C++20

The Big Four

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History of C++

C++98 — 1998

- Templates
- STL wit containers and algorithms
- Strings
- I/O Streams

C++11 — 2011

- Move semantic
- Unified initialisation
- `auto` and `decltype`
- Lambda expressions
- `constexpr`
- Multithreading and the memory model
- Regular expressions
- Smart pointers
- Hash tables
- `std::array`

C++14 — 2014

- Reader-writer locks
- Generic lambdas
- Extended `constexpr` functions

C++17 — 2017

- Fold expressions
- constexpr if
- Structured binding
- `std::string_view`
- Parallel algorithms of the STL
- Filesystem library
- `std::any`, `std::optional`, and `std::variant`

C++20 — 2020

- Coroutines
- ~~Contracts~~
- Modules
- Concepts
- Ranges library

The Big Four

- Coroutines
- ~~Contracts~~
- Modules
- Concepts
- Ranges Library

Coroutines

Coroutines are generalised functions that can be suspended and resumed while keeping their state.

- Typical use-case
  - Cooperative Tasks (protection from data races)
  - Event loops
  - Infinite data streams
  - Pipelines

Coroutines

Design Principles

- **Scalable**, to billions of concurrent coroutines
- **Efficient**: Suspend/resume operations comparable in cost to function call overhead
- **Open-Ended**: Library designers can develop coroutine libraries
- **Seamless Interaction** with existing facilities with no overhead
- **Usable** in environments where exceptions are forbidden or not available

Coroutines

	Function	Coroutine
invoke	`func(args)`	`func(args)`
return	`return statement`	`co_return someValue`
suspend		`co_await someAwaitable` `co_yield someValue`
resume		`coroutine_handle<>::resume()`

A function is a coroutine if it has a `co_return`, `co_await`, `co_yield` call or if it has a range-based for loop with a `co_await` call.

Coroutines

```
Generator<int> genForNumbers(int begin, int inc = 1){
    for (int i = begin; ; i += inc){
        co_yield i;
    }
}

int main(){
    auto gen = genForNumbers(-10);
    for (int i = 1; i <= 20; ++i) std::cout << gen.get() << " ";

    auto gen2 = genForNumbers(0, 5);
    for (int i = 1; ; ++i) std::cout << gen2.get() << " ";
}
```

-10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 . . . .

Coroutines

Blocking

```
Acceptor accept{443};

while (true){
  Socket so = accept.accept(); // block
  auto req = so.read();         // block
  auto resp = handleRequest(req);
  so.write(resp);               // block
}
```

Waiting

```
Acceptor accept{443};

while (true){
  Socket so = co_await accept.accept();
  auto req = co_await so.read();
  auto resp = handleRequest(req);
  co_await so.write(resp);
}
```

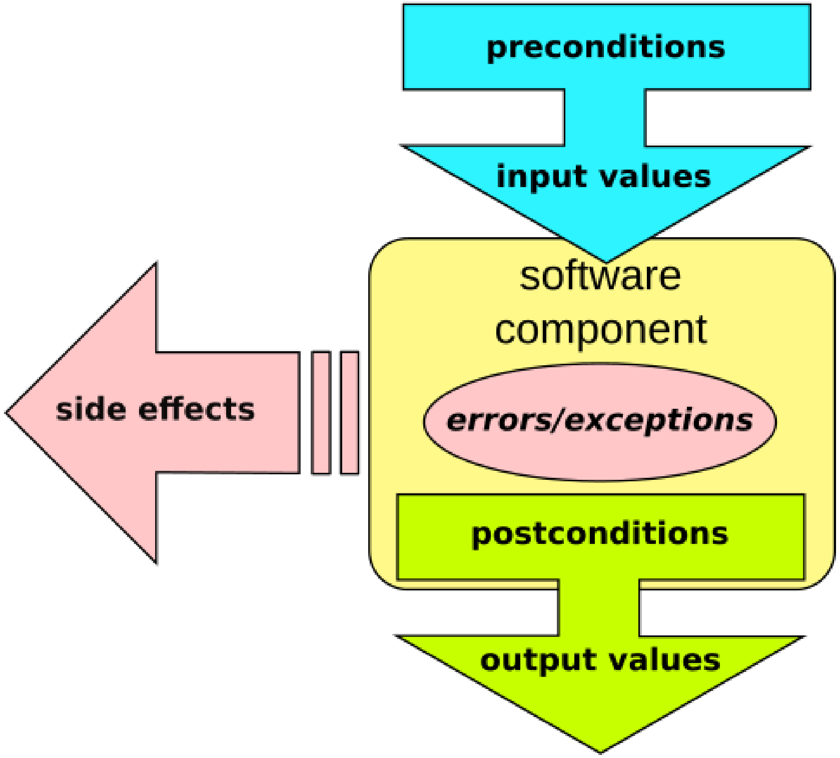
Couroutines - Waiting

```
Event event1{};
auto sendThread1 = std::thread([&event1]{ event1.notify(); });
auto receiThread1 = std::thread(receiver, std::ref(event1));

receiThread1.join(), sendThread1.join();

Event event2{};
auto receiThread2 = std::thread(receiver, std::ref(event2));
auto sendThread2 = std::thread([&event2]{
    std::this_thread::sleep_for(2s);
    event2.notify();
});

 receiThread2.join(), sendThread2.join();
```

The Big Four

- Coroutines
- ~~Contracts~~
- Modules
- Concepts
- Ranges Library

Contracts



A contract is a verifiable interface for a software component. It consists of preconditions, postconditions, and invariants.

→ Design By Contract

The Big Four

- Coroutines
- ~~Contracts~~
- **Modules**
- Concepts
- Ranges Library

Modules

```
// math.cppm

// Modules declaration
export Moduls math;


// exported function
export int add(int fir, int sec){
    return fir + sec;
}
```

```
// main.cpp

// imported Modules
import math;

int main(){

   add(2000, 20);

}
```

Advantages of Modules

- Faster compile times
  - A module is only imported once
- Isolation of macros
  - Name collisions and dependencies to marcro disappear
- Express the logical structure of the code
  - Explicit exporting of names
  - Packing of Modules
- Header files superfluous
  - No separations of interface and implementation files
  - Amount of source files may be reduced
- Get rid of an ugly workaround
  - No include guards with LONG_UPPERCASE_NAMES are necessary any more

Module Interface Unit

```
// math1.cppm

export module math1;

export int add(int fir, int sec);
```

The Module Interface Unit

- Contains the exported names: `export module math1`
- Can only export names
- Names that are not exported are not visible outside the module

- A module can only have one Module Interface Unit.

Module Implementation Unit

```
// math1.cpp

module math1;

int add(int fir, int sec){
    return fir + sec;
}
```

The Module Implementation Unit

- contains the non-exported module defintion: `module math1;`

- A module can have more than one Module Implementation Unit.

Predefined Modules

- **std.regex:** <regex>
- **std.filesystem:** <experimental/filesystem>
- **std.memory:** <memory>
- **std.threading:** <atomic>, <condition_variable>, <future>, <mutex>, <shared_mutex>, <thread>
- **std.core:** Remaining parts of the STL

The Module `math3`

Module Interface Unit

```
// math3.cppm

import std.core;

export module math3;

int add(int fir, int sec);

export int mult(int fir, int sec);

export void doTheMath();
```

Module Implementation Unit

```
// math3.cpp

module math3;

int add(int fir, int sec){
    return fir + sec;
}

int mult(int fir, int sec){
    return fir * sec;
}

void doTheMath(){
        std::cout << add(2000, 20);
}
```

Usage of the Module `math3`

```
// main3.cpp

// #include <iostream>
// #include <numeric>
// #include <string>
// #include <vector>
import std.core;

import math3;

int main(){
    // std::cout << "add(2000, 20): " << add(2000, 20) << std::endl;
    std::vector<int> myVec = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
    std::string doc = "std::accumulate(myVec.begin(), myVec.end(), mult): ";
    auto prod = std::accumulate(myVec.begin(), myVec.end(), 1, mult);
    std::cout << doc << prod << std::endl;
    doTheMath();
}
```

x64 Native Tools Command Prompt for VS 2019

```
C:\Users\rainer>math3.exe

std::accumulate(myVec.begin(), myVec.end(), mult): 3628800
add(2000, 20): 2020

C:\Users\rainer>
```

The Big Four

- Coroutines
- ~~Contracts~~
- Modules
- **Concepts**
- Ranges Library

The Advantages of Concepts

- Express the template parameter requirements as part of the interface
- Support the overloading of functions and the specialisation of class templates
- Produce drastically improved error messages by comparing the requirements of the template parameter with the template arguments
- Use them as placeholders for generic programming
- Empower you to define your concepts
- Can be used for class templates, function templates, and non-template members of class templates

Functions

Using of the concept `Sortable`.

implicit

```
template<Sortable Cont>
void sort(Cont& container){
    ...
}
```

explicit

```
template<typename Cont>
    requires Sortable<Cont>()
void sort(Cont& container){
    ...
}
```

- Usage:

```
std::list<int> lst = {1998, 2014, 2003, 2011};
sort(lst); // ERROR: lst is no random-access container with <
```

- `Sortable`
  - has to be a constant expression and a predicate

Classes

```
template<Object T>
class MyVector{};

MyVector<int> v1; // OK
MyVector<int&> v2 // ERROR: int& does not satisfy the constraint Object
```

➡ A reference is not an object.

Methods

```
template<Object T>
class MyVector{
    ...
    requires Copyable<T>()
    void push_back(const T& e);
    ...
};
```

- The type parameter `T` must be copyable.
- The concepts has to be placed before the method declaration.

More Requirements

```
template <SequenceContainer S,
          EqualityComparable<value_type<S>> T>
Iterator_type<S> find(S&& seq, const T& val){
    ...
}
```

- `find` requires that the elements of the container must
  - build a sequence
  - be equality comparable

Overloading

```
template<InputIterator I>
void advance(I& iter, int n){...}

template<BidirectionalIterator I>
void advance(I& iter, int n){...}

template<RandomAccessIterator I>
void advance(I& iter, int n){...}
```

- `std::advance` puts its iterator `n` positions further
- depending on the iterator, another function template is used

```
std::list<int> lst{1,2,3,4,5,6,7,8,9};
std::list<int>:: iterator i = lst.begin();
std::advance(i, 2);   //  BidirectionalIterator
```

Specialisation

```
template<typename T>
class MyVector{};

template<Object T>
class MyVector{};

➡ MyVector<int> v1; // Object T
   MyVector<int&> v2 // typename T
```

`MyVector<int&>` goes to the unconstrained template parameter.

`MyVector<int>` goes to the constrained template parameter.

Placeholder Syntax: `auto`

Detour: Asymmetry in C++14

```
auto genLambdaFunction = [](auto a, auto b) {
    return a < b;
};

template <typename T, typename T2>
auto genFunction(T a, T2 b){
    return a < b;
}
```

➡ Generic lambdas introduced a new way to define templates.

Placeholder Syntax: `auto`

C++20 unifies this asymmetry.

- `auto`: Unconstrained placeholder
- Concept: Constrained placeholder

➡ Usage of a placeholder generates a function template.

Constrained and Unconstrained

Constrained concepts can be used where `auto` is usable.

```
#include <iostream>
#include <type_traits>
#include <vector>

template<typename T>
concept bool Integral(){
    return std::is_integral<T>::value;
}

Integral auto getIntegral(int val){
    return val;
}
```

```
int main(){

    std::vector<int> vec{1, 2, 3, 4, 5};
    for (Integral auto i: vec)
        std::cout << i << " ";

    Integral auto b = true;
    std::cout << b << std::endl;

    Integral auto integ = getIntegral(10);
    std::cout << integ << std::endl;

    auto integ1 = getIntegral(10);
    std::cout << integ1 << std::endl;

}
```

Syntactic Sugar

Classical

```
template<typename T>
requires Integral<T>()
T gcd(T a, T b){
    if (b == 0) return a;
    else return gcd(b, a % b);
}

template<Integral T>
T gcd1(T a, T b){
    if (b == 0) return a;
    else return gcd1(b, a % b);
}
```

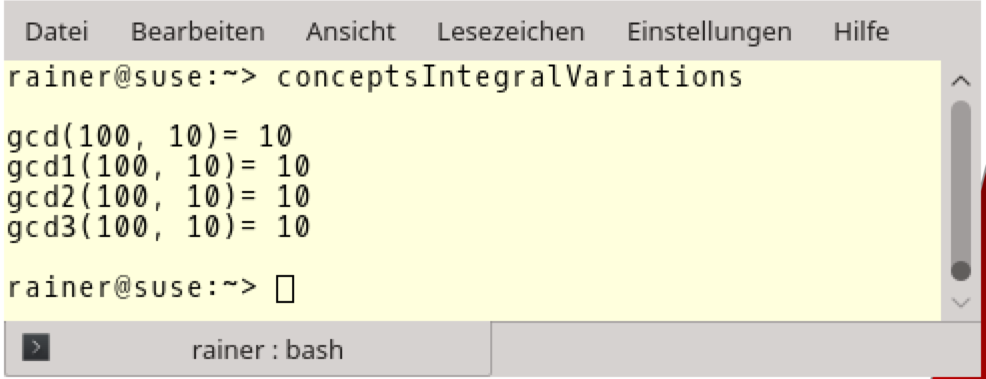
Abbreviated Function Templates

```
Integral auto gcd2(Integral auto a,
                   Integral auto b){
    if (b == 0) return a;
    else return gcd2(b, a % b);
}

auto gcd3(auto a, auto b){
    if (b == 0) return a;
    else return gcd3(b, a % b);
}
```

Syntactic Sugar

```
int main(){

  std::cout << std::endl;
  std::cout << "gcd(100, 10)= " <<  gcd(100, 10)  << std::endl;
  std::cout << "gcd1(100, 10)= " <<  gcd1(100, 10)  << std::endl;
  std::cout << "gcd2(100, 10)= " <<  gcd2(100, 10)  << std::endl;
  std::cout << "gcd3(100, 10)= " <<  gcd3(100, 10)  << std::endl;
  std::cout << std::endl;

}
```

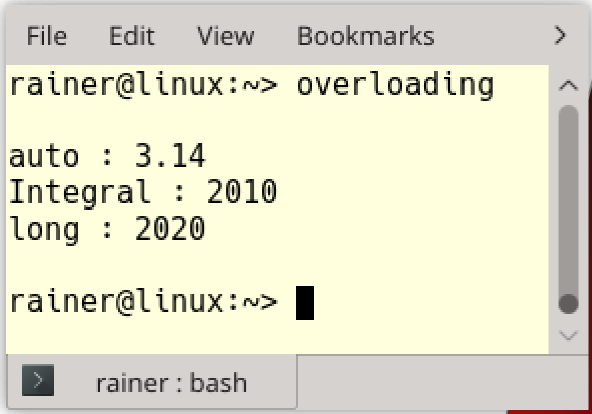
Compiled with GCC 6.3 and the Flag `-fconcepts`



Syntactic Sugar: Overloading

```
void overload(auto t){
    std::cout << "auto : " << t << std::endl;
}

void overload(Integral auto t){
    std::cout << "Integral : " << t << std::endl;
}

void overload(long t){
    std::cout << "long : " << t << std::endl;
}
```

```
int main(){

  overload(3.14);
  overload(2010);
  overload(2020l);

}
```



Predefined Concepts % Naming

- Core language concepts
  - Same
  - DerivedFrom
  - ConvertibleTo
  - Common
  - Integral
  - SignedIntegral
  - UnsignedIntegral
  - Assignable
  - Swappable

- Comparison concepts
  - Boolean
  - EqualityComparable
  - StrictTotallyOrdered

- Object concepts
  - Destructible
  - Constructible
  - DefaultConstructible
  - MoveConstructible
  - CopyConstructible
  - Movable
  - Copyable
  - Semiregular
  - Regular
- Callable concepts
  - Callable
  - RegularCallable
  - Predicate
  - Relation
  - StrictWeakOrder

Concept Definition: Variable Concept

```
template<typename T>
concept bool Integral =
    std::is_integral<T>::value;
}
```

- `T` fulfils the variable concept if `std::integral<T>::value` evaluates to `true`

Concept Definition: Function Concept

Concepts TS

```
template<typename T>
concept bool Equal(){
  return requires(T a, T b) {
    { a == b } -> bool;
    { a != b } -> bool;
  };
}
```

Draft C++20 standard

```
template<typename T>
concept Equal =
  requires(T a, T b) {
    { a == b } -> bool;
    { a != b } -> bool;
};
```

- T fulfils the function concept if `==` and `!=` are overloaded and return a boolean

The Concept Equal

```
bool areEqual(Equal auto a, Equal auto b) return a == b;

/*
struct WithoutEqual{
    bool operator == (const WithoutEqual& other) = delete;
};
struct WithoutUnequal{
    bool operator != (const WithoutUnequal& other) = delete;
};
*/
. . .
std::cout << "areEqual(1, 5): " << areEqual(1, 5) << std::endl;

/*
bool res = areEqual(WithoutEqual(),  WithoutEqual());
bool res2 = areEqual(WithoutUnequal(),  WithoutUnequal());
*/
```

The Concept Equal

```
File   Edit   View   Bookmarks   Settings   Help
rainer@suse:~> conceptsDefinitionEqual

areEqual(1, 5): false

rainer@suse:~> 
rainer : bash
```

```
File   Edit   View   Bookmarks   Settings   Help
rainer@suse:~> g++ -fconcepts conceptsDefinitionEqual.cpp -o conceptsDefinitionEqual
conceptsDefinitionEqual.cpp: In function ‘int main()’:
conceptsDefinitionEqual.cpp:37:54: error: cannot call function ‘bool areEqual(auto:1, auto:1) [with auto:1 = WithoutEqual]’
   bool res = areEqual(WithoutEqual(),  WithoutEqual());
                                                      ^
conceptsDefinitionEqual.cpp:13:6: note:   constraints not satisfied
 bool areEqual(Equal a, Equal b){
      ^~~~~~~~
conceptsDefinitionEqual.cpp:6:14: note: within ‘template<class T> concept bool Equal() [with T = WithoutEqual]’
 concept bool Equal(){
              ^~~~~
conceptsDefinitionEqual.cpp:6:14: note:     with ‘WithoutEqual a’
conceptsDefinitionEqual.cpp:6:14: note:     with ‘WithoutEqual b’
conceptsDefinitionEqual.cpp:6:14: note: the required expression ‘(a == b)’ would be ill-formed
conceptsDefinitionEqual.cpp:6:14: note: ‘b->a.WithoutEqual::operator==()’ is not implicitly convertible to ‘bool’
conceptsDefinitionEqual.cpp:6:14: note: the required expression ‘(a != b)’ would be ill-formed
conceptsDefinitionEqual.cpp:39:59: error: cannot call function ‘bool areEqual(auto:1, auto:1) [with auto:1 = WithoutUnequal]’
   bool res2 = areEqual(WithoutUnequal(),  WithoutUnequal());
                                                           ^
conceptsDefinitionEqual.cpp:13:6: note:   constraints not satisfied
 bool areEqual(Equal a, Equal b){
      ^~~~~~~~
conceptsDefinitionEqual.cpp:6:14: note: within ‘template<class T> concept bool Equal() [with T = WithoutUnequal]’
 concept bool Equal(){
              ^~~~~
conceptsDefinitionEqual.cpp:6:14: note:     with ‘WithoutUnequal a’
conceptsDefinitionEqual.cpp:6:14: note:     with ‘WithoutUnequal b’
conceptsDefinitionEqual.cpp:6:14: note: the required expression ‘(a == b)’ would be ill-formed
conceptsDefinitionEqual.cpp:6:14: note: the required expression ‘(a != b)’ would be ill-formed
conceptsDefinitionEqual.cpp:6:14: note: ‘b->a.WithoutUnequal::operator!=()’ is not implicitly convertible to ‘bool’
rainer@suse:~> 
rainer : bash
```

`Eq` versus `Equal`

The Typeclass `Eq`

```
class Eq a where
     (==) :: a -> a -> Bool
     (/=) :: a -> a -> Bool
```

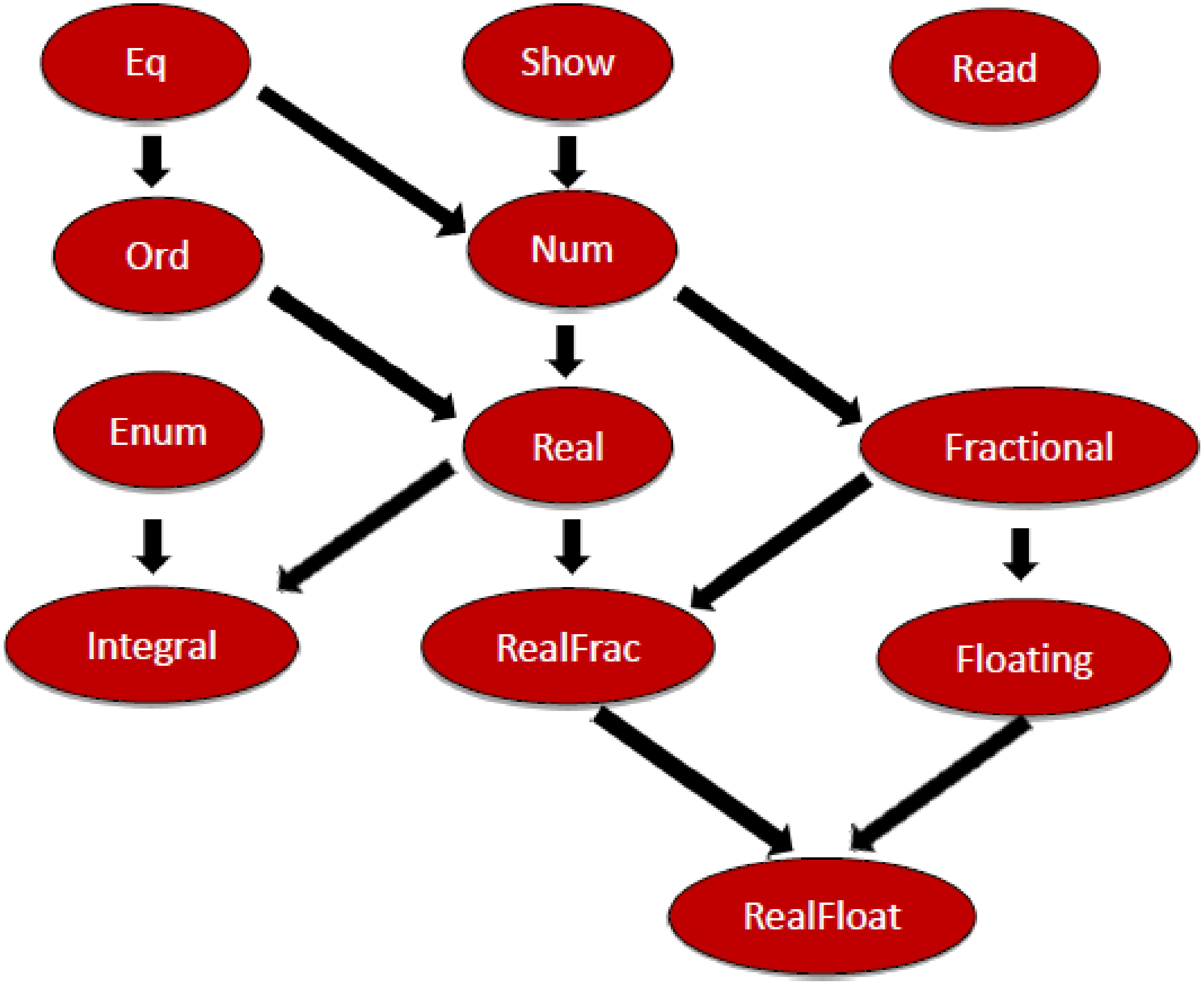
The Concept `Equal`

```
template<typename T>
concept Equal =
  requires(T a, T b) {
    { a == b } -> bool;
    { a != b } -> bool;
};
```

The typeclass `Eq` (Haskell) and the `concept Equal` (C++) require for the concrete types

- they have to support equal and the unequal operations
- the operations have to return a boolean
- both types have to be the same

Haskells Typeclasses



Haskells Typeclass `Ord`

```
class Eq a => Ord a where
  compare :: a -> a -> Ordering
  (<) :: a -> a -> Bool
  (<=) :: a -> a -> Bool
  (>) :: a -> a -> Bool
  (>=) :: a -> a -> Bool
  max :: a -> a -> a
```

➡ Each type supporting `Ord` must support `Eq`.

The Concept `Ord`

The concept **`Equal`**

```
template<typename T>
concept bool Equal(){
    return requires(T a, T b){
        { a == b } -> bool;
        { a != b } -> bool;
    };
}
```

The concept **`Ord`**

```
template <typename T>
concept Ord =
    Equal<T> &&
    requires(T a, T b) {
        { a <= b } -> bool;
        { a < b } -> bool;
        { a > b } -> bool;
        { a >= b } -> bool;
};
```

The Concept `Ord`

```
bool areEqual(Equal auto a,
              Equal auto b){
    return a == b;
}

Ord auto getSmaller(Ord auto a,
                    Ord auto b){
    return (a < b) ? a : b;
}
```

```
int main(){

  std::cout << areEqual(1, 5);

  std::cout << getSmaller(1, 5);

  std::unordered_set<int> firSet{1, 2, 3, 4, 5};
  std::unordered_set<int> secSet{5, 4, 3, 2, 1};

  std::cout << areEqual(firSet, secSet);

  // auto smallerSet = getSmaller(firSet, secSet);

}
```

The Concept `Ord`

```
rainer@suse:~> conceptsDefinitionOrd

areEqual(1, 5): false
getSmaller(1, 5): 1
areEqual(firSet, secSet): true

rainer@suse:~>
```

```
rainer@suse:~> g++ -fconcepts conceptsDefinitionOrd.cpp -o conceptsDefinitionOrd
conceptsDefinitionOrd.cpp: In function 'int main()':
conceptsDefinitionOrd.cpp:44:45: error: cannot call function 'auto getSmaller(auto:2, auto:2)
 [with auto:2 = std::unordered_set<int>]'
   auto smallerSet= getSmaller(firSet, secSet);
                                             ^
conceptsDefinitionOrd.cpp:27:5: note:   constraints not satisfied
 Ord getSmaller(Ord a, Ord b){
     ^~~~~~~~~~
conceptsDefinitionOrd.cpp:13:14: note: within 'template<class T> concept bool Ord() [with T =
 std::unordered_set<int>]'
 concept bool Ord(){
              ^~~
conceptsDefinitionOrd.cpp:13:14: note:     with 'std::unordered_set<int> a'
conceptsDefinitionOrd.cpp:13:14: note:     with 'std::unordered_set<int> b'
conceptsDefinitionOrd.cpp:13:14: note: the required expression '(a <= b)' would be ill-formed
conceptsDefinitionOrd.cpp:13:14: note: the required expression '(a < b)' would be ill-formed
conceptsDefinitionOrd.cpp:13:14: note: the required expression '(a > b)' would be ill-formed
conceptsDefinitionOrd.cpp:13:14: note: the required expression '(a >= b)' would be ill-formed
rainer@suse:~>
```

The Big Four

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- ~~Contracts~~
- Modules
- Concepts
- **Ranges Library**

Die Ranges Library

The ranges library supports algorithms which operate

- directly on the container
- can be evaluated lazily
- can be composed

➡ The ranges library extend C++20 with functional pattern.

Lazy Evaluation

```
#include <ranges>
#include <vector>
#include <iostream>

int main(){
  for (int i : std::views::iota{1, 5})
      std::cout << i << ' ';          // 1 2 3 4 5

  std::cout << '\n';

  for (int i : std::views::iota(1) | std::views::take(10))
      std::cout << i << ' ';          // 1 2 3 4 5 6 7 8 9 10
}
```

Function Composition

```
#include <vector>
#include <ranges>
#include <iostream>

int main(){
  std::vector<int> ints{0, 1, 2, 3, 4, 5};
  auto even = [](int i){ return 0 == i % 2; };
  auto square = [](int i) { return i * i; };

  for (int i : ints | std::views::filter(even) |
                      std::views::transform(square)) {
      std::cout << i << ' ';                // 0 4 16
  }
}
```

The Big Four

- Coroutines
  - Asynchronous Programming
- Contracts
  - Design by Contract
- Modules
  - Software Components
- Concepts
  - Semantic Categories
- Ranges Library
  - Lazy Evaluation and Function Compostion

Blogs

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