Concepts

Evolution or Revolution?

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Concepts

- Motivation
- The long, long History
- Functions and Classes
- Placeholder Syntax
- Syntactic Sugar
- Define your Concepts

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Two Extrems

Too Specific

- Concrete functions

➡ Type conversions

- Narrowing conversion
- Numeric promotion

```
#include <iostream>

void needInt(int i) {
    std::cout << i;
}

int main() {

    double d{1.234};
    needInt(d);

    bool b{true};
    needInt(true);

}
```

Two Extrems

Too Generic

- Generic functions

⇨ Ugly compile-time errors

```
#include <iostream>

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

int main() {

    std::cout << gcd(100, 10);
    std::cout << gcd(3.5, 4.0);

}
```

Concepts to the Rescue

- Expresses template parameter requirements as part of the interface
- Supports overloading of functions and specialisation of class templates
- Produces drastically improved error messages
- Useable as placeholders for generic programming
- Empowers definition of concepts
- Applicable for class templates, function templates, and non-template members of class templates

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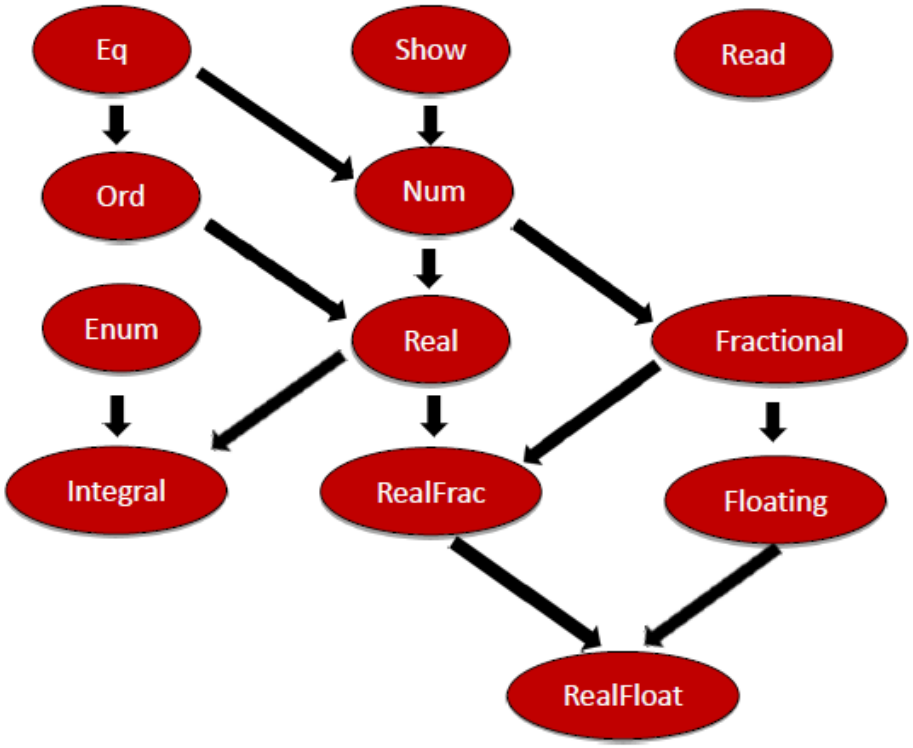
My First Impression

- Concepts are similar to Haskells typeclasses.
- Typeclasses are interfaces for similar types.



The Long Way

- 2009: removed from the C++11 standard

  "The C++0x concept design evolved into a monster of complexity." (Bjarne Stroustrup)

- 2017: "Concept Lite“ removed from the C++17 standard

- 2020: part of the C++20 standard

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Functions

Using of the concept `Sortable`.

- Requires clause

```
template<typename Cont>
    requires Sortable<Cont>
void sort(Cont& container);
```

- Trailing requires clause

```
template<typename Cont>
void sort(Cont& container) requires Sortable<Cont>;
```

- Constrained template parameters

```
template<Sortable Cont>
void sort(Cont& container);
```

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

Functions

- Usage:

```
std::list<int> lst = {1998, 2014, 2003, 2011};
std::sort(lst.begin(), lst.end());
```

cannot call `std::sort` with `std::_List_iterator<int>`

`concept RandomAccessIterator<std::_List_iterator<int>>` was not satisfied

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.

Member-Functions

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

➡ The type parameter `T` must be copyable.

Variadic Templates

```
template<Arithmetic... Args>
bool all(Args... args) { return (... && args); }

template<Arithmetic... Args>
bool any(Args... args) { return (... || args); }

template<Arithmetic... Args>
bool none(Args... args) { return not(... || args); }

std::cout << all(true);                    // true
std::cout << all(5, true, 5.5, false);     // false
```

➡ The type parameters `Args` must be `Arithmetic`.

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.

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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.

auto

C++20 unifies this asymmetry.

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

⇨ Usage of a placeholder generates a function template.

Constrained and Unconstrained

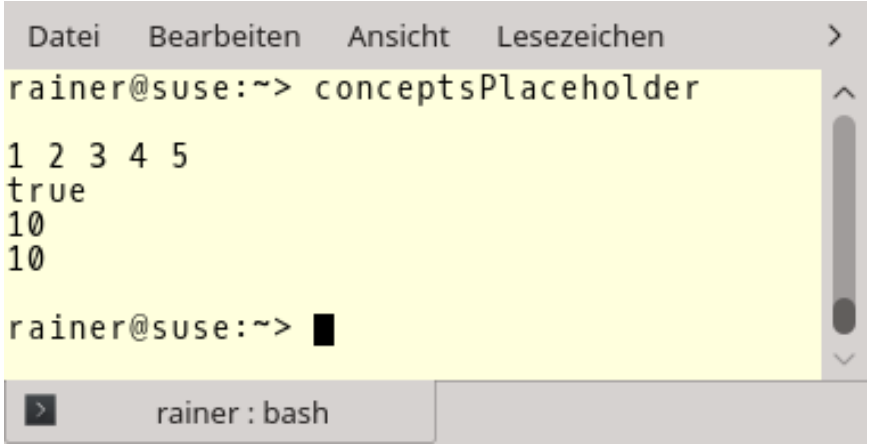
Constrained concepts can be used where `auto` is usable.

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

template<typename T>
concept Integral =
    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;


}
```

Constrained and Unconstrained

Constraint and unconstrained placeholder behave as expected.



Syntactic Sugar

Motivation

The long, long History

Functions and Classes

Placeholder Syntax

Syntactic Sugar

Define your Concepts

Syntactic Sugar

Classical

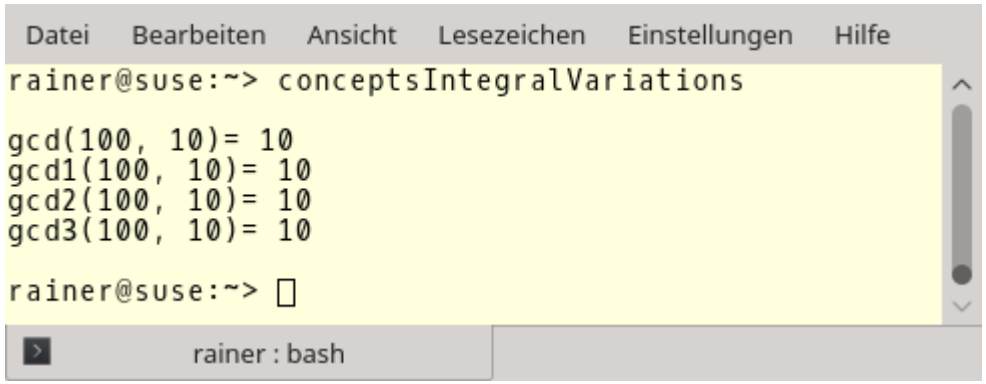
```
template<typename T>
    requires Integral<T>
T gcd(T a, T b){
    if( b == 0 ) return a;
    else return gcd(b, a % b);
}

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

Abbreviated Function Templates

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

auto gcd3(auto a, auto b){
    if( b == 0 ) return a;
    else return gcd(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;

}
```



Small Detour

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

`gcd2's` type parameters

- have to be `Integral`.
- ~~must have the same type.~~

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

`gcd3's` type parameter

- can have different types.

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);

}
```

```
File  Edit  View  Bookmarks
rainer@linux:~> overloading

auto : 3.14
Integral : 2010
long : 2020

rainer@linux:~>
rainer : bash
```

Template Introduction

Template introduction is a simplified syntax for declaring templates

- `template <Integral T>` ➡ `Integral{T}`

- Syntax is only available for constrained placeholders (concepts) but not for unconstrained placeholders (`auto`)

  ➡ Create a concept which always evaluates to `true`

Template Introduction

Constrained Placeholder

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


Integral{T}
class ConstrainedClass{};
```

Unconstrained Placeholder

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


auto{T}
class ConstrainedClass{};
```

Error

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Predefined Concepts

- Language-related
  - `same_as`
  - `derived_from`
  - `convertible_to`
  - `common_reference_with`
  - `common_with`
  - `assignable_from`
  - `swappable`
- Arithmetic
  - `integral`
  - `signed_integral`
  - `unsigned_integral`
  - `floating_point`
- Comparison
  - `boolean`
  - `equality_comparable`
  - `totally_ordered`
- Lifetime
  - `destructible`
  - `constructible_from`
  - `default_constructible`
  - `move_constructible`
  - `copy_constructible`
- Object
  - `movable`
  - `copyable`
  - `semiregular`
  - `regular`
- Callable
  - `invocable`
  - `regular_invocable`
  - `predicate`

Direct Definition

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

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

Requires-Expressions

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

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

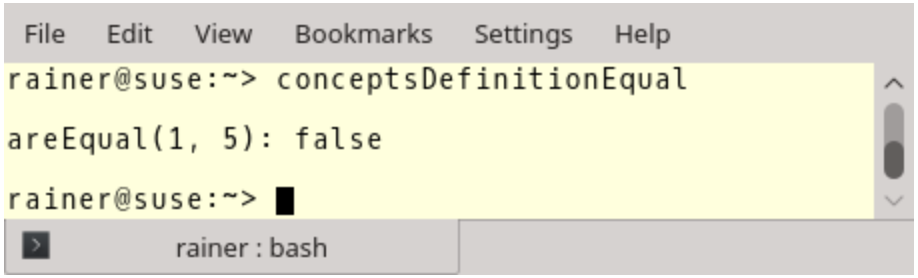
The Concept Equal

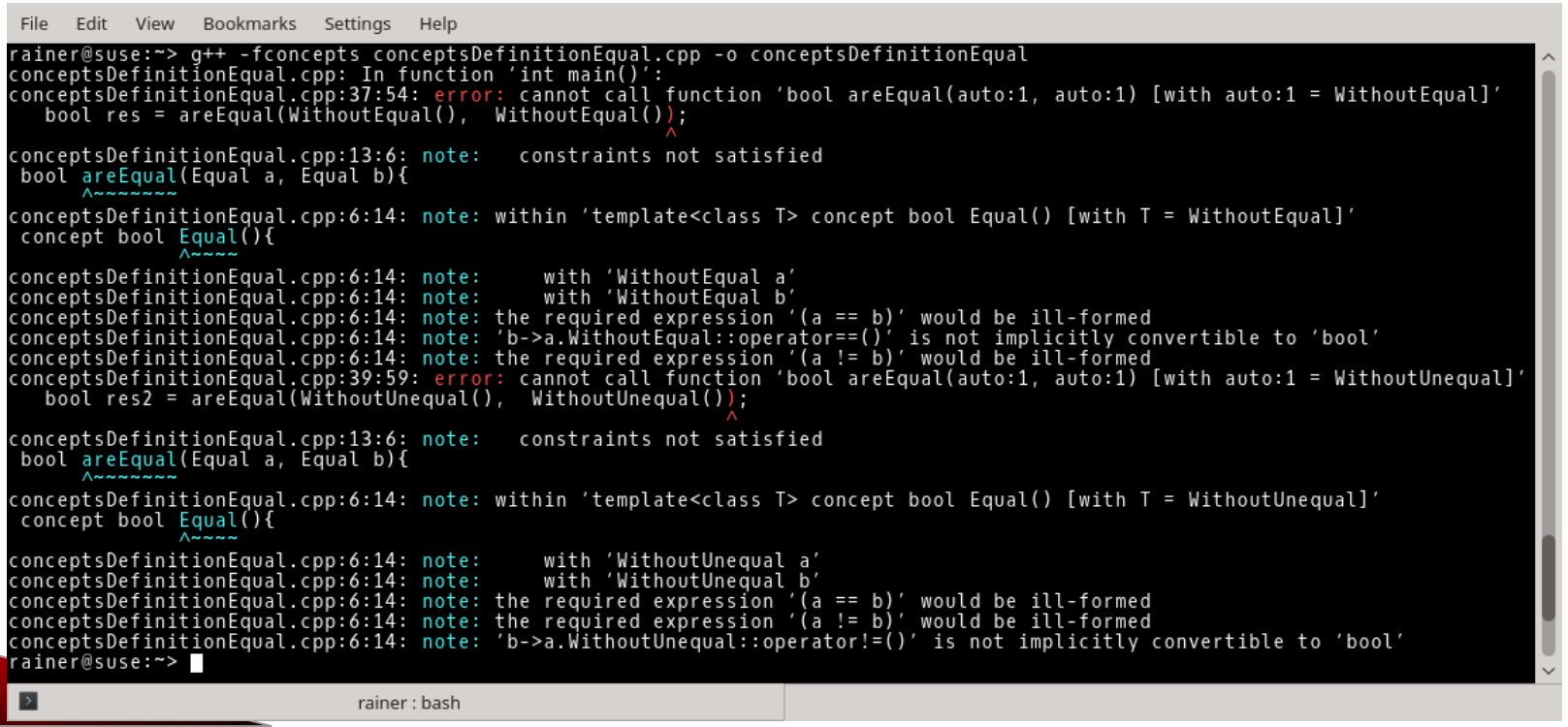
```
bool areEqual(Equal auto a, Equal auto b) return a == b;

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





`Eq` versus `Equal`

The Typeclass `Eq`

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

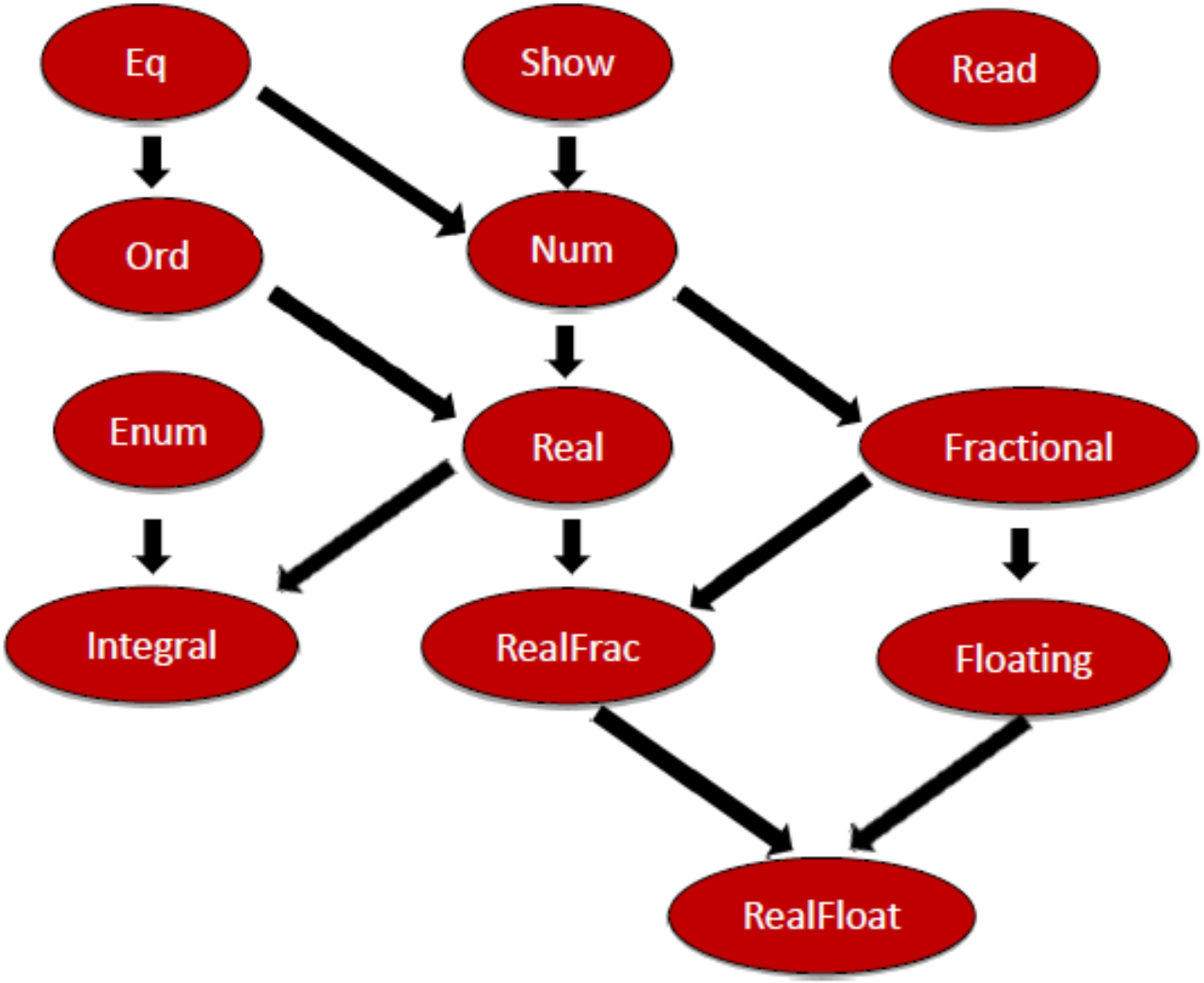
The Concept `Equal`

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

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

- They have to support equal and the non-equal 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`

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

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

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`

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

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

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

```
File  Edit  View  Bookmarks  Settings  Help
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:~>
rainer : bash
```

`SemiRegular` and `Regular`

SemiRegular

- Default constructor: `X()`
- Copy constructor: `X(const X&)`
- Copy assignment: `X& operator=(const X&)`
- Move constructor: `X(X&&)`
- Move assignment: `X& operator=(X&&)`
- Destructor: `~X()`

- Swappable: `swap(X&, Y&)`

Regular

- `SemiRegular`
- Equality comparable

SemiRegular and Regular

```
template<typename T>
struct isSemiRegular:
  std::integral_constant<bool,
                         std::is_default_constructible<T>::value &&
                         std::is_copy_constructible<T>::value &&
                         std::is_copy_assignable<T>::value &&
                         std::is_move_constructible<T>::value &&
                         std::is_move_assignable<T>::value &&
                         std::is_destructible<T>::value &&
                         std::is_swappable<T>::value
                        >{};
template<typename T>
concept SemiRegular = isSemiRegular<T>::value;

template<typename T>
concept Regular = Equal<T> && SemiRegular<T>;
```

semiregular and regular

```
template<class T>
concept movable = is_object_v<T> && move_constructible<T> &&
assignable_from<T&, T> && swappable<T>;

template<class T>
concept copyable = copy_constructible<T> && movable<T> &&
assignable_from<T&, const T&>;

template<class T>
concept semiregular = copyable<T> && default_constructible<T>;

template<class T>
concept regular = semiregular<T> && equality_comparable<T>;
```

Regular and std::regular

```
#include <concept>

template <Regular T>
void behavesLikeAnInt(T) {}

template <std::regular T>
void behavesLikeAnInt2(T) {}

struct EqualityComparable { };
bool operator ==
  (EqualityComparable const&,
   EqualityComparable const&) {
      return true;
}

struct NotEqualityComparable { };
```

```
int myInt{};
behavesLikeAnInt(myInt);
behavesLikeAnInt2(myInt);

std::vector<int> myVec{};
behavesLikeAnInt(myVec);
behavesLikeAnInt2(myVec);

EqualityComparable equComp;
behavesLikeAnInt(equComp);
behavesLikeAnInt2(equComp);

NotEqualityComparable notEquComp;
behavesLikeAnInt(notEquComp);
behavesLikeAnInt2(notEquComp);
```

`Regular` and `std::regular`

- GCC (latest version, https://godbolt.org/z/XAJ2w3)
  - The concept `Regular`

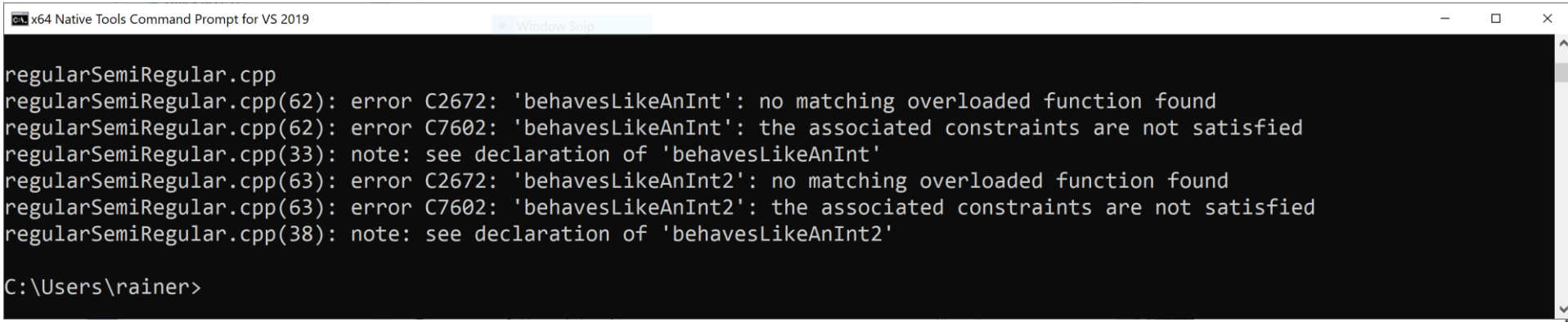
```
<source>:24:13: note: the required expression '(a == b)' is invalid
   24 |         { a == b } -> std::convertible_to<bool>;
      |           ~~^~~~
<source>:25:13: note: the required expression '(a != b)' is invalid
   25 |         { a != b } -> std::convertible_to<bool>;
      |           ~~^~~~
```

  - The concept `std::regular`

```
/opt/compiler-explorer/gcc-trunk-20200131/include/c++/10.0.0/concepts:290:10: note: the required expression '(__t == __u)' is invalid
  290 |     { __t == __u } -> boolean;
      |       ~~~~^~~~~
/opt/compiler-explorer/gcc-trunk-20200131/include/c++/10.0.0/concepts:291:10: note: the required expression '(__t != __u)' is invalid
  291 |     { __t != __u } -> boolean;
      |       ~~~~^~~~~
/opt/compiler-explorer/gcc-trunk-20200131/include/c++/10.0.0/concepts:292:10: note: the required expression '(__u == __t)' is invalid
  292 |     { __u == __t } -> boolean;
      |       ~~~~^~~~~
/opt/compiler-explorer/gcc-trunk-20200131/include/c++/10.0.0/concepts:293:10: note: the required expression '(__u != __t)' is invalid
  293 |     { __u != __t } -> boolean;
      |       ~~~~^~~~~
```

`Regular` and `std::regular`

- MSVC (Microsoft Visual C++ 2019, 16.4.3)
  - The concepts `Regular` and `std::regular`



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Evolution or Revolution?

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Evolution

- `auto` as unconstrained placeholders
- Generic lambdas as new way to define templates

```
auto add = [](auto a, auto b) {
    return a + b;
}
```

Revolution

- Template requirements are verified by the compiler
- Declaration and definition of templates radically improve
- **Concepts define semantic categories and not syntactic requirements**

Blogs

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Rainer Grimm

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