Department I - C Plus Plus

Modern and Lucid C++ Advanced for Professional Programmers

Week 8 – Compile-Time Computation

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Rapperswil, 11.04.2019
FS2019

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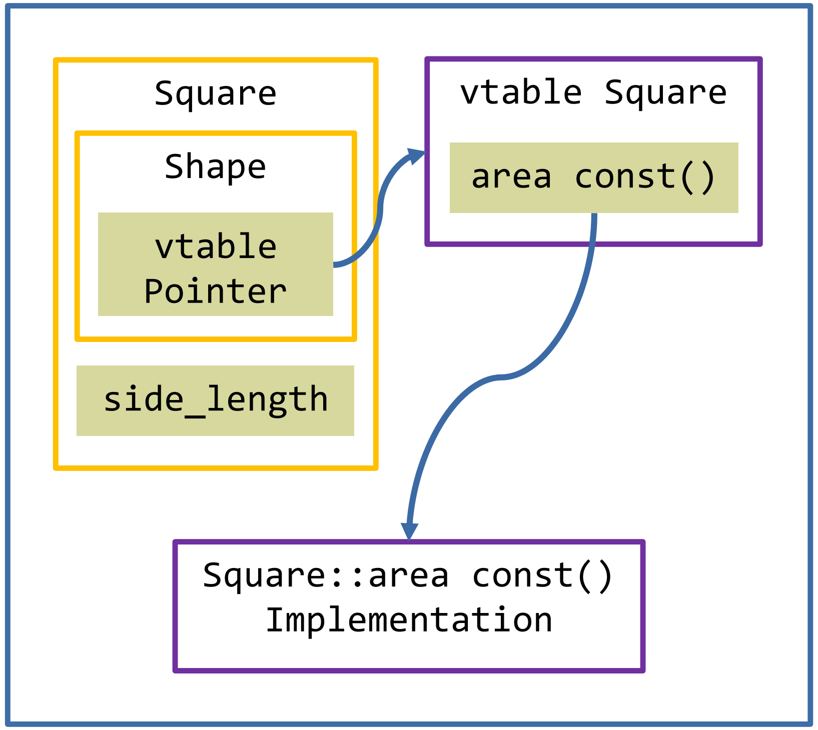
- **A polymorphic call of a virtual function requires lookup of the target function**

```
struct Shape {
  virtual unsigned area() const = 0;
  virtual ~Shape();
};

struct Square : Shape {
  Square(unsigned side_length)
    : side_length{side_length} {}
  unsigned area() const {
    return side_length * side_length;
  }
  unsigned const side_length;
};
```

```
decltype(auto) amountOfSeeds(Shape const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```



- **Article on this topic:** http://eli.thegreenplace.net/2013/12/05/the-cost-of-dynamic-virtual-calls-vs-static-crtp-dispatch-in-c

```
struct SpaceDriveTag {};

struct HyperspaceDriveTag : SpaceDriveTag {};

struct InfniteProbabilityDriveTag : SpaceDriveTag {};
```

```
struct MultiPurposeCrewVehicle;

struct GalaxyClassShip;

struct HeartOfGoldPrototype;
```

- **Approach 1: Derive space ship from the associated tag typ**
  - This is not applicable for all types (e.g. for primitive types, as we will see later)
  - This is not extensible (i.e. you cannot specify new kinds of tag kinds as a user of the API)
- **Approach 2: `SpaceshipTraits` template**

```
template<typename>
struct SpaceshipTraits {
  using Drive = SpaceDriveTag;
};
```

```
template<>
struct SpaceshipTraits<GalaxyClassShip> {
  using Drive = HyperspaceDriveTag;
};
```

Example DIY Iterator for Integers


```
struct IntIterator { /* Member Types Omitted */
  explicit IntIterator(int const start = 0) :
    value { start } {}
  bool operator==(IntIterator const & r) const {
    return value == r.value;
  }
  bool operator!=(IntIterator const & r) const {
    return !(*this == r);
  }
  value_type operator*() const {
    return value;
  }
  IntIterator & operator++() {
    ++value;
    return *this;
  }
  IntIterator operator++(int) {
    auto old = *this;
    ++(*this);
    return old;
  }
private:
  value_type value;
};
```

Explicit constructor

Implement != through operator ==

Implement postfix through prefix operators

Reuse pre-defined type

Goals

- **You can write C++ code that is evaluated by the compiler**
- **You know the restrictions of constexpr functions**
- **You can write your own literal types**
- **You know how SFINAE works and can apply it to your code**

Constexpr

Compile-Time Computation Motivation

- **ROMable data (guaranteed!)**
  - Smaller binary
- **Better run-time performance**
- **Plain C++**
- **Not yet everything possible provided**
  - Standard library not made up for everything desirable
- **Compiletimes can increase horrendously**
  - Example that is supposed to take 24h to be compiled
    http://cpptruths.blogspot.ch/2005/11/c-templates-are-turing-complete.html

- **(static) const variables in namespace scope of built-in types initialized with constant expression are usually put into ROMable memory, if at all.**
- **Allowed in constant expression context**
- **No complicated computations (except with macros)**
- **No guarantee to be done at compile-time in all cases**

```
size_t const SZ = 6 * 7;
double x[SZ];
```

Constant expression context

Compile-time evaluation

Constant Expression Contexts

- **Non-type template arguments**

```
std::array<Element, 5> arr{};
```

- **Array bounds**

```
double matrix[ROWS][COLS]{};
```

- **Case expressions**

```
switch (value) {
case 42:
  //...
}
```

- **Enumerator initializers**

```
enum Light {
  Off = 0, On = 1
};
```

- **`static_assert`**

```
static_assert(order == 66);
```

- **`constexpr` variables**

```
constexpr unsigned pi = 3;
```

- **`constexpr if` statements**

```
if constexpr (size > 0) {
}
```

- **`noexcept`**

```
Blob(Blob &&) noexcept(true);
```

- ...

```
static_assert(sizeof(int) == 4, "unexpected size of int");

static_assert(isGreaterThanZero(Capacity));
```

- **`static_assert` checked at compile-time**
  - Compilation fails if it evaluates to `false`
  - The compiler needs to be able to evaluate the expression
- **Syntax:**
  - `static_assert(condition, message);`
  - `static_assert(condition);`

```
constexpr unsigned pi = 3;
```

- **Evaluated at compile-time (mandatory)**
- **Initialized by a constant expression**
  - Literal value
  - Expression computable by the compiler
  - `constexpr` function calls
- **Require literal type**
- **Can be used in constant expression contexts**
- **Possible contexts**
  - Local scope
  - Namespace scope
  - `static` data members
- **`constexpr` variables are `const`**

```cpp
constexpr auto factorial(unsigned n) {
  ...
}
```

- **`constexpr` functions can...**
  - ... have local variables of “literal” type. The variables must be initialized before used.

```cpp
int local;
```

```cpp
LiteralType local{};
```

```cpp
int local;
f(local);
```

```cpp
std::string local{};
```

  - ... use loops, recursion, arrays, references
  - ... even contain branches that rely on run-time features, if branch is not executed during compile-time computations, e.g., `throw`
  - ... but can only call `constexpr` functions

`constexpr` Functions Restrictions

- **`constexpr` evaluation cannot...**
  - ... allocate dynamic memory (`new`, `delete`)

```
constexpr int * allocate() {
  return new int{};
}
```

  - ... use exception handling (`throw`, `try/catch`)

```
constexpr void throwError() {
  throw std::logic_error{""};
}
```

  - ... be virtual member functions

```
struct Base {
  constexpr virtual void modify() {
};
```

- **Constexpr functions are useable in constexpr and non-constexpr contexts**

```
constexpr auto factorial(unsigned n) {
  auto result = 1u;
  for (auto i = 2u; i <= n; i++) {
    result *= i;
  }
  return result;
}

constexpr auto factorialOf5 = factorial(5);

int main() {
  static_assert(factorialOf5 == 120);
  std::cout << factorial(5);
}
```

- **The compiler will prevent Undefined Behavior**
  - Leads to compilation error

```
constexpr int divide(int n, int d) {
  return n / d;
}

constexpr auto surprise = divide(0, 0);

int main() {
  std::cout << surprise;
}
```

```
..\CTUB.cpp:7:33:   in 'constexpr' expansion of 'divide(0, 0)'
..\CTUB.cpp:4:12: error: '(0 / 0)' is not a constant expression
   return n / d;
          ~~^~~
```

- **If constexpr evaluation does not reach invalid statement the code is valid**

```
constexpr void throwIfZero(int value) {
  if (value == 0) {
    throw std::logic_error{""};
  }
}

constexpr int divide(int n, int d) {
  throwIfZero(d);
  return n / d;
}

constexpr auto five = divide(120, 24);
constexpr auto failure = divide(120, 0);
```

?

```
int whatIsTheAnswer() {
  return 42;
}

static_assert(whatIsTheAnswer() == 42);
```

```
constexpr int global = 42;
constexpr int const * allocate(bool
useGlobal) {
  if (useGlobal) {
    return &global;
  } else {
    return new int{};
  }
}
constexpr int const * ptr = allocate(true);
```

?

<code>int whatIsTheAnswer() {</code> <code> return 42;</code> <code>}</code> <code>static_assert(whatIsTheAnswer() == 42);</code>	Incorrect The expression in static_assert requires a compile-time expression. `whatIsTheAnswer()` is not a constexpr function.
<code>constexpr int global = 42;</code> <code>constexpr int const * allocate(bool useGlobal) {</code> <code> if (useGlobal) {</code> <code> return &global;</code> <code> } else {</code> <code> return new int{};</code> <code> }</code> <code>}</code> <code>constexpr int const * ptr = allocate(true);</code>	Correct As long as the path with the new expression is not taken, it is valid to have the code in a `constexpr` function. `allocate(false);` could not be used to initialize a compile-time constant.

- **Built-in scalar types, like `int`, `double`, pointers, enumerations, etc.**
- **Structs with some restrictions[1]**
  - Trivial destructor (non-user-defined)
  - With a `constexpr` constructor and no virtual members
- **Lambdas**
- **References**
- **Arrays of literal types**
- **`void`**
- **Literal Types can be used in `constexpr` functions, but only `constexpr` member functions can be called on values of literal type**

[1] https://en.cppreference.com/w/cpp/named_req/LiteralType

Literal Class Type Example

- **Trivial Destructor**
- **Constexpr Constructor**
  - At least one
- **Constexpr Member Functions**
  - `const` & `non-const`
  - Only `constexpr` useable in `constexpr` context
  - All are non-virtual
- **Can be a template**

```
template <typename T>
class Vector {
  constexpr static size_t dimensions = 3;
  std::array<T, dimensions> values{};
public:
  constexpr Vector(T x, T y, T z)
    : values{x, y, z}{}
  constexpr T length() const {
    auto squares = x() * x() +
                   y() * y() +
                   z() * z();
    return std::sqrt(squares);
  }
  constexpr T & x() {
    return values[0];
  }
  constexpr T const & x() const {
  return values[0];
  }
  //...
};
```

Using the Vector Literal Type

- **Can be used in constexpr and non-constexpr contexts**
- **Non-constexpr member functions can be used to modify the object**
- **constexpr variables are const**

```
constexpr Vector<double> create() {
  Vector<double> v{1.0, 1.0, 1.0};
  v.x() = 2.0;
  return v;
}

constexpr auto v = create();
static_assert(doubleEqual(v.length(), 2.4495));

int main() {
  //v.x() = 1.0;
  auto v2 = create;
  v2.x() = 2.0;
}
```

```
template <size_t n>
struct fact {
  static size_t const value{(n > 1)?  n * fact<n-1>::value : 1};
};

template <>
struct fact<0> { // recursion base case: template specialization
  static size_t const value = 1;
};

void testFactorialCompiletime() {
  constexpr auto result = fact<5>::value;
  ASSERT_EQUAL(result, 2 * 3 * 4 * 5);
}
```

- **"Integer" only (almost) through non-type template parameters**
  - Would need out-of-class static member variable definition for ODR-use at run-time or C++11 constexpr

- **Capture types (the types returned by lambda expressions) are literal types as well**
  - They can be used as types of `constexpr` variables
  - They can be used in `constexpr` functions
  - Restrictions to `constexpr` functions and variables apply as well
- **Examples for demonstration purposes**

```
constexpr double pi = 3.14159;

constexpr auto area = [](double r) {
  return pi * r * r;
};

constexpr auto circleArea = area(2.0);
```

```
constexpr auto cubeVolume(double x) {
  auto area = [x] {return pi * x * x;};
  return area() * x;
}

constexpr auto cV = cubeVolume(5.0);
```

Compile-Time Computation (pre C++11)

- **Only preprocessor macros and templates (class & function)**
- **Templates allow Turing-complete computation**
  - But it looks ugly and can be hard to understand
  - Compiler error-messages can be lengthy
  - Compile-time long and recursion depth limited (depends on the compiler and its settings)
- **Almost only single values can be computed**
  - Arrays/structs possible, but ugly
- **Observation: static const member variables of class templates are variables that depend on template parameters**

Variable Templates

- **Syntax**

```
template<[Parameters]>
Type name [= initialization];
```

  - Can be specialized
  - Usually `constexpr`

- **Purpose**
  - Compile-time predicates and properties of types
  - Usually applied in template meta programming
  - Before C++14 it was necessary to create a class template with a static member variable
    - Now less code is required for the same effect

```
template<typename T>
constexpr T pi = T(3.1415926535897932385);

template<typename T>
constexpr bool is_integer = false;

template<>
constexpr bool is_integer<int> = true;
```

Compile-Time Factorial with Variable Templates


```
template <size_t N>
constexpr size_t factorial = factorial<N - 1> * N;

template <> //Base case
constexpr size_t factorial<0> = 1;
```

- **Variable templates...**
  - ... can be `constexpr`
  - ... can be defined recursively `->` specialization to define the base case
- **Useage**
  - Template-ID (Name and template arguments)

```
static_assert(factorial<0> == 1);
static_assert(factorial<5> == 120);
```

- **Base case required for `printAll` because of the recursion**

```
void printAll() {
}

template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
  }
  printAll(rest...);
}
```

- **Compile-time conditional inclusion statement**

```
void printAll() {
}

template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
  std::cout << first;
  if constexpr (sizeof...(Types)) {
    std::cout << ", ";
    printAll(rest...);
  }
}
```

- **Requires compile-time expression**

`if constexpr` Instantiated

- **Instance for `printAll("Hello"s);`**

```
void printAll(std::string const & first) {
  std::cout << first;
  if constexpr (0) {
    std::cout << ", ";
    printAll(); //rest... expansion
  }
}
```

```
void printAll(std::string const & first) {
  std::cout << first;





}
```

- **We don't need a base case anymore!**

Right or Wrong? (Preview)

?

```
template <std::size_t N>
constexpr size_t McCarthy91 = [] {
    if constexpr (N <= 100) {
      return McCarthy91<McCarthy91<(N + 11)>>;
    }
    return N - 10;
    }();
```

```
struct Point {
  constexpr Point(double x, double y)
    : x{x}, y{y}{}
  Point() : Point{0.0, 0.0}{}
private:
  double x;
  double y;
};

constexpr Point origin{0.0, 0.0};
```

?

<pre>template <std::size_t N>
constexpr size_t McCarthy91 = [] {
    if constexpr (N <= 100) {
      return McCarthy91<McCarthy91<(N + 11)>>;
    }
    return N - 10;
    }();</pre>
	Correct
	
	Variable templates can be initialized by lambdas, which are literal types, as long as there is a base case. With `constexpr if` we reach that base case.

<pre>struct Point {
  constexpr Point(double x, double y)
    : x{x}, y{y}{}
  Point() : Point{0.0, 0.0}{}
private:
  double x;
  double y;
};
 	
constexpr Point origin{0.0, 0.0};</pre>
	Correct
	
	Point is a literal type. Not all constructors need to be `constexpr`. However, in compile-time constant expressions only the `constexpr` constructors can be used.

Substitution Failure Is Not An Error (SFINAE)

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- **What do you expect is the return value of the program on the right?**
  - None, the program does not compile!

Name increment is looked up

`increment(unsinged)` | `increment` Template

↓

Template arguments are deduced

`increment(unsinged)` | `increment<int>(int)`

↓

Best overload is selected

`increment(int)`

```cpp
unsigned increment(unsigned i) {
  return i++;
}

template<typename T>
T increment(T value) {
  return value.increment();
}

int main() {
  return increment(42);
}
```

```
error: request for member 'increment' in 'value',
which is of non-class type 'int'
```

Substitution Failure Is Not An Error

- **During overload resolution the template parameters in a template declaration are substituted with the deduced types**
  - This may result in template instances that cannot be compiled
  - Or otherwise suboptimal selection
- **If the substitution of template parameter fails that overload candidate is discarded**
- **Substitution failure might happen in**
  - Function return type
  - Function parameter
  - Template parameter declaration
  - And expressions in the above
- **Errors in the instance body are still errors**

Substitution

Substitution

Substitution

```
template<typename T>

T increment(T value) {
  return value.increment();
}
```

```
int increment(int value) {
  return value.increment();
} //T = int
```

Possible Solution (Not Recommended)


```cpp
template<typename T>
auto increment(T value) -> decltype(value.increment()) {
  return value.increment();
}
```

- **We can break the return type**
- **If we tell the compiler to use the type of `value.increment()` as return type for `increment<int>`**
  - That type cannot be determined during substitution

```
error: no matching function for call to 'increment(int)'
  increment(42);
              ^
note: candidate: template<class T> decltype (value.increment()) increment(T)
 auto increment(T value) -> decltype(value.increment()) {
      ^~~~~~~~~
note:   template argument deduction/substitution failed:
In substitution of 'template<class T> decltype (value.increment()) increment(T) [with T = int]':
error: request for member 'increment' in 'value', which is of non-class type 'int'
 auto increment(T value) -> decltype(value.increment()) {
```

Overload Selection with SFINAE

- **Since there is a problem during substitution that overload is discarded**

Name increment is looked up

`increment(unsinged)` | `increment` Template

Template arguments are deduced

`increment(unsigned)` | ~~`increment<int>(int)`~~

Best overload is selected

`increment(unsigned)`

- **Now the result is 42**

```
unsigned increment(unsigned i) {
  return i++;
}

template<typename T>
auto increment(T value) ->
    decltype(value.increment()) {
  return value.increment();
}

int main() {
  return increment(42);
}
```

- **This approach, using decltype(...) as trailing return type, is infeasible in general**
  - Function might have return type `void`
- **It is not elegant for complex bodies**

<type_traits>

- **Let's examine our example again**
  - We want the `increment` template to be selected only for class type arguments
- **There exists a template `std::is_class<T>`**
  - contains `static constexpr bool value;`
  - `value` is `true` if `T` is a class, `false` otherwise
- **Variable template: `std::is_class_v<T>`**
  - Type `bool` (direct access of `::value`)
- **Can we apply this to the increment template directly?**
  - No, either value (`true` or `false`) is still valid
  - We need something to create an error in the type of the function

```
template<typename T>
T increment(T value) {
  return value.increment();
}

int main() {
  return increment(42);
}
```

```
#include <type_traits>

struct S {};

int main() {
  std::is_class<S>::value; //true
  std::is_class<int>::value; //false
}
```

<type_traits>

```
template<bool expr, typename T = void>
struct enable_if;
```

- **The `std::enable_if_t` template takes an expression and a type**
  - If the expression evaluates to `true` `std::enable_if_t` represents the given type
  - Otherwise it does NOT represent a type

```
int main() {
  std::enable_if_t<true, int> i;       //int
  std::enable_if_t<false, int> error; //no type
}
```

- **Inside `std::enable_if`**

```
template<bool expr,
         typename T = void>
struct enable_if {};
```

```
template<typename T>
struct enable_if<true, T> {
  using type = T;
};
```

```
template<bool expr,
         typename T = void>
using enable_if_t = typename
      enable_if<expr, T>::type;
```

```cpp
template<typename T, >

T increment( T  value) {
  return value.increment();
}
```

Spots to apply enable_if (SFINAE)

- **Possibilities**

```cpp
template<typename T>
std::enable_if_t<std::is_class<T>::value, T> increment(T value) {
  return value.increment();
}
```

```cpp
template<typename T>
T increment(std::enable_if_t<std::is_class<T>::value, T> value) {
  return value.increment();
}
```

enable_if as parameter impairs type deduction

```cpp
template<typename T, typename = std::enable_if_t<std::is_class<T>::value, void>>
T increment(T value) {
  return value.increment();
}
```

would be void per default

- **Example: Box-Container with**
  - Default constructor
  - Copy constructor
  - Move constructor
  - Size constructor

```
Box<MemoryOperationCounter> b{1};
```

```
template <typename T>
struct Box {
  Box() = default;
  Box(Box const & box)
    : items{box.items}{}
  Box(Box && box)
    : items{std::move(box.items)} {}
  explicit Box(size_t size)
    : items(size) {}
  //...
private:
  std::vector<T> items{};
};
```

- **What if we replace the copy/move constructors with a forwarding constructor?**

```
Box<MemoryOperationCounter> b{1};
```

```
template <typename T>
struct Box {
  Box() = default;
  template <typename BoxType>
  explicit Box(BoxType && other)
    : items(std::forward<BoxType>(other).items) {}
  explicit Box(size_t size)
    : items(size) {}
  //...
private:
  std::vector<T> items{};
};
```

```
Test.cpp:14:41: error: request for member 'items' in 'std::forward<int>((* & other))',
                              which is of non-class type 'int'
    : items(std::forward<BoxType>(other).items) {}
            ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~^~~~~
```

- **We don't want the forwarding constructor to match anything else than Boxes**
    - Type traits can be used to narrow down the valid calls.

```
template <typename T>
struct Box {
  Box() = default;
  template <typename BoxType, typename = std::enable_if_t<std::is_same_v<Box, BoxType>>>
  explicit Box(BoxType && other)
    : items(std::forward<BoxType>(other).items) {}
  explicit Box(size_t size)
    : items(size) {}
  //...
private:
  std::vector<T> items{};
};
```

- **The standard library provides many predefined checks for type traits**[1]
- **A trait contains a boolean value**
- **Usually they are available in two versions**
- **Example:**
  - `std::is_same<T, U>`
  - `std::is_same_v<T, U>`

```
template <typename T, typename U>
struct is_same : false_type {
  // inherits;
  // static constexpr bool value = false;
};

template <typename T>
struct is_same<T, T> : true_type {
  // inherits;
  // static constexpr bool value = true;
};

template <typename T, typename U>
constexpr bool is_same_v = is_same<T, U>::value;
```

[1] https://en.cppreference.com/w/cpp/header/type_traits

Summary

- **Many computations for which the arguments are known upfront can be computed at compile time**
- **Until C++20 dynamic memory allocation is not possible**
- **All literal types can be used in constexpr contexts**
- **SFINAE is used to eliminate overload candidates**

?

<pre>template <typename T>
std::enable_if_t<
   std::negation_v<
      std::is_reference<T>
   >
>
consume(T && value) { /*...*/ }
 	
//This function can only be called with rvalues</pre>	

<pre>template <typename T>
int convert(T value) {
  using namespace std;
  enable_if_t<
    is_constructible_v<int, T>, int
  > converted{value};
  return converted;
}
//This function can be eliminated by SFINAE</pre>	

?

<pre>template <typename T>
std::enable_if_t<
   std::negation_v<
      std::is_reference<T>
   >
>
consume(T && value) { /*...*/ }
 	
//This function can only be called with rvalues</pre>
	Correct
	
	`std::is_reference` is `std::true_type` if T is a reference otherwise `std::false_type`. If the forwarding reference is initialized with an lvalue T is a reference. `std::negation_v` negates the `true/false_type`. The overload is only enabled for rvalues.

<pre>template <typename T>
int convert(T value) {
  using namespace std;
  enable_if_t<
    is_constructible_v<int, T>, int
  > converted{value};
  return converted;
}
//This function can be eliminated by SFINAE</pre>
	Incorrect
	
	This is not SFINAE! It will compile if called with something that can be used to construct an int, but the overload will be taken anyway.

Self Study

Compile time code

Cevelop
Your C++ deserves it

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- **Have a look at the following code on Godbolt and the binary that is generated**

```cpp
constexpr auto factorial(unsigned n) {
  auto result = 1u;
  for (auto i = 2u; i <= n; i++) {
    result *= i;
  }
  return result;
}

constexpr auto factorialOf5 = factorial(5);

int main() {
  static_assert(factorialOf5 == 120);
  return factorialOf5;
}
```

```asm
main:
  push rbp
  mov rbp, rsp
  mov eax, 120
  pop rbp
  ret
```

https://www.godbolt.org/z/suMDYp

- **No calls to the `factorial` function are present anymore**