Concepts

Evolution or Revolution?

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Concepts

A first Overview

The long, long History

Functions and Classes

Placeholder Syntax

Syntactic Sugar

Define your Concepts

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Concepts

- A first Overview
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- Syntactic Sugar
- Define your Concepts

Two Extrems

Too Specific

- Concrete functions

➡ Type conversions

- Narrowing conversion
- Integral promotion

Too Generic

- Generic functions

➡ Ugly compile time errors

Two Extrems

Too Specific

```
#include <iostream>

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

int main(){

    double d{1.234};
    needInt(d);

}
```

Too Generic

```
#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::endl;
    std::cout << gcd(3.5, 4.0) << std::endl;

}
```

Concepts to the Rescue

Advantages

- 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 class templates, function templates, and non-template members of class templates

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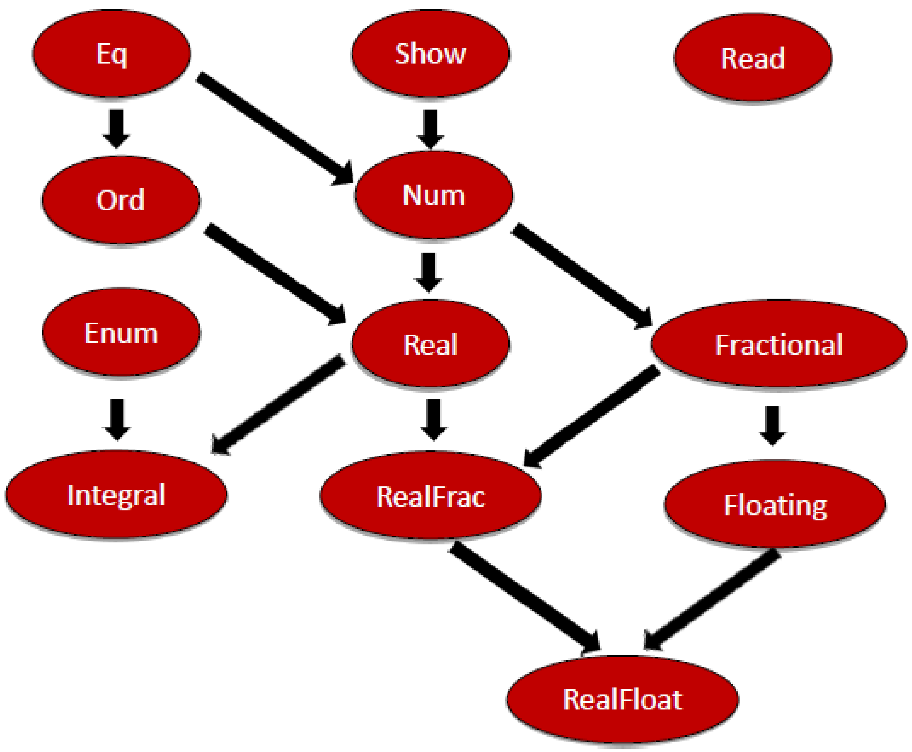
My First Impression

- Concepts reminds me 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);
```

- Constrained template parameters

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

- Trailing requires clause

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

Functions

- 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.

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.

The Concept Integral

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

template<typename T>
concept bool Integral =
    std::is_integral<T>::value;
}
template<typename T>
requires Integral<T>()
T gcd(T a, T b){
    if( b == 0 ){ return a; }
    else return gcd(b, a % b);
}
```

```
int main(){
    std::cout << "gcd(5.5, 4.5)= "
              << gcd(5.5, 4.5) << std::endl;

}
```

Datei Bearbeiten Ansicht Lesezeichen Einstellungen Hilfe

```
rainer@suse:~> g++ -fconcepts conceptsIntegral.cpp
conceptsIntegral.cpp: In Funktion »int main()«:
conceptsIntegral.cpp:26:49: Fehler: cannot call function »T gcd(T, T) [mit T = double]«
   std::cout << "gcd(5.5, 4,5)= " << gcd(5.5, 4.5) << std::endl;
                                                 ^
conceptsIntegral.cpp:13:3: Anmerkung:   constraints not satisfied
 T gcd(T a, T b){
   ^~~
conceptsIntegral.cpp:7:14: Anmerkung: within »template<class T> concept bool Integral() [mit T = double]«
 concept bool Integral(){
              ^~~~~~~~
conceptsIntegral.cpp:7:14: Anmerkung: »std::is_integral<double>::value« evaluated to false
rainer@suse:~>
```

rainer : bash

Constrained and Unconstrained

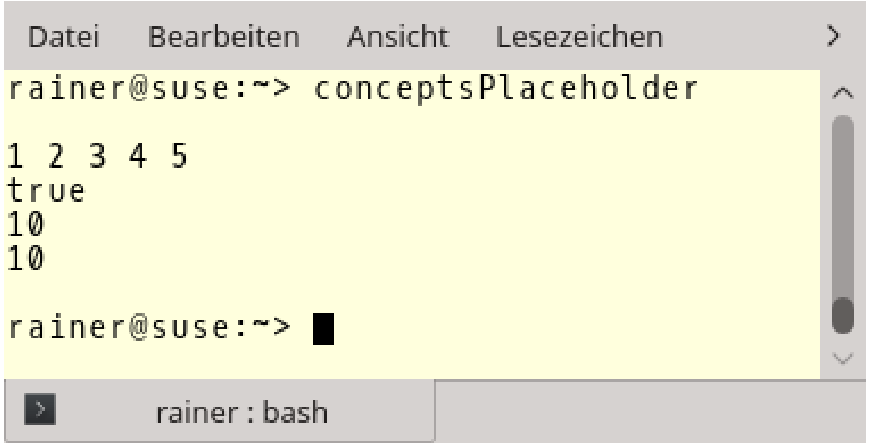
Constrained concepts can be used where `auto` is usable.

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

template<typename T>
concept bool Integral =
    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.



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Syntactic Variations

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

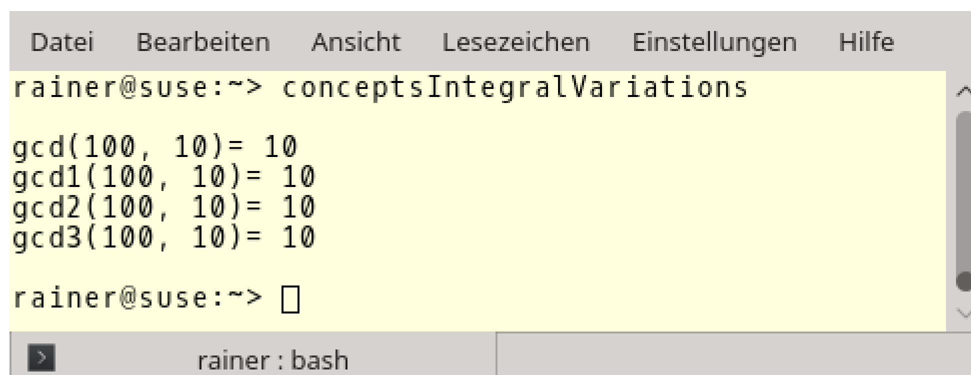
```
Integral auto gcd2(Integral auto a,
                   Integral auto b){
    if( b == 0 ) return a;
    else return gcd(b, a % b);
}

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

Syntactic Variations

```
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

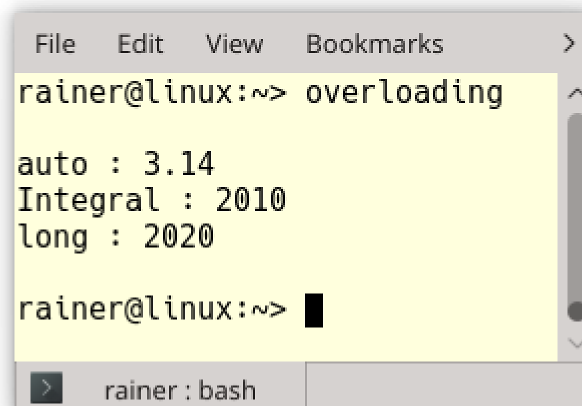
Flag `-fconcepts`



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);

}
```



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 constrained placeholder 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{};
```

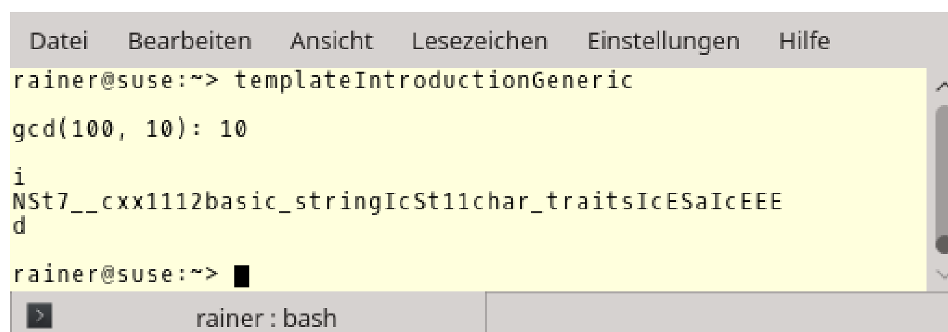
Error

Template Introduction

```
template<typename T>
concept bool Generic(){
    return true;
}

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

Generic{T}
class ConstrainedClass{
public:
  ConstrainedClass(){
      std::cout << typeid(decltype(std::declval<T>())).name() << std::endl;
  }
};
```

Template Introduction

```
int main(){

    std::cout << "gcd(100, 10): " << gcd(100, 10) << std::endl;

    std::cout << std::endl;

    ConstrainedClass<int> genericClassInt;
    ConstrainedClass<std::string> genericClassString;
    ConstrainedClass<double> genericClassDouble;


}
```



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- **Define your Concepts**

Predefined Concepts % Spelling

- 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

Direct Definition

Concepts TS

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

Draft C++20 standard

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

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

Requires-Expressions

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

```
rainer@suse:~> conceptsDefinitionEqual

areEqual(1, 5): false

rainer@suse:~>
```

```
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:~>
```

`Eq` versus `Equal`

The Typeclass `Eq`

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

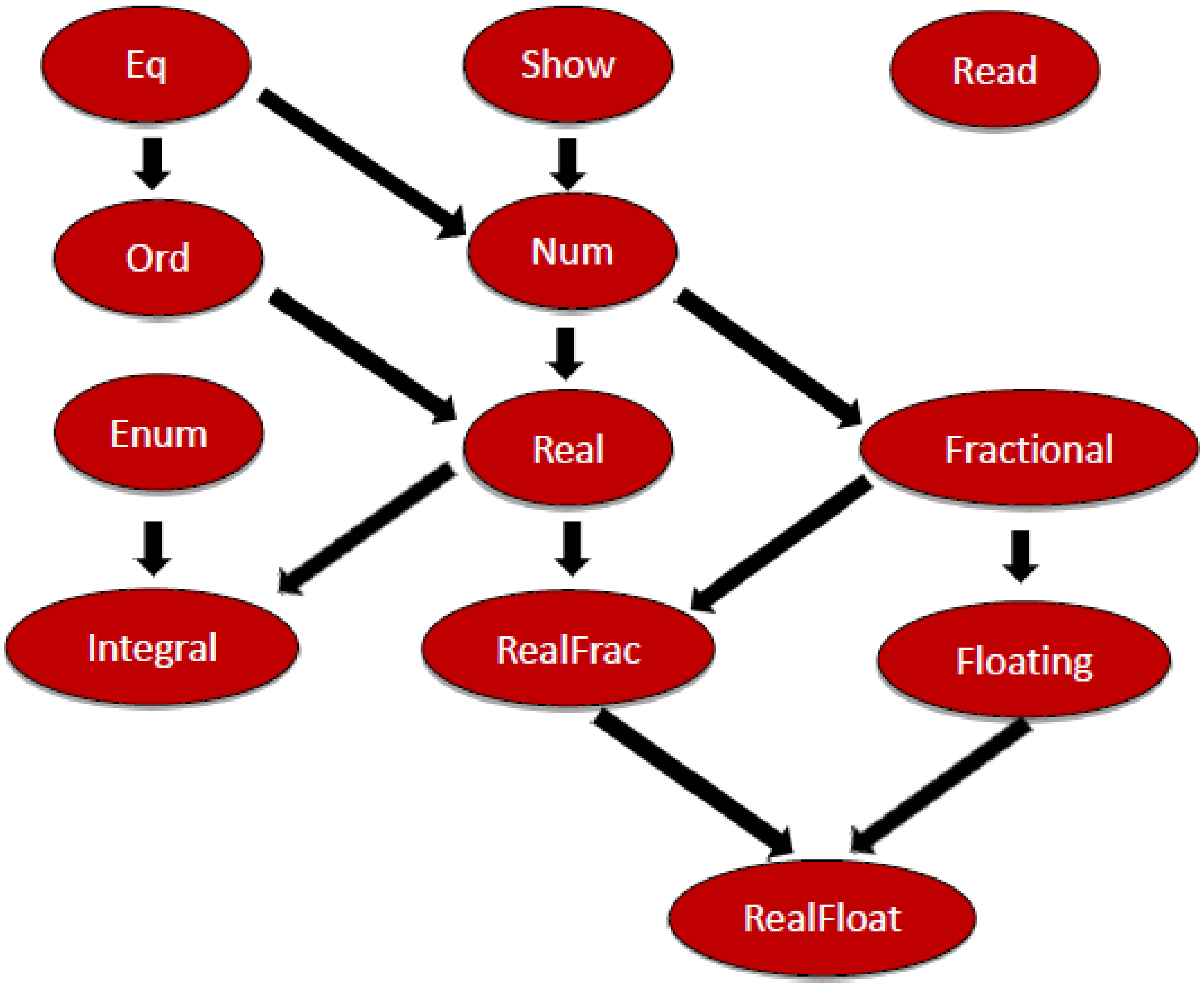
The Concept `Equal`

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

The concept **`Ord`**

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

```
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
```

Regular and SemiRegular

Regular

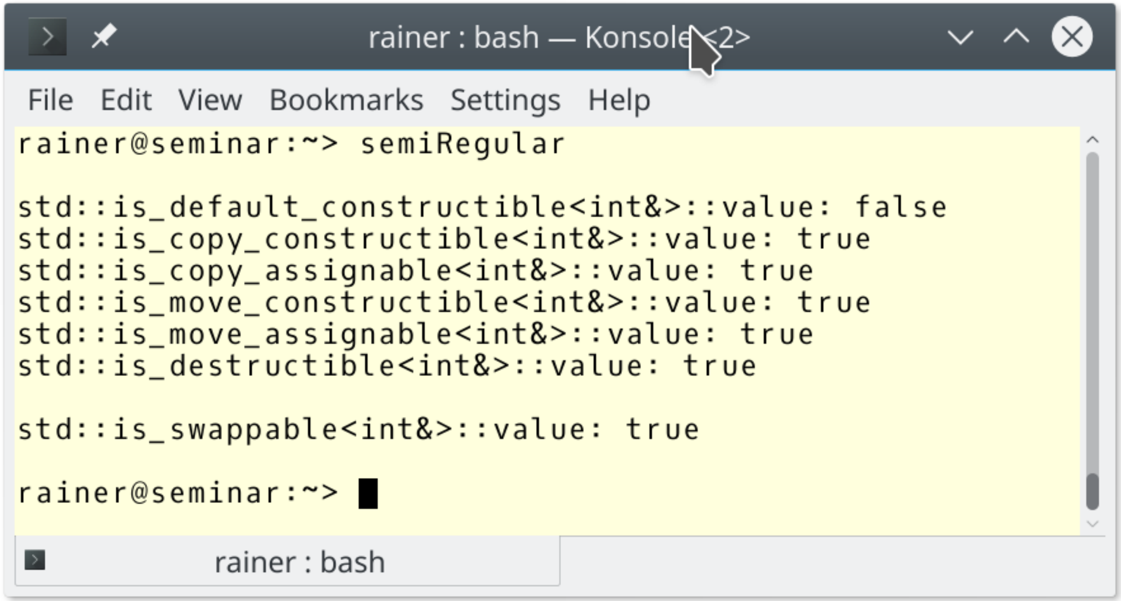
- DefaultConstructible
- CopyConstructible, CopyAssignable
- MoveConstructible, MoveAssignable
- Destructible
- Swappable
- EqualityComparable

SemiRegular

- **Regular** – EqualityComparable

Regular and SemiRegular

```
std::cout << std::is_default_constructible<int&>::value;
std::cout << std::is_copy_constructible<int&>::value;
std::cout << std::is_copy_assignable<int&>::value;
std::cout << std::is_move_constructible<int&>::value;
std::cout << std::is_move_assignable<int&>::value;
std::cout << std::is_destructible<int&>::value;
std::cout << std::is_swappable<int&>::value;
```



`Regular` and `SemiRegular`

The type-trait `isEqualityComparable`:

```
template<typename T>
using equal_comparable_t = decltype(std::declval<T&>() ==
                                    std::declval<T&>());


template<typename T>
struct isEqualityComparable:
        std::experimental::is_detected<equal_comparable_t, T> {};
```

`Regular` and `SemiRegular`

The type-traits `Regular` and `SemiRegular`

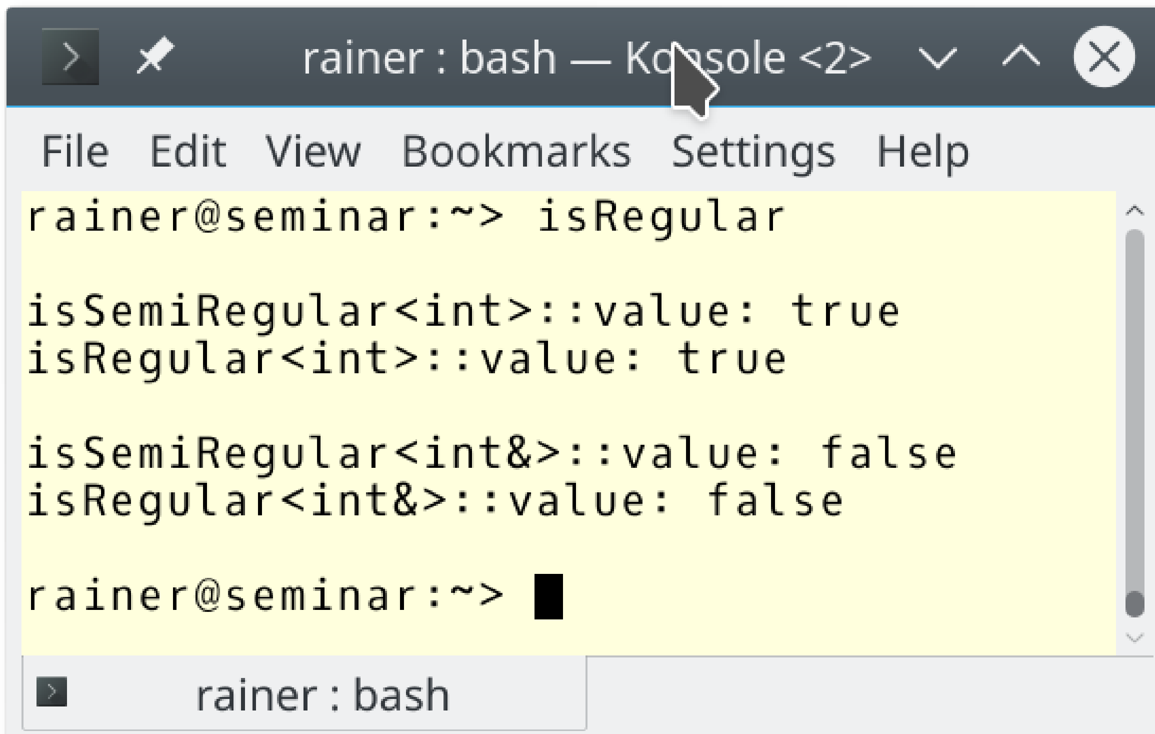
```
template<typename T>
struct isSemiRegular: std::integral_constant<bool,
        std::is_default_constructible<T>::value &&
        std::is_copy_constructible<T>::value &&
        std::is_copy_assignable<T>::value &&
        std::is_move_constructible<T>::value &&
        std::is_move_assignable<T>::value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

template<typename T>
struct isRegular: std::integral_constant<bool,
       isSemiRegular<T>::value &&
       isEqualityComparable<T>::value >{};
```

Regular and SemiRegular

```
std::cout << isSemiRegular<int>::value;
std::cout << isRegular<int>::value;

std::cout << isSemiRegular<int&>::value;
std::cout << isRegular<int&>::value;
```



Regular and SemiRegular

```
template<typename T>
concept Regular = isRegular<T>::value;
```

```
template<typename T>
concept SemiRegular = isSemiRegular<T>::value;
```

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Evolution or Revolution in C++?

Evolution or Revolution in C++

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 improved
- **Concepts define semantic categories and not syntactic requirements**

Blogs

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