

Department I - C Plus Plus

## Modern and Lucid C++ Advanced for Professional Programmers

Week 8 – Compile-Time Computation

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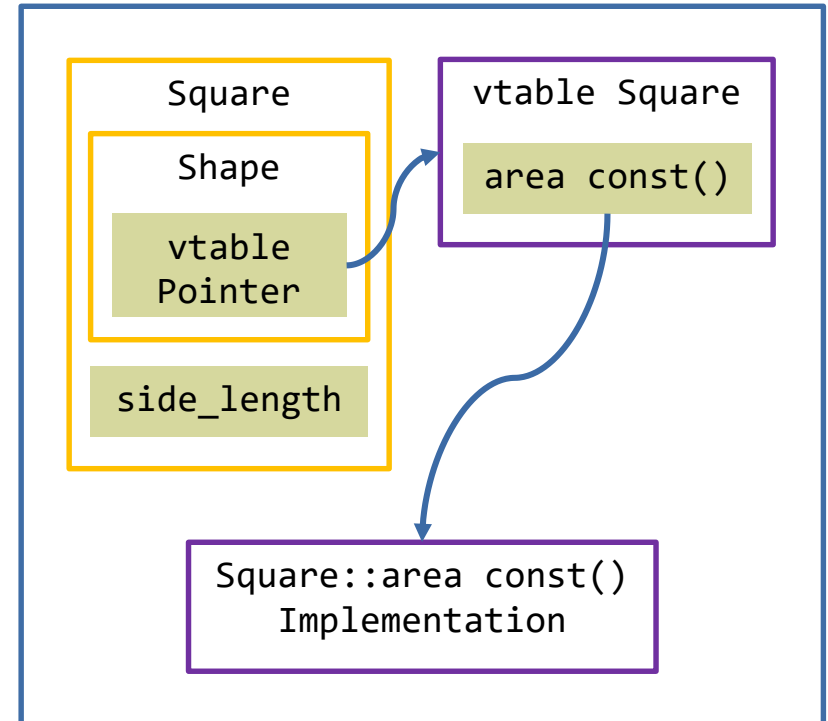
## Recap Week 7



- 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 InfiniteProbabilityDriveTag : SpaceDriveTag {};
```

```
struct MultiPurposeCrewVehicle;  
  
struct GalaxyClassShip;  
  
struct HeartOfGoldPrototype;
```

- **Approach 1: Derive space ship from the associated tag type**
  - 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;  
};
```

```
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

- 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

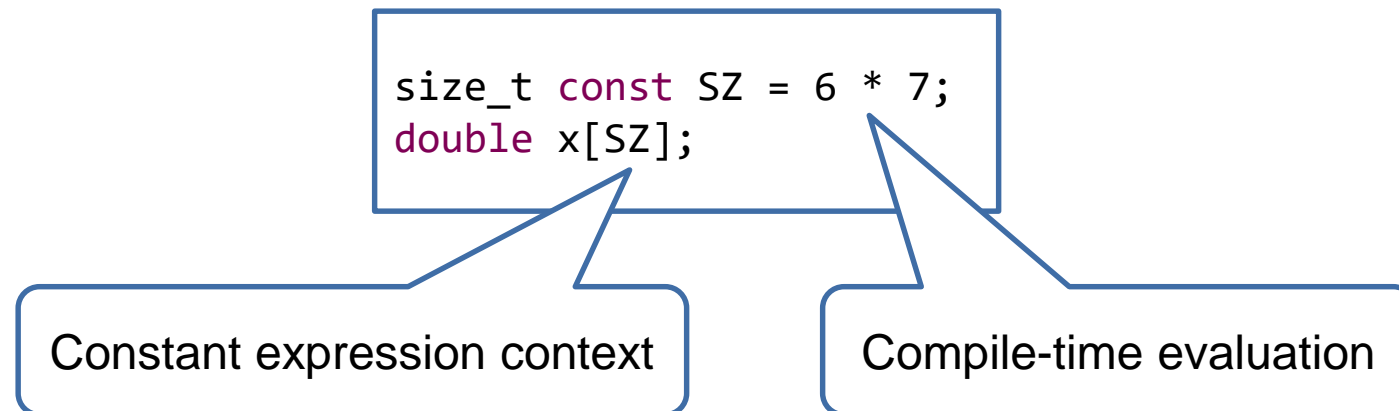
Constexpr



- **ROMable data (guaranteed!)**
  - Smaller binary
- **Better run-time performance**
- **Plain C++**
- **Not yet everything possible provided**
  - Standard library not made up for everything desirable
- **Compile times 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



- 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**

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

- **constexpr functions can...**

- ... have local variables of “literal” type. The variables must be initialized before used.

```
int local;
```

```
LiteralType local{};
```

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

```
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 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);
```

- **Built-in scalar types, like `int`, `double`, pointers, enumerations, etc.**
- **Structs with some restrictions<sup>1</sup>**
  - 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**

<sup>1</sup> [https://en.cppreference.com/w/cpp/named\\_req/LiteralType](https://en.cppreference.com/w/cpp/named_req/LiteralType)

- **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];
    }
    //...
};
```

- 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);
```

- **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**

## ● 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;
```



```
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

- **Usage**

- 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...);  
}
```

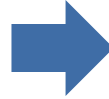
- Compile-time conditional inclusion statement

```
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

- 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;  
  
}
```

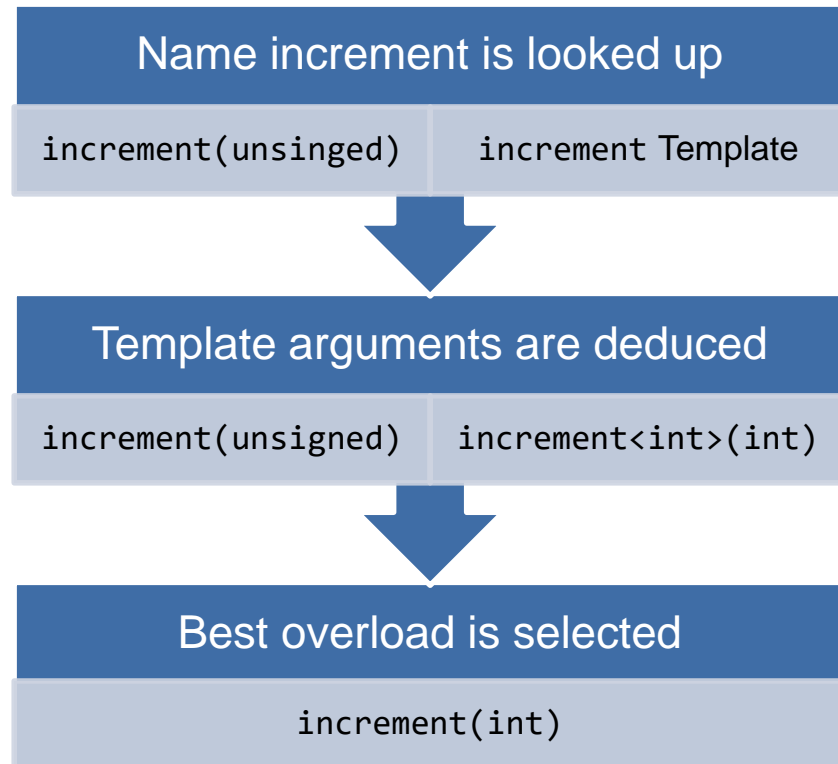
- We don't need a base case anymore!

# Substitution Failure Is Not An Error (SFINAE)



- What do you expect is the return value of the program on the right?

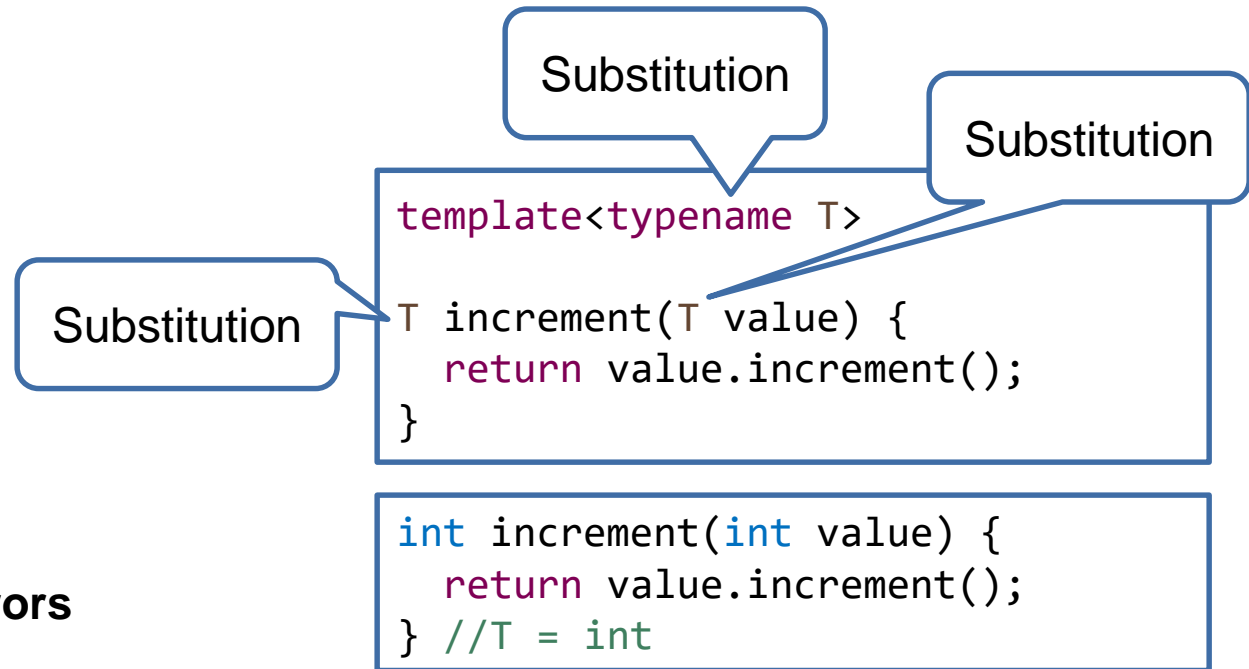
- None, the program does not compile!



```
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'
```

- 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



```
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:
```

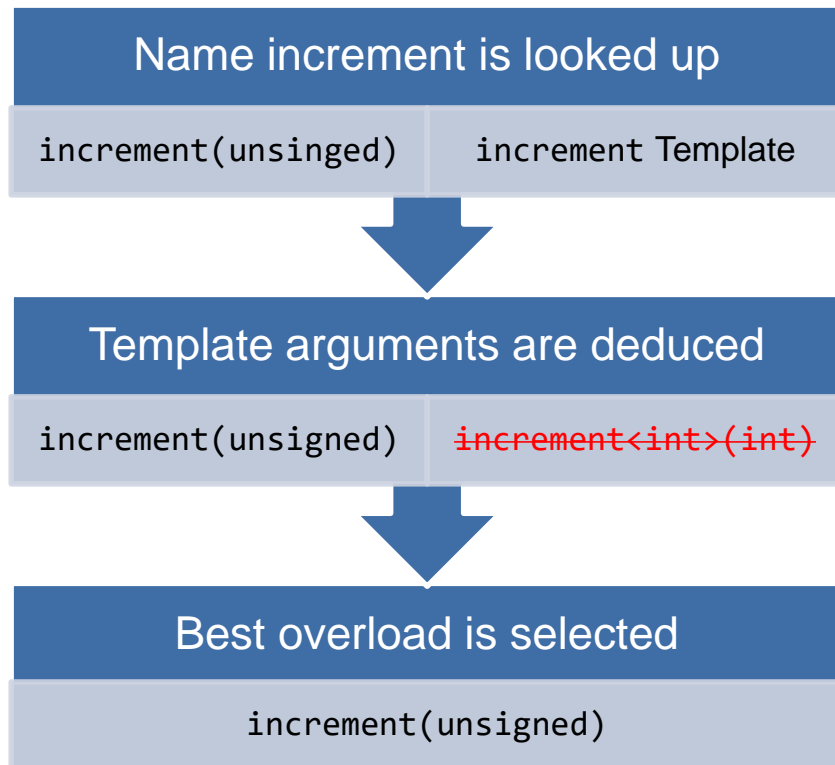
```
In substitution of 'template<class T> decltype (value.increment()) increment(T) [with T = int]':
```

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

```
    auto increment(T value) -> decltype(value.increment()) {
```



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



- 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

&lt;type\_traits&gt;

- **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
}
```

&lt;type\_traits&gt;

```
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;
```

```
template<typename T, >
```

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

 Spots to apply enable\_if (SFINAE)

## ● Possibilities

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

```
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

```
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<sup>1</sup>

- 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;
```

<sup>1</sup> [https://en.cppreference.com/w/cpp/header/type\\_traits](https://en.cppreference.com/w/cpp/header/type_traits)



- **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**

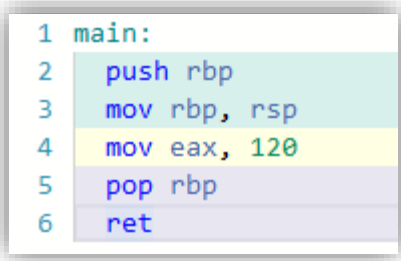
Self Study

Compile time code



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

```
constexpr auto factorial(unsigned n) {  
    auto result = 1u;  
    for (auto i = 2u; i <= n; i++) {  
        result *= i;  
    }  
    return result;  
}  
  
constexpr auto factorial0f5 = factorial(5);  
  
int main() {  
    static_assert(factorial0f5 == 120);  
    return factorial0f5;  
}
```



```
1 main:  
2     push rbp  
3     mov rbp, rsp  
4     mov eax, 120  
5     pop rbp  
6     ret
```

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

- No calls to the factorial function are present anymore