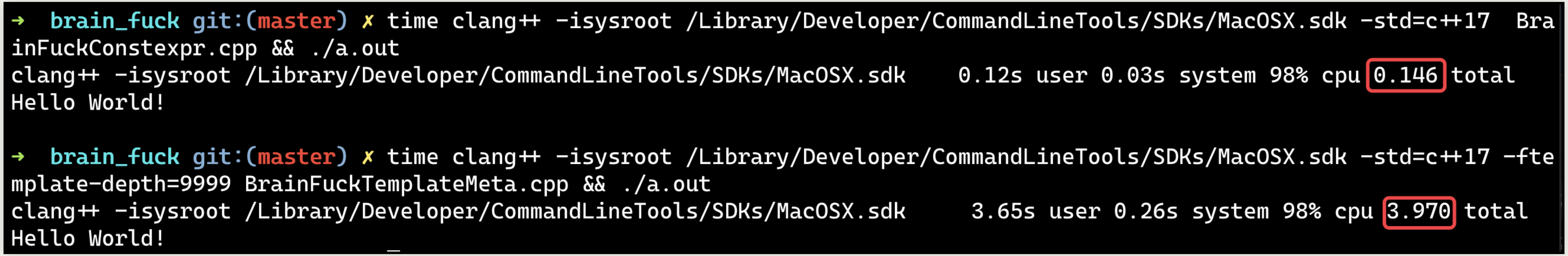
```
template<size_t OUTPUT_SIZE = 15>
constexpr auto brain_fuck(const char* input);
```

❓如何提前知道OUTPUT_SIZE所需要大小

```
// calculate output size
constexpr auto brain_fuck_output_size(const char* input) -> size_t {
    struct {
        size_t sz{};
        constexpr void push(...) { ++sz; }
    } dummy;
    return parse(input, dummy).sz + 1; // include '\0'
}

#define BRAIN_FUCK(in) brain_fuck< brain_fuck_output_size(in) >(in)
constexpr auto res = BRAIN_FUCK(R"(
    ++++++++[>++++[>++>+++>+++>+<<<<-]>+>+>->>+[<]<-]>>.
    >---.+++++++..+++.>>.<-.<.+++.------.--------.>>+.>++.
)");
```

constexpr vs 模板元编程

❓ 编译时间



```
➜  brain_fuck git:(master) ✗ time clang++ -isysroot /Library/Developer/CommandLineTools/SDKs/MacOSX.sdk -std=c++17  Bra
inFuckConstexpr.cpp && ./a.out
clang++ -isysroot /Library/Developer/CommandLineTools/SDKs/MacOSX.sdk    0.12s user 0.03s system 98% cpu 0.146 total
Hello World!

➜  brain_fuck git:(master) ✗ time clang++ -isysroot /Library/Developer/CommandLineTools/SDKs/MacOSX.sdk -std=c++17 -fte
mplate-depth=9999 BrainFuckTemplateMeta.cpp && ./a.out
clang++ -isysroot /Library/Developer/CommandLineTools/SDKs/MacOSX.sdk     3.65s user 0.26s system 98% cpu 3.970 total
Hello World!
```

0.146s vs 3.970s ! 27x speed up ⏫

constexpr vs 模板元编程

模板元 http://redd.it/jnz5p1

- Looks both **scary** and **exciting** at the same time. :P
- After reading this code I gotta **remove C++** from the programming languages I know list. Sweet mother of god this is **incredible**! :,)
- Nice, definitely **scary** stuff though.
- Where does one learn to use templates like that? I have no idea what I’m looking at
- From my experience, templates like this are **hard to casually read** even if you are the one who wrote them. It makes perfect sense when you are **creating the monstrosity** though.
- Actually, for what it is, it’s incredibly **readable**.
- Awesome, Now make a c++ compiler with brainfuck :p

constexpr http://redd.it/jp7k0u

- Amazing, very neat, show the **power** of constexpr functions, way more **readable** than template.
- Wow. Your constexpr code is vastly more **readable** than the template metaprogramming one.

constexpr vs 模板元编程

简单设计：模板元

- 通过所有测试(static_assert) ✅
- 没有重复，易于重用 ✅
- 表达意图，易于理解（~200 lines） ❌
- 没有冗余，避免过度设计 •••

简单设计：constexpr

- 通过所有测试(static_assert) ✅
- 没有重复，易于重用 ✅
- 表达意图，易于理解（~80 lines） ✅
- 没有冗余，避免过度设计 ✅

constexpr vs 模板元编程

模板元优缺点

- 运行时效率
- 体系成熟，拥有大量的库
  参考资料多
- 可变参数模板类可以任意扩容
- 可读性差，维护性差
- 编译错误信息难懂；编译速度慢；跨平台（编译器）弱

constexpr优缺点

- 运行时效率
- 新兴势力，生态待完善
  参考资料少，挖掘空间大
- C++20之前需要提前计算容器大小
- 可读性强，维护性强，更少的魔法
- 编译错误信息易懂；编译速度快；跨平台（编译器）强

Constexpr all the things!

constexpr历程

- C++11 引入constexpr简单函数
  - 只允许一条return语句
  - 递归解决问题！简单的数学函数、字符串hash函数
- C++14 放开constexpr约束, 模板变量
  - 泛化constexpr
  - 一些库出现
- C++17 if constexpr、constexpr lambda、折叠表达式
  - 表达力提升
- C++20 constexpr容器、constexpr new、constexpr析构函数、constexpr虚函数、consteval/constinit、lambda模板参数
- constexpr STL algorithms

深入constexpr

- constexpr常量
- 折叠表达式
- constexpr函数、lambda
- consteval/constinit
- if constexpr
- constexpr容器、算法
- constexpr析构函数
- 检测Undefined Behaviour

constexpr常量

```cpp
constexpr size_t strLen(const char* str) {
    return (*str == '\0') ? 0 : 1 + strLen(str + 1);
}

#define STR "hello world"
static_assert(strLen(STR) == 11);
```

```cpp
const char* str = "hello world";
// error: static_assert expression is not an integral constant expression
static_assert(strLen(str) == 11);
```

```cpp
constexpr const char* str = "hello world";
static_assert(strLen(str) == 11);
```

constexpr模板常量

做常量别名

```
template<class T>
constexpr bool is_class_v =
    std::is_class<T>::value;
```

表达式计算

```
template<char c>
constexpr bool is_digit =
    (c >= '0' && c <= '9');
template<char c>
constexpr bool is_digit_or_dot =
    (is_digit<c> || c == '.');

static_assert(! is_digit<'x'>);
static_assert(is_digit<'0'>);
```

模板特化

```
template<size_t N>
constexpr size_t fibonacci =
    fibonacci<N - 1> + fibonacci<N - 2>;
template<>
constexpr size_t fibonacci<0> = 0;
template<>
constexpr size_t fibonacci<1> = 1;

static_assert(fibonacci<10> == 55);
```

折叠表达式

```
template<char c, char... cs>
constexpr bool is_sign_valid = ((c == '+' || c == '-') && sizeof...(cs) > 0)
                                || is_digit_or_dot<c>;

template<char... cs>
constexpr size_t number_of_dots = ((cs == '.' ? 1 : 0) + ... + 0);

template<char c, char... cs>
constexpr bool is_integer = is_sign_valid<c, cs...> &&
                            (is_digit<cs> && ...);

template<char... cs>
constexpr bool is_double = is_sign_valid<cs...> &&
                           ( (is_digit_or_dot<cs>) && ...) &&
                           number_of_dots<cs...> == 1;

template<char... cs>
constexpr bool is_number_valid = (is_integer<cs...> || is_double<cs...>);

static_assert(is_number_valid<'1', '2', '3', '.', '4'>);
static_assert(! is_number_valid<'a', 'b', 'c', 'd'>);
```

constexpr 函数 & lambda

C++17起，lambda默认为constexpr

```
// constexpr int fibonacci(int n);
auto fibonacci = [](int n) {
    int a = 0, b = 1;
    for (int c = 0; c < n; ++ c) {
        int t = a + b;
        a = b;
        b = t;
    }
    return a;
};

constexpr auto v = fibonacci(10);
static_assert(v == 55);
```

consteval/constinit

consteval

specifies that a function is an immediate function, that is, every call to the function must produce a **compile-time** constant.

constinit

asserts that a variable has **static initialization**, i.e. zero initialization and constant initialization, otherwise the program is ill-formed.

if constexpr

? 如何求结构体字段个数

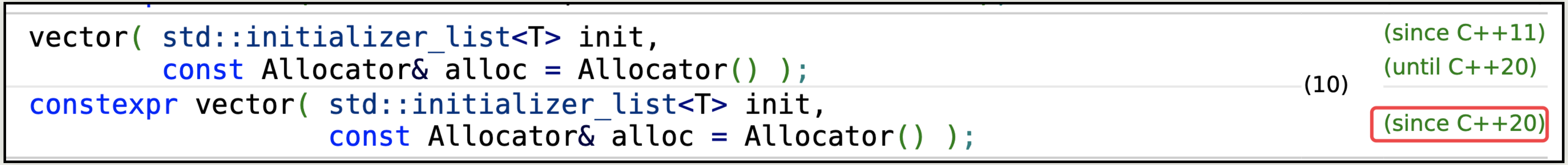
```
struct AnyType {
    template <typename T>
    operator T();
};

template <typename T>
consteval size_t CountMember(auto&&... Args) {
    if constexpr (requires { T{ Args... }; }) {      1
        return CountMember<T>(Args..., AnyType{});   2
    } else {
        return sizeof...(Args) - 1;                  3
    }
}

struct Test { int a; int b; int c; int d; };
static_assert(CountMember<Test>() == 4);
```

1 判断当前参数包是否能够成功 **聚合初始化** 对象T，C++20 concept特性

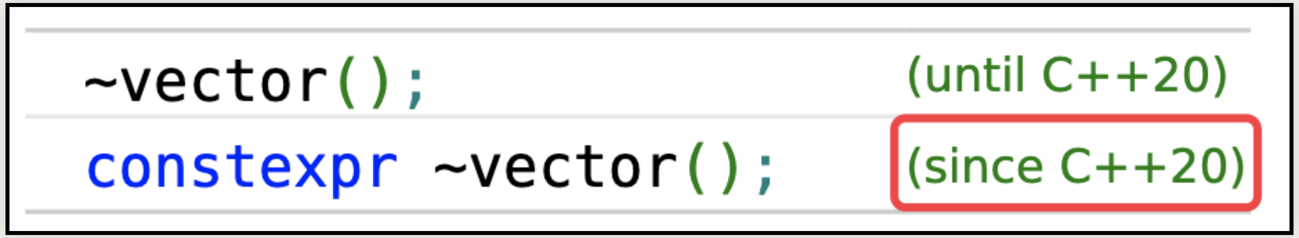
2 若 **聚合初始化** 成功，不断添加参数对T进行进一步 **聚合初始化**

3 若 **聚合初始化** 失败，字段个数为参数个数-1

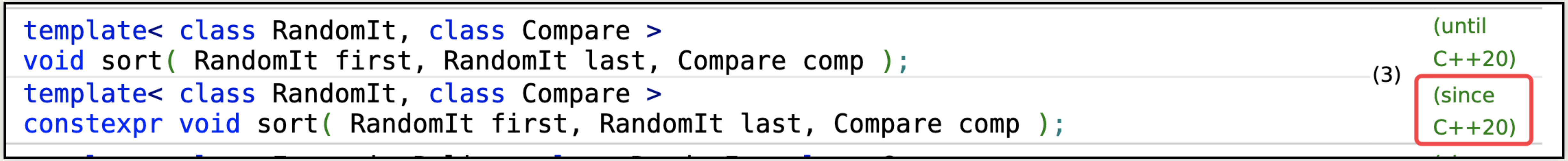
constexpr容器、算法



```
vector( std::initializer_list<T> init,                                   (since C++11)
        const Allocator& alloc = Allocator() );                          (until C++20)
                                                                   (10)
constexpr vector( std::initializer_list<T> init,                         (since C++20)
                  const Allocator& alloc = Allocator() );
```



```
~vector();                         (until C++20)
constexpr ~vector();               (since C++20)
```



```
template< class RandomIt, class Compare >                                  (until
void sort( RandomIt first, RandomIt last, Compare comp );                  C++20)
                                                                     (3)
template< class RandomIt, class Compare >                                  (since
constexpr void sort( RandomIt first, RandomIt last, Compare comp );        C++20)
```

constexpr析构函数 - 析构优化

❓ 如何优化

```
struct OptionalTrivially {};
template <typename T, typename Contained>
struct OptionalNonTrivially {
    ~OptionalNonTrivially() {
        if (static_cast<T*>(this)->initialized_) {
            static_cast<T*>(this)->storage_.data.~Contained();
        }
    }
};

template <typename Contained>
struct Optional: conditional_t<is_trivially_destructible_v<Contained>,
                               OptionalTrivially,
                               OptionalNonTrivially<Optional<Contained>, Contained>> {
    constexpr Optional& operator=(Contained&& data) {
        storage_.data = std::move(data);
        initialized_ = true;
        return *this;
    }
    Storage<Contained> storage_;
    bool initialized_{};
};
```

constexpr析构函数 - 使用if constexpr

```
template <typename Contained>
struct Optional {
    constexpr Optional& operator=(Contained&& data) {
        storage_.data = std::move(data);
        initialized_ = true;
        return *this;
    }

    constexpr ~Optional() {
        if constexpr(! is_trivially_destructible_v<Contained>) {
            if (initialized_) {
                this->storage_.data.~Contained();
                initialized_ = false;
            }
        }
    }

    Storage<Contained> storage_;
    bool initialized_{};
};
```

constexpr析构函数 - 使用概念约束

```
template <typename Contained>
struct Optional {
    constexpr Optional& operator=(Contained&& data) {
        storage_.data = std::move(data);
        initialized_ = true;
        return *this;
    }

    constexpr ~Optional() requires (! is_trivially_destructible_v<Contained>) {
        if (initialized_) {
            this->storage_.data.~Contained();
        }
    }
    constexpr ~Optional() = default;

    Storage<Contained> storage_;
    bool initialized_{};
};
```

检测Undefined Behaviour

```
const double x1=100/0; ①
const int x2 =
    numeric_limits<int>::min() / -1; ②

constexpr double y1=100/0; ③
constexpr int y2 =
    numeric_limits<int>::min() / -1; ④
```

① warning: division by zero

② no warning in clang

③ error: division by zero is not a constant expression

④ error: overflow in constant expression

```
constexpr int bar() {
    int* p = nullptr;
    return *p;
}

constexpr auto foo = bar(); ①
```

① error: dereferencing a null pointer

检测Undefined Behaviour

```
constexpr int foo(const int *p) {
    return *(p + 12); ①
}

constexpr void bar() {
    constexpr int arr[10]{};
    constexpr int x = foo(arr);
}
```

① error: array subscript value '12' is outside the bounds of array 'arr' of type 'const int [10]'

```
constexpr int& foo(){
    int x = 23;
    return x;
}

constexpr int bar() {
    constexpr int x = foo(); ①
    return x;
}
```

① error: constexpr variable 'x' must be initialized by a constant expression. note: read of variable whose lifetime has ended

检测Undefined Behaviour

```
constexpr int foo(int x) {
   if(x) return 1;
}

void bar(){
    constexpr int x = foo(0); 1
}
```

1 error: 'constexpr' call flows off the end of the function

辅助工具： https://github.com/trailofbits/constexpr-everything

? 如下代码的意图

```
constexpr void push_back(Value t_v) {
    if (m_size >= Size) {
        throw std::range_error("Index past end
of vector");
    } else {
        m_data[m_size++] = std::move(t_v);
    }
}
```

constexpr应用

- 领域特定语言(EDSL)
    - 编译期解析Json (Parser Combinator)
    - 编译期构建正则表达式FSM (LL1分析器)
    - constexpr-sql (递归下降分析器)
    - graph-dsl (语法树文法，lisp风格)
- constexpr元编程库
    - boost::hana
    - holo

领域特定语言(EDSL)

编译期解析Json (Parser Combinator)

完整Talk： CppCon 2017: Ben Deane & Jason Turner “constexpr ALL the Things!”

```cpp
constexpr auto jsv = R"({
    "feature-x-enabled": true,
    "value-of-y": 1729,
    "z-options": {"a": null,
                  "b": "220 and 284",
                  "c": [6, 28, 496]} }
)"_json;

if constexpr (jsv["feature-x-enabled"]) {
    // code for feature x
} else {
    // code when feature x turned off
}
```

编译期解析Json (Parser Combinator)

Parser Combinator:

```
template <typename T>
using Parser = auto(*)(string_view) -> optional<pair<T, ParserInput>>;

// a parser for skipping whitespace
constexpr auto skip_whitespace() {
    constexpr auto ws_parser = make_char_parser(' ')
                             | make_char_parser('\t')
                             | make_char_parser('\n')
                             | make_char_parser('\r');
    return many(ws_parser, std::monostate{}, [] (auto m, auto) { return m; });
}

// parse a JSON array
static constexpr auto array_parser() {
    return make_char_parser('[') <
            separated_by_val(value_parser(),
                            skip_whitespace() < make_char_parser(','),
                            Sizes{1, 0}, std::plus<>{})
            > skip_whitespace()
        > (make_char_parser(']') | fail(']', [] { throw "expected ]"; }));
}
```

编译期正则表达式(LL1分析器)

https://github.com/hanickadot/compile-time-regular-expressions

```
struct date {
    std::string_view year;
    std::string_view month;
    std::string_view day;
};

std::optional<date> extract_date(std::string_view s) {
    if (auto [whole, year, month, day] =
            ctre::match<"(\\d{4})/(\\d{1,2})/(\\d{1,2})">(s); whole) {
        return date{year, month, day};
    } else {
        return std::nullopt;
    }
}

static_assert(extract_date("2018/08/27"sv).has_value());
static_assert((*extract_date("2018/08/27"sv)).year == "2018"sv);
static_assert((*extract_date("2018/08/27"sv)).month == "08"sv);
static_assert((*extract_date("2018/08/27"sv)).day == "27"sv);
```

constexpr-sql (递归下降分析器)

https://github.com/mkitzan/constexpr-sql

```
using books = sql::schema<"books",
    sql::index<"title">,
    sql::column<"title", std::string>,
    sql::column<"genre", std::string>,
    sql::column<"year",  unsigned>,
    sql::column<"pages", unsigned>>;
```

```
using authored = sql::schema<"authored",
    sql::index<>,
    sql::column<"title", std::string>,
    sql::column<"name",  std::string>>;
```

```
using query = sql::query<R"(
    SELECT title AS book, name AS author, year, pages
    FROM books NATURAL JOIN (SELECT * FROM authored WHERE name = "Harlan Ellison")
    WHERE year = 1967 OR year >= 1972 AND genre = "science fiction"
    )", books, authored>;

authored a { sql::load<authored>("tests/data/authored.tsv", '\t') };
books    b { sql::load<books>("tests/data/books.tsv",       '\t') };

for (query q { b, a }; auto const& [book, author, year, pages]: q)
    std::cout << book << '\t' << author << '\t' << year << '\t' << pages << '\n';
```

graph-dsl (语法树文法，lisp风格)

https://github.com/godsme/graph-dsl

```
using sub_graph_1 = SUBGRAPH(
    (root_0 , (port_1) -> node_8
            , (port_2) -> MAYBE(cond_2, node_3)
            , (port_4) -> FORK(node_5, node_4, MAYBE(cond_2, node_8))),
    (node_5 , (port_5) -> node_8
            , (port_6) -> FORK(node_4, MAYBE(cond_2, node_3))),
    (node_3 , (port_8) -> FORK(node_8, node_6)
            , (port_9) -> node_7));
using sub_graph_2 = SUBGRAPH(
    (root_0  , (port_1) -> node_9),
    (root_1  , (port_2) -> MAYBE(cond_2, node_11)
             , (port_3) -> EITHER(cond_1, node_12, node_13)),
    (node_11 , (port_11) -> FORK(node_13, node_14)
             , (port_12) -> node_15));
using graph = GRAPH(
    (root_0, root_1),
    (cond_3) -> sub_graph_1,
    (cond_4) -> sub_graph_2);

graph g;
while (g.refresh(context) == OK) { };
```

constexpr元编程库

boost::hana

https://www.boost.org/doc/libs/1_61_0/libs/hana/doc/html/index.html

```
constexpr auto result = append(make_tuple(type_c<int>, type_c<double>), type_c<long>);
static_assert(make_basic_tuple(type_c<int>, type_c<double>, type_c<long>) == result);

constexpr auto result = concat(make_tuple(type_c<int>, type_c<double>),
                               make_tuple(type_c<long>, type_c<float>));
static_assert(make_basic_tuple(
        type_c<int>, type_c<double>, type_c<long>, type_c<float>
    ) == result);

auto result = partition(tuple_t<int, double, double, int>,
                        [](auto x) { return x == type_c<int>; });
static_assert(make_pair(tuple_t<int, int>, tuple_t<double, double>) == result);
```

holo

编译期Ranges: https://github.com/godsme/holo

```
constexpr static auto sorted_non_leaf_nodes =
    all_decedents_map
    | holo::sort([](auto l, auto r) { return holo::contains(holo::first(l), holo::second(r)); })
    | holo::transform([](auto elem) { return holo::first(elem); })
    | holo::reverse();

constexpr static auto root_nodes =
    holo::list_t<NODES...>
    | holo::filter([](auto elem){
        return decltype(elem)::type::is_root == holo::true_c; })
    | holo::transform([](auto elem){
        return holo::type_c<typename decltype(elem)::type::node_type>;
    });
```

展望未来

- constexpr_trace/constexpr_assert
- for constexpr & 静态反射

constexpr_trace/constexpr_assert

P0596

```
constexpr int sqr(int n) {
    if (n > 100) {
        std::constexpr_report("Largish sqr operand", n);
    }
    return n*n;
}
constexpr int n1 = sqr(128); ①
int x = 1000;
int n2 = sqr(x);  ②
```

① Some kind of output, ideally.

② No diagnostic output.

for constexpr & 静态反射

https://twitter.com/cor3ntin/status/1127210941718962177

P1306R1: Expansion statements

```
#include <iostream>
#include <experimental/meta>
namespace meta = std::experimental::meta;

namespace n {
    struct hello {};
    int world;
};

int main() {
    static constexpr auto range = meta::range(reflexpr(n));
    for...(constexpr auto member: range)
        std::cout << meta::name_of(member) << " ";
    return 0;
}
```

结论

- 简化库、框架开发难度
- 更清晰的代码，更少的魔法
- 跨编译器兼容
- 更容易实现领域特定语言EDSL

Reference

- Introduction to C++ Metaprogramming
- C++ Weekly - Ep 231 - Multiple Destructors in C++20?! How and Why
- Exploring Undefined Behavior Using Constexpr
- CppCon 2017: Ben Deane & Jason Turner “constexpr ALL the Things!”
- 我的博客 https://netcan.github.io/
- 相关代码 https://github.com/netcan/recipes
- 演讲文件 https://github.com/netcan/presentation

Thank you!

Question?