The concepts of concepts

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Science to the CORE

Who Am I?

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- Curious home baker
- Happy father of two

Agenda

Why do we need something like `concepts`?

What are `concepts` and constraints?

How to use `concepts` with functions?

How to use `concepts` with classes?

How to write `concepts`?

Real-life examples

Why do we need something like concepts?

Overloads don’t scale

Tedious to write all

Verbose

Difficult to maintain

```
double add(double a, double b) {
  return a+b;
}

int add(int a, int b) {
  return a+b;
}

int main() {
  add(42, 66);
  add(4.2, 6.6);
}
```

Templates allow just anything

No constraints

Potentially unexpected behaviour

Is that really what you want?

```
template <typename T>
T add(T a, T b) {
   return a+b;
}

int main() {
  add(42, 66);
  add(42.42L, 66.6L);
  add('a', 'b');
}
```

Forbid template specializations

Works

But doesn't scale!

```
#include <string>

template <typename T>
T add(T a, T b) { return a+b; }

template<>
std::string add(std::string,
                std::string) = delete;

int main() {
 // ERROR
 add(std::string{"a"}, std::string{"b"});
}
```

What about type traits?

Nice(r) error messages!

Less overhead

Everything is at one place

Not intuitively easily reusable

Hidden requirements

```
template <typename T>
T add(T a, T b) {
 static_assert(std::is_integral_v<T> ||
   std::is_floating_point_v<T>,
   "Call add only with numbers!");
  return a+b;
}

int main() {
  add(std::string{"a"},
      std::string{"b"});
}
```

`concepts` to the rescue

Readable

Reusable

Scalable

Safer

```
template <typename T>
concept number = std::integral<T> ||
    std::floating_point<T>;

template <number T>
auto add(T a, T b) {
 return a+b;
}

int main() {
  add(1, 2);
}
```

What are `concepts` and constraints?

What are `concepts`?

One of the new major features of C++20

- **Concepts**
- Coroutines
- Modules
- Ranges

Extension for templates

Compile-time booleans to validate template arguments

```
template <typename T>
bool concept Any = true;
```

```
template <typename T>
concept any = true;
```

Concepts as constraints

Template arguments can be constrained

A concept can be used as a constraint

A concept is a set of requirements

Concepts appearing at different positions

Requires clause

Type-constraint

Trailing requires clause

```
template<c_1 T>
requires c_2<T>
c_3 auto foo(c_4 auto param) requires c_5<T>;
```

Constrained
placeholder type

4 ways to use `concepts` with functions

Disclaimer: concept incomplete!

We are going use the concept `number`

It’s incomplete!

Bear with me

```
#include <concepts>


template <typename T>
concept number =
   std::integral<T> ||
   std::floating_point<T>;
```

Using the `requires` clause

`requires` following the template parameter list

After `requires` write your concept(s) to be satisfied

```
template <typename T>
requires number<T>
auto add(T a, T b) {
   return a+b;
}
```

Concepts can be combined in different ways

In fact not only concepts

- Type traits
- Any boolean expression
- Compile-time values

```
template <typename T>
requires std::integral<T>
 || std::floating_point<T>
auto add(T a, T b) {
  return a+b;
}
```

Function calls as usual with better error messages

```
add(2, 3);

add(2, 3.14);
```

```
no matching function for call to 'add(int,
double)'

   17 |    std::cout << add(2, 3.14);

candidate: 'template<class T>  requires
number<T> auto add(T, T)'

    9 | auto add(T a, T b) {

template argument deduction/substitution
failed:

deduced conflicting types for parameter 'T'
('int' and 'double')

   17 |    std::cout << add(2, 3.14);
```

Trailing `requires` clause

`requires` comes after cv qualifiers

Apart from that, same as "normal" `requires` clause

Supports complex constraints

```
template <typename T>
auto add(T a, T b)
requires number<T> {
  return a+b;
}
```

Constrained template parameter

No more `requires` clause

`typename` is replaced by the concept

Doesn't support complex constraints

```
template <number T>
auto add(T a, T b) {
  return a+b;
}
```

Abbreviated function templates

No `requires`, no template parameter list

Use ***`concept_name`*** **`auto`** in the parameter list

> [*T.12: Prefer concept names over auto for local variables*]()

Parameter types can be implicitly different

No support for `requires` expressions

```
number auto add(number auto a,
                number auto b){
  return a+b;
}
```

How to choose among the 4 ways?

Do you have a complex requirement?

Choose requires or trailing requires!

Only a simple requirement?

[T.13: Take abbreviated function templates!]()

Simple requirements? Want to keep it short and want to control to binded types of the parameters?

Go with the constrained template parameter!

Are they all the same after all?

```
#ifdef INSIGHTS_USE_TEMPLATE
template<>
int addRequiresClause<int>(int a, int b)
{
  return a + b;
}
#endif
```

```
#ifdef INSIGHTS_USE_TEMPLATE
template<>
int addConstrainedTemplate<int>(int a, int b)
{
  return a + b;
}
#endif
```

```
#ifdef INSIGHTS_USE_TEMPLATE
template<>
int addTrailingRequiresClause<int>(int a, int b) requires number<int>
{
  return a + b;
}
#endif
```

There is an expected difference

```
#ifdef INSIGHTS_USE_TEMPLATE
template<>
int addAbbreviatedFunctionTemplate<int, int>(int a, int b)
{
  return a + b;
}
#endif
```

How to use concepts with classes

Fewer syntactical choices

Abbreviated function templates wouldn’t make sense

Trailing `requires` clause only in certain circumstances

The `requires` clause

`requires` following the template parameter list

After `requires` write your concept(s) to be satisfied

You can use complex constraints

```
template <typename T>
requires number<T>
class WrappedNumber {
 public:
  WrappedNumber(T num):
    m_num(num) {}
 private:
  T  m_num;
};
```

Constrained template parameters

Instead of `typename` keyword use simply a `concept`

No complex constraints

```
template <number T>
class WrappedNumber {
 public:
  WrappedNumber(T num):
    m_num(num) {}
 private:
  T  m_num;
};
```

Overload by constraints

Class level templates with concepts on functions

Provide different overloads for different parameter types

```
template <typename T>
class MyNumber {
 public:

  T divide(const T& divisor)
    requires std::integral<T> {
    // …
  }

  T divide(const T& divisor)
   requires std::floating_point<T> {
    // …
  }
};
```

Functions are available based on constraints

```
template <typename T>
concept car = requires (T car) {
    car.startEngine();
    car.openDoor();
};

template <typename T>
concept is_convertible = car<T> && requires (T car) {
    car.openRoof();
};

template<car C>
class VacationDriver {
 public:
  void cruise() { /* .. */ }
  void openRoof() requires is_convertible<C> { /* .. */}
private:
  C m_car;
};
```

```
class SUV {
 public:
  void openDoor() {}
  void startEngine() {}
};


int main(){
  VacationDriver<SUV> vd;

  // error
  // invalid reference to function 'openRoof':
  // constraints not satisfied
  vd.openRoof()
}
```

How to write concepts?

How to write a simple concept?

List all template parameters

After the keyword `concept` comes the name

Then the requirements

```
template<typename T>

concept any = true;
```

What kind of requirements can we express?

Expectations on the public interface

Syntactic requirements

Also semantic requirements

T.20: Avoid “concepts” without meaningful semantics

```
template <typename C>
concept car = requires (C c) {
  c.openDoor();
  c.closeDoor();
  c.startEngine();
  c.stopEngine();
  c.accelerate();
  c.brake();
};

class Tank {
  // …
};

// syntactically valid but
// a car is still not a tank…
static_assert(car<Tank>);
```

Combine already defined concepts

T.11: Whenever possible use standard concepts

User defined ones are also OK

Use them in any logical combination*

```
#include <concepts>

template<typename T>

concept number =
  std::integral<T> ||
  std::floating_point<T>;
```

What does combining concepts mean?

Conjunctions (&&) and disjunctions (||) are OK

You are free to combine

- concepts
- bool literals
- bool expressions
- type traits (`::value`, `_v`)
- `requires` expressions

Beware of the `!`

```
#include <concepts>
#include <type_traits>

template <typename T>
concept number =
  std::integral<T> ||
  (std::is_floating_point_v<T> ==
    true);
```

What does the `!` say?

For boolean expressions, subexpressions

- Are well-formed
- Compile
- Return `false`

For concepts, a subexpression

- Might return `false`
- Can be ill-formed
- The rest can be still satisfied

The opposite of `true` is not `false`

It doesn’t have to be compilable

It might return `false`

Expecting `false` is possible

- With a cast to bool
- Or with a more explicit way

```
template <typename T, typename U>
  requires std::unsigned_integral<
      typename T::Blah> ||
           std::unsigned_integral<
      typename U::Blah>
void foo(T bar, U baz) { /*...*/ }

class MyType {
public:
    using Blah = unsigned int;
    // …
};

foo(MyType{}, 42);
```

There is always another way

```
template <typename T, typename
U>

requires
(bool(std::unsigned_integral<
         typename T::Blah> ||
       std::unsigned_integral<
         typename U::Blah>))

void foo(T bar, U baz) {
/*...*/ }
```

```
template <typename T, typename
U>
requires (
  requires {typename T::Blah;}
  && requires {
       typename U::Blah;}) &&
(std::unsigned_integral<
    typename T::Blah> ||
std::unsigned_integral<
    typename U::Blah>)
void foo(T bar, U baz) {
/*...*/ }
```

How to find the most constrained constraint?

A few words on overload resolution

The best candidate is the most constrained one

A more constrained concept is based on another one

Multiple overloads with the same priority => ambiguity

The constrained one will be automatically chosen

The right path will be chosen based on the template parameter type's characteristics

T.25: Avoid complementary constraints

```
template <typename Key>
class Ignition {

public:

  void start(Key key)
   requires (!Smart<Key>) {
    // …
  }

  void start(Key key)
   requires Smart<Key> {
    // …
  }
};
```

The most constrained will be automatically chosen

The most appropriate overload will be chosen at compile-time

All this happens via concepts subsumption

```
template <typename Key>
class Ignition {

public:

  void start(Key key){}

  void start(Key key)
   requires Smart<Key> {}


  void start(Key key)
   requires Smart<Key> &&
            Personal<Key> {}
};
```

Negations bring ambiguity - use named concepts

```
template <typename Key>
class Ignition {

public:

   void start(Key key){}

   void start(Key key)
    requires (!Smart<Key>) {}

   void start(Key key)
    requires (!Smart<Key>) &&
             Personal<Key> {}
};
```

```
template <typename Key>
class Ignition {

public:

   void start(Key key){}

   void start(Key key)
    requires NotSmart<Key> {}

   void start(Key key)
    requires NotSmart<Key> &&
             Personal<Key> {}
};
```

So how to write concepts?

Simple requirements on the interface

Use *wishful writing*!

Write down the operation you expect to be compiled

List all the variables used in the requirements after the `requires` keyword

[T.21: Require a complete set of operations for a concept]()

[T.26: Prefer to define concepts in terms of use-patterns rather than simple syntax]()

```
template <typename T>
concept test_concept =
requires (T a, T b,
          int exponent) {
   a + b;
   t.square();
   t.power(exponent);
};
```

Requirements on return types (compound requirements)

Constraint the return types with:

```
std::convertible_to<From, To>
std::same_as<T, U>
```

Don’t forget the braces!

No bare type for future generalizations

```
template <typename T>
concept has_square = requires (T t) {
   {t.square()} ->
      std::convertible_to<int>;
};
```

Type requirements

A certain nested type exists

A class template specialization names a type

An alias template specialization names a type

Require nested types

`std::vector` has inner member type `value_type`

`int` doesn't have any member type =>

`error: deduced initializer does not satisfy placeholder constraints ... the required type 'typename T::value_type' is invalid`

```
template<typename T>
concept type_requirement =
requires {
  typename T::value_type;
};

int main() {
 type_requirement auto myVec =
   std::vector<int>{1, 2, 3};
 type_requirement auto
   myInt{3};
}
```

Require nested template specializations

Make sure that a type can be used as a template parameter for another type

Error: *the required type 'Other<T>' is invalid ... constraints not satisfied ... 'template<class T> requires !(same_as<T, int>) struct Other [with T = int]'...*

```
#include <concepts>

template <typename T>
requires (!std::same_as<T, int>)
struct Other {};

template<typename T>
concept type_requirement = requires
{ typename Other<T>; };

int main() {
   type_requirement auto c = 'c';
   type_requirement auto i = 4;
}
```

Requirements on alias template specializations

To make sure that an alias template specialization names a type

```
template<typename T> using
Reference = T&;


template<typename T>

concept type_requirement =
requires {

  typename Reference<T>;

};
```

Nesting is often overcomplication

Use nested requirements on local variables without declaring named concepts

Nested requirement to check what `clonable` returns

But...

```
#include <concepts>

struct Droid {
  Droid clone() { return {}; }
};
struct DroidV2 {
  Droid clone() { return {}; }
};

template <typename C>
concept cloneable = requires (C cloneable) {
  cloneable.clone();
  requires std::same_as<C, decltype(cloneable.clone())>;
};

int main() {
  cloneable auto c = Droid{};
  // nested requirement 'same_as<C, decltype (cloneable.clone())>'
  //  is not satisfied [with C = DroidV2]
  // cloneable auto c2 = DroidV2{};
}
```

But there is often a simpler option

```
template<typename C>
concept clonable = requires (C clonable) {
    { clonable.clone() } -> std::same_as<C>;
};
```

Nest to simulate boolean expressions

```
template <typename T, typename
U>

requires
(bool(std::unsigned_integral<
        typename T::Blah> ||
      std::unsigned_integral<
        typename U::Blah>))

void foo(T bar, U baz) {
/*...*/ }
```

```
template <typename T, typename
U>
requires (
  requires {typename T::Blah;}
  && requires {
       typename U::Blah;}) &&
(std::unsigned_integral<
    typename T::Blah> ||
std::unsigned_integral<
    typename U::Blah>)
void foo(T bar, U baz) {
/*...*/ }
```

Real-life examples

Numbers, nothing else, please

Some integral types are not numbers:

`bool`

`char` et al.

```
#include <concepts>
#include <iostream>

template <typename T>
concept number = std::integral<T> ||
  std::floating_point<T>;

auto add(number auto a, number auto b) {
  return a + b;
}

int main() {
  std::cout << add(1, 2) << '\n';
  std::cout << add(1, 2.14) << '\n';
  std::cout << add('1', '2') << '\n';
  std::cout << add(true, false) << '\n';
}
```

Let’s forbid unwanted types

No bools

No chars

```
#include <concepts>

template <typename T>
concept number = (std::integral<T> ||
  std::floating_point<T>) && !std::same_as<T, bool>
  && !std::same_as<T, char> && !std::same_as<T, unsigned char>
  && !std::same_as<T, char8_t && !std::same_as<T, char16_t>
  && !std::same_as<T, char32_t> && !std::same_as<T, wchar_t>;

number auto add(number auto a, number auto b) { return a+b; }

int main() {
  // constraints not satisfied, [with auto:11 = bool;
  // auto:12 = bool]': the expression '!(same_as<T, bool>)
  // [with T = bool]' evaluated to 'false'
  add(true, false); // ERROR
}
```

Turn poorly documented utility functions...

Usually taking any type

No static assertions

Bad template parameter names (T, U, etc.)

No documentation

```
template <typename
          BusinessObjectT>

void encodeSomeStuff(
  BusinessObjectT iBusinessObject)
{

  // ...

}
```

… into self-documenting code

No more naked `T`s

No more unconstrained `typename`s

[T.10: Specify concepts for all template arguments]

```
template <typename
BOWithEncodeableStuff_t>
concept bo_with_encodeable_stuff =
requires (BOWithEncodeableStuff_t bo)
{
  bo.interfaceA();
  bo.interfaceB();
  { bo.interfaceC() } ->
      std::same_as<int>;
};

void encode(bo_with_encodeable_stuff
auto iBusinessObject) { /*...*/ }
```

Even if some concepts are not for reuse

Concept can be “inlined”

Cannot use a parameter in an unnamed context

Hence the nested `requires` clause

```
template <typename
BOWithEncodeableStuff_t>
requires requires
(BOWithEncodeableStuff_t bo) {

  bo.interfaceA();
  bo.interfaceB();
  { bo.interfaceC() } ->
      std::same_as<int>;
}
void
encodeSomeStuff(BOWithEncodeableStuff_t
iBusinessObject) { /*...*/ }
```

How to test whether your class models a concept?

Use `static_assert` to make sure your class models the desired concepts

You can similarly test your concepts too!

```
template <typename C>
concept car = requires (C c) {
  c.startEngine();
  c.stopEngine();
  c.accelerate();
  c.brake();
  // ...
};

class Tank { /* … */ };
static_assert(!car<Tank>);


class SUV { /* … */ };
static_assert(car<SUV>);
```

Conclusion

Key takeaways

Concepts help validate template arguments at compile-time

Concepts provide a reusable and scalable way to constrain templates

The standard library gives dozens of generic concepts

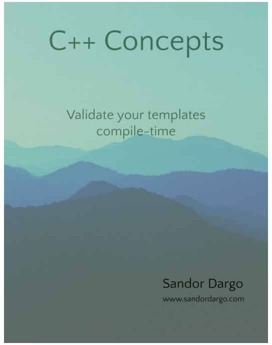
There are plenty of ways to define our concepts

Call to action

Start using concepts as soon as you switch to C++20

Use them for your applications

No more naked `T`s and `typename`s



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