accu 2022

WHAT HAS C++20 EVER DONE FOR TEMPLATES?

HENDRIK NIEMEYER

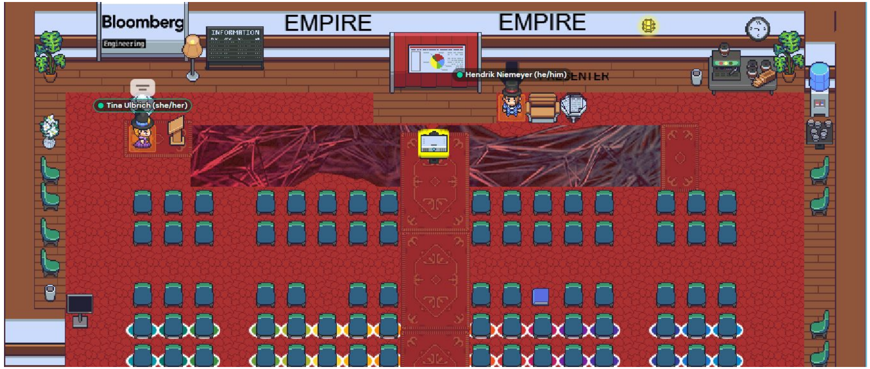
What Has C++20 Ever Done for Templates

Hendrik Niemeyer (he/him)

Link to Slides:

https://tinyurl.com/2p8dj5cr

Feedback and Questions



- Twitter: [@hniemeye]
- LinkedIn: [hniemeyer87]
- GitHub: [hniemeyer]

Ask questions in Q&A section of zoom now or later in the gathertown room.

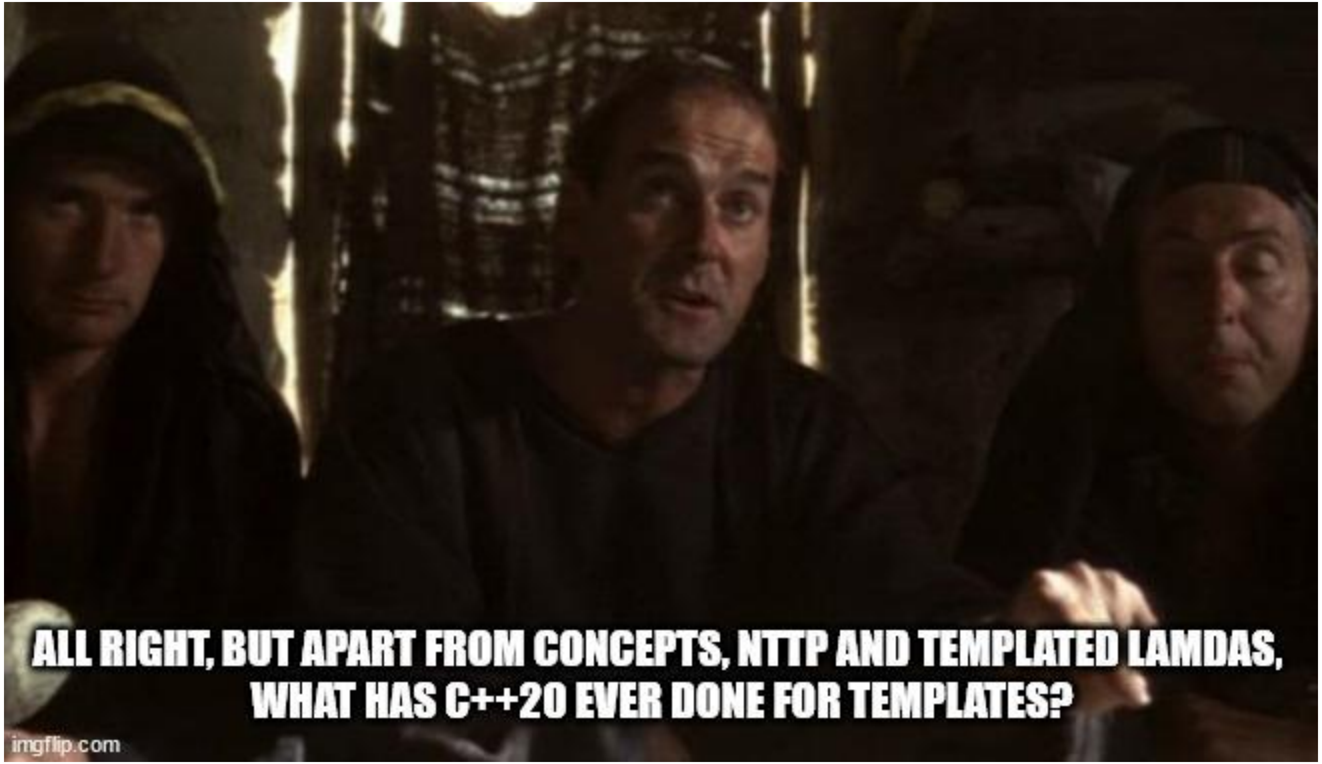
More Resources

[C++20 Concepts: 11:00 - 12:30 Wednesday 6th April 2022 BST]

[C++20 – My Favourite Code Examples: 11:00 - 12:30 Thursday 7th April 2022 BST]

[Documentation in the Era of Concepts and Ranges: 16:00 - 17:30 Friday 8th April 2022 BST]

What Has C++20 Ever Done for Templates?



Concepts

Use Case

- A function or a class template
- but we want to limit what the template parameters can be
- this is already possible in C++17 (using enable_if, static_assert, type traits, void_t)
- but concepts improve readability, error messages and the overall design of type constraints
- not necessarily compile time improvements

What Is a Concept?

- compile-time predicate on template parameters
  - `std::forward_iterator<T>` is true if T is a forward iterator
  - `std::constructible_from<T, Args...>` is true if T can be initialized with the given Args
- used together with constraints

Concepts From the Standard Library

```
#include <concepts>
#include <iterator>
#include <ranges>
```

Core language concepts

same_as (C++20)	specifies that a type is the same as another type (concept)
derived_from (C++20)	specifies that a type is derived from another type (concept)
convertible_to (C++20)	specifies that a type is implicitly convertible to another type (concept)
common_reference_with (C++20)	specifies that two types share a common reference type (concept)
common_with (C++20)	specifies that two types share a common type (concept)
integral (C++20)	specifies that a type is an integral type (concept)
signed_integral (C++20)	specifies that a type is an integral type that is signed (concept)
unsigned_integral (C++20)	specifies that a type is an integral type that is unsigned (concept)
floating_point (C++20)	specifies that a type is a floating-point type (concept)
assignable_from (C++20)	specifies that a type is assignable from another type (concept)
swappable swappable_with (C++20)	specifies that a type can be swapped or that two types can be swapped with each other (concept)
destructible (C++20)	specifies that an object of the type can be destroyed (concept)
constructible_from (C++20)	specifies that a variable of the type can be constructed from or bound to a set of argument types (concept)
default_initializable (C++20)	specifies that an object of a type can be default constructed (concept)
move_constructible (C++20)	specifies that an object of a type can be move constructed (concept)
copy_constructible (C++20)	specifies that an object of a type can be copy constructed and move constructed (concept)

Comparison concepts

boolean (C++20)	specifies that a type can be used in Boolean contexts (concept)
equality_comparable equality_comparable_with (C++20)	specifies that operator == is an equivalence relation (concept)
totally_ordered totally_ordered_with (C++20)	specifies that the comparison operators on the type yield a total order (concept)

Constraints

```
template <typename T>
auto norm(const std::vector<T>& values) requires std::floating_point<T> {
    T result = 0.0;
    for (const auto value : values) {
        result += value*value;
    }
    return std::sqrt(result);
}
```

https://godbolt.org/z/Cov-tp

Error Messages and Templates With Constraints

```
<source>:27:44: error: use of function 'auto norm(const std::vector<T>&)
requires  floating_point<T> [with T = std::__cxx11::basic_string<char>]'
with unsatisfied constraints
   27 |      const auto result2 = norm(my_string_vec );
      |                                            ^
note: the expression 'is_floating_point_v<_Tp> [with _Tp =
std::__cxx11::basic_string<char, std::char_traits<char>,
std::allocator<char> >]' evaluated to 'false'
  111 |      concept floating_point =  is_floating_point_v<_Tp>;
      |                                ^~~~~~~~~~~~~~~~~~~~~~~~
```

```
cc1plus: note: set '-fconcepts-diagnostics-depth=' to at least 2 for more detail
Execution build compiler returned: 1
```

Requires Clause

```
template<typename T>
T f(T t) requires MyConcept<T> {return t;}

template<typename T> requires MyConcept<T>
T f(T t) { return t;}

template<typename T> requires MyConcept<T> && MyOtherConcept<T>
T f(T t) { return t;}
```

Even More Constraints

```
template <typename T>
auto norm(const T& values) requires std::floating_point<typename
T::value_type> && std::forward_iterator<typename T::const_iterator>
{
    typename T::value_type result = 0.0;
    for (const auto value : values) {
        result += value*value;
    }
    return std::sqrt(result);
}
```

https://godbolt.org/z/BVRPLs

Concepts

template < *template-parameter-list* **>**

concept *concept-name* **=** *constraint-expression***;**

```
//Constraint-expression: other concept plus type trait
template <typename T>
concept MyConcept = OtherConcept<T> || std::is_integral<T>::value
```

Pitfalls

```
template<typename T>
concept Recursion = Recursion<const T>; // Not OK: recursion

template<class T> requires C1<T>
concept C2 = ...; // Not OK: Attempting to constrain a concept
definition
```

Requires Expression

requires (*parameter-list*(optional)) { *requirement-seq* }

```
template<typename T>
concept Addable =
requires (T a, T b) {
    a + b; // Meaning: "the expression a+b is a valid
expression that will compile for type T"
};
```

Type Requirements

```
template<typename T> concept HasNestedTypes =
requires {
    typename T::value_type; // Meaning: "Nested type
T::value_type exists"
    typename T::size_type; //Meaning: "Nested type
T::size_type exists"
};
```

Compound Requirements

```
template<typename T> concept AddableLikeFloats =
requires (T a, T b) {
    {a + b} noexcept -> std::convertible_to<float>;
    //Meaning: "a+b is valid, does not throw and the
result is convertible to float"
};
```

Nested Requirements

```
template <typename T>
concept Addable = requires (T a, T b) {
    requires std::convertible_to<float, decltype(a+b)>;
};
```

FloatingPointContainer Concepts

```
template <typename T>
concept IterableWithFloats =
std::floating_point<typename T::value_type> &&
std::forward_iterator<typename T::const_iterator>;
```

FloatingPointContainer Concepts

```
template <typename T>
auto norm(const T& values) requires IterableWithFloats<T>
{
    typename T::value_type result = 0.0;
    for (const auto value : values) {
        result += value*value;
    }
    return std::sqrt(result);
}
```

https://godbolt.org/z/EVUMT6

FloatingPointContainer Concepts

```
template <IterableWithFloats T>
auto norm(const T& values) {
    typename T::value_type result = 0.0;
    for (const auto value : values) {
        result += value*value;
    }
    return std::sqrt(result);
}
```

A Function Which Takes Another Callable

```
template <typename Callable>
int call_twice(Callable callable, int argument) {
    return callable(argument) + callable(argument);
}
```

std::function for Constraining

```
int call_twice(std::function<int(int)> callable, int argument) {
    return callable(argument) + callable(argument);
}
```

https://godbolt.org/z/vTqmxH

Implementation With Standard Concepts

```
template<typename Func, typename Arg, typename Ret> concept
FuncWithStd =
std::regular_invocable<Func, Arg> &&
std::same_as<std::invoke_result_t<Func, Arg>, Ret>;


template <typename Callable> requires FuncWithStd<Callable, int,
int>
int call_twice(Callable callable, int argument) {
    return callable(argument) + callable(argument);
}
```

https://godbolt.org/z/ZCE2j4

Concepts and Auto

```
std::floating_point auto divide(std::floating_point auto first,
std::floating_point auto second) {
    return first / second;
}
```

Overload Resolution

- compiler starts looking at the most constrained version of the template
- and ends with the least constrained or unconstrained version of the template
- we do not need a negated concept in overload resolution because of this
- a named concept can restrict other named concepts via subsumption
- overload resolution prefers the concept that subsumes another
- subsumption only works with named concepts and boolean combinations of concepts
- concepts of the standard library are carefully designed to use this

Examples for Subsumption

https://gcc.godbolt.org/z/Too7x3Kb3

https://gcc.godbolt.org/z/1hGcWoq7E

https://gcc.godbolt.org/z/dxEo3Kbvs

https://gcc.godbolt.org/z/hxnjbh4h4

Overload Resolution With Standard Concepts

```
template <typename Callable, typename Arg>
void print(Callable func, Arg a) {
  puts("Base case without constraints!");
}

template <typename Callable, typename Arg>
requires std::predicate<Callable, Arg> void print(Callable func, Arg a) {
  puts("This is a predicate!");
}

template <typename Callable, typename Arg>
requires std::invocable<Callable, Arg> void print(Callable func, Arg a) {
  puts("This is a general callable!");
}
```

https://godbolt.org/z/aRLHNF

Overload Resolution With Standard Concepts

```
template <typename T>
requires std::convertible_to<T, float> void print(T x) {
  puts("This is convertible to float!");
}

template <typename T>
requires std::convertible_to<T, double> void print(T x) {
  puts("This is convertible to double!");
}

int main() {
    print(5.0);
}
```

https://godbolt.org/z/8aWKc9

Summary

- Concepts provide an easy to use functionality to constrain templates
- overload resolution mechanism based on subsumption for fined grained overload control
- concepts from the standard library provide a well designed hierarchy of concepts

Are there any questions?

NTTP

What Can Be Used As NTTP?

- floats and doubles
- structural types: literal class types
  - with public, non-mutable members and base classes
  - all types of members and base classes fulfil the same requirement
- literal class type = constexpr constructor and destructor
- lambdas (without captures)

Examples For Structural Types

```
struct A {};  // OK: no user defined constructor


struct A {
    constexpr A(){};
    A(int x){};
};  // OK or Not OK: a user defined constructor which is not
constexpr
```

Examples For Structural Types

```
struct A {
    constexpr A(){};
};  // OK: only constexpr constructor


struct A {
     private:
          int y; };  // not OK: private member
```

Examples For Structural Types

```
struct A {
    constexpr A(int i) {};
    ~A() {};
}; //not OK: destructor is defined and not constexpr
```

Floats and Doubles as NTTP

- Floating point numbers are considered equivalent as NTTP if their underlying representation is the same
- this can lead to problems if floating point math is involved

https://gcc.godbolt.org/z/56T45qvh6

Reminder: auto and NTTP

- Since C++17 we can declare non-type template parameters with auto
- very useful for C++20 if we want to pass lambdas as NTTP

Lambdas as NTTP

https://gcc.godbolt.org/z/sGE8abGs5

https://gcc.godbolt.org/z/j7TqdcWbh

Application: Strong Types

https://gcc.godbolt.org/z/nxKjs9oT9

https://gcc.godbolt.org/z/vqaa53P56

Application: Ratio as NTTP

- std::ratio is designed as a type template parameter
- uses template metaprogramming for operations
- with new NTTP rules we can do it differently
- can be useful if you are writing a units library (look at mp-units)

https://gcc.godbolt.org/z/fjMe9f7PG

Are there any questions?

Templated Lambdas

Generic Lambdas

```
auto comparator = [](auto x, auto y) {return x<y;};
```

Generic Lambdas With Concepts

```
auto comparator = [](std::integral auto x,
std::integral auto y) {

        return x < y;

    };
```

Templated Lambdas

```
auto comparator = []<typename T>(T x, T y) {return
x<y;};


auto first_elem = []<typename T>(std::vector<T> vec)
{ return vec[0]; };
```

Templated Lambdas And Concepts

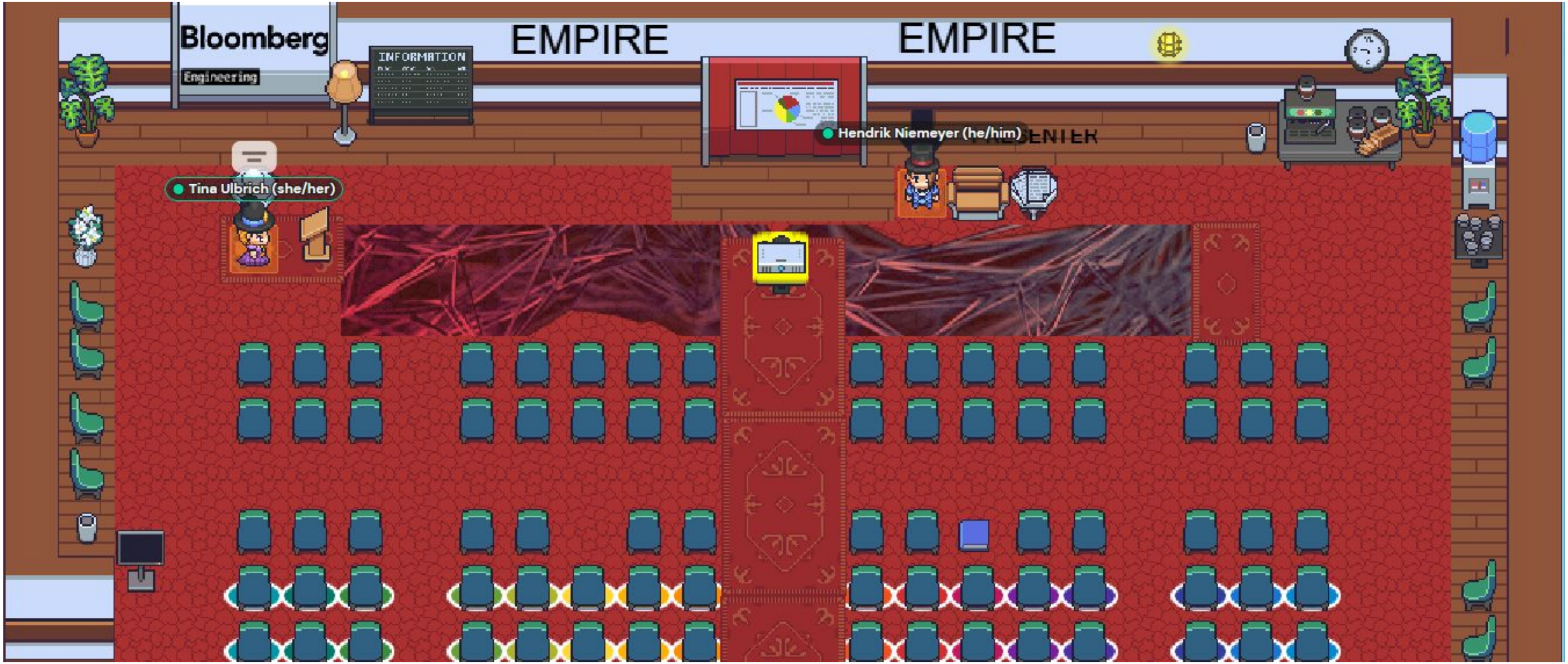
```
auto a = []<typename T>(T a, T b)requires std::floating_point<T>{};

auto b = []<std::integral T>(T a, T b){};
```

Are there any questions?

Fewer Places Which Require Typename

- fewer place which require `typename X<T>::name`

Are there any questions?


Bloomberg
Engineering
INFORMATION
EMPIRE
EMPIRE
Hendrik Niemeyer (he/him)
Tina Ulbrich (she/her)