

# C++ Concepts Primer:

*“defining and applying constraints”*

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**Warning:** the author is neither an expert or a member of the standardization committee; only a fool would take everything that is written here as the truth. However, the author has tried (within his knowledge) to keep this document as accurate as possible. If you, the reader, find any mistakes in this document, please send an e-mail (or even better, create an issue on [GitHub](https://github.com/ericniebler/c3primer), and fix it!)

# 1 Introduction

Right now C++ is experiencing a *renaissance*, fueled by new language features and an extended standard library introduced with C++11, C++14, and C++17. It's a different beast than C++98 (want to feel old?: that's two decades ago!), while still keeping to its core philosophies: the *zero-overhead principle*, having a *simple & direct mapping to hardware*, and to be completely *multi-paradigm*. The language has become more powerful, but also simpler, since a lot of the rough edges in C++98 have been removed, or replaced, with modern variants. Interest in C++ has surged again, and with C++20 coming soon™, doubly so.

C++20 is expected to bring features such as *Contracts*, *Coroutines*, *Ranges*, and *Concepts* to the language. Each one of these features deserves their own version of this primer, a self-contained, textbook-style way to introduce people to these features. It should motivate why this feature is needed, what problems it's trying to solve, and present previous alternatives already in the language. After explaining where these existing methods fall short, the feature is shown, demonstrating in which cases it's better than the alternatives. Finally, the featured syntax is presented by using short (to the point!) practical examples.

In this primer we'll be looking at Concepts, a way to *constrain templates*, which leads to: *clearer template errors*, a way to *overload based on constraints*, and more *explicitly defined function template interfaces* by using requirements. The goals of this primer are to teach you how to *apply constraints* to template parameters by using the *requires clause*, and how to *define* your own set of *requirements* by using the various forms of *requires expressions*. You'll then see that we can compose requirements together to form useful *concepts*, that can be used together with *terse syntax*, for writing less verbose generic code.

The primer has the following structure: in Section 2 we present the state of *generic programming* with *unconstrained templates*, and some of its problems. We then show some solutions (e.g. type traits), where they fall short, and where concepts may help. In Section 3 we introduce concepts, and show how *requires clauses* together with *requires expressions* can constrain templates. The three major terse syntax proposals are then presented in Section 4, and is followed by Section 5 with an overview of the *concepts and ranges library*. Finally, we wrap things up in Section 6, and see what the future might hold.

## Building Examples

Alongside this document you'll find plenty of examples on how to use concepts, and you'll be happy to know *almost* all of them compile out-of-the-box when using GCC with the `-fconcepts` flag! If you are a boring person, you can clone the [repository](#), or, if you're feeling adventurous, *unzip* this PDF with:

---

```
1 unzip concepts-primer.pdf
2 cd examples
3 make gcc-test && make -j8
```

---

## 2 Generic Programming

Ever since the humble beginnings of C++ there's been extensive support for different kinds of *polymorphism*, which can be split into two “main” categories: *run-time polymorphism* and *compile-time polymorphism*. The former is a key component in class-based OOP, and takes the form of inheritance, while the latter one enables *generic programming*, and is synonymous with *templates*.

Templates are a bit special in C++ since they are *unconstrained*. Meaning, when we *instantiate* e.g. function templates, the compiler will first generate the function (that's the instantiation part) by replacing T with whatever type you've passed to the function, and only after, check if the syntax is correct! This leads to some very unfortunate side-effects, as you'll see soon enough :)

But before digging into the gritty details on that, let's start with a simple example of “regular programming” (i.e. with no templates), which we'll then use to iteratively build a scenario where generic programming will be needed. This will help us understand the thought process that goes into designing a generic function, and how *requirements* are gathered by the function's author.

Below is a function that calculates the arithmetic mean by taking in two pointers to a C-style array of doubles, one for the first, and last elements. Notice, that even if we would mangle the names, we would still recognize this as the mean, since the operations (summing elements and dividing by size), would still be familiar to us, since we know what {}, +=, / do to doubles.

---

```
1 double mean(const double* begin,
2             const double* const end) {
3     double sum { };
4     const double size = end - begin;
5     while (begin != end)
6         sum += *begin++;
7     return sum / size;
8 }
```

---

By using *operator overloading*, we can make our user-defined types behave just like built-in types. This is very powerful, because it allows us to transfer our knowledge about e.g. doubles, and apply it for our own types as well, by using the same syntax as before. This last part is particularly important!

---

```
1 struct point2 {
2     double x, y;
3     point2& operator/=(const double);
4     point2& operator*=(const double);
5     point2& operator+=(const point2&);
6 };
7
8 point2 operator+(const point2&, const point2&);
9 point2 operator/(const point2&, const double);
10 point2 operator*(const point2&, const double);
11 point2 operator*(const double, const point2&);
```

---

---

```

1 point2 centroid(const point2* begin,
2                 const point2* const end) {
3     point2 sum { };
4     const double size = end - begin;
5     while (begin != end)
6         sum += *begin++;
7     return sum / size;
8 }

```

---

As can be seen above, providing all those overloads to `point2` proved fruitful, since we can now represent the algorithm to find the centroid of a cluster of points in a very natural way, quite similarly to how we did the `mean` function. In fact, this function is *exactly* the same as `mean`, with the only difference being that the type `double`  $\rightarrow$  `point2` and that now `mean`  $\rightarrow$  `centroid`.

## 2.1 Unconstrained Templates

---

```

1 template<typename T>
2 T average(const T* begin,
3           const T* const end) {
4     T sum { };
5     const double size = end - begin;
6     while (begin != end)
7         sum += *begin++;
8     return sum / size;
9 }

```

---



---

```

1 std::list l { 5, 1, 2, 4, 3 };
2 std::sort(l.begin(), l.end());

```

---



---

```

1 struct Widget { };
2 std::set<Widget> w;
3 w.insert(Widget{});

```

---



---

```

1 template<typename T>
2     requires DefaultConstructible<T> &&
3             SummableWith<T, T> &&
4             ScalableWith<T, double>
5 T average(const T* begin,
6           const T* const end) {
7     T sum { };
8     const double size = end - begin;
9     while (begin != end)
10         sum += *begin++;
11     return sum / size;
12 }

```

---

## 2.2 Type Traits and SFINAE

Expression	Return Type	Requirement Specification
<code>x == y</code>	<code>bool</code> convertible	<p><code>==</code> is an equivalence relation, that is, it has the following properties:</p> <p>→ for all <code>x</code>, <code>x == x</code></p> <p>→ if <code>x == y</code>, then <code>y == x</code></p> <p>→ if <code>x == y</code>, <code>y == z</code>, then <code>x == z</code></p>
<pre> 1 template&lt;typename T, typename U, typename = void&gt; 2 struct is_equality_comparable : std::false_type { }; 3 4 template&lt;typename T, typename U&gt; 5 struct is_equality_comparable&lt;T, U, 6     typename std::enable_if&lt;true, 7     decltype(std::declval&lt;T&amp;&gt;() == std::declval&lt;U&amp;&gt;()), 8     (void) 0)&gt;::type&gt; : std::true_type { }; </pre>		
<pre> 1 template&lt;typename T, typename U&gt; 2 concept EqualityComparableWith = requires(T x, U y) { 3     { x == y } -&gt; bool; { x != y } -&gt; bool; 4     { y != x } -&gt; bool; { y == x } -&gt; bool; 5 }; </pre>		
<pre> 1 struct NumberFactory { 2     enum { INTEGRAL, FLOATING } number_type; 3 4     template&lt;typename T, 5         typename = std::enable_if&lt; 6             std::is_integral_v&lt;T&gt;&gt;&gt; 7     NumberFactory(T) : number_type { INTEGRAL } {} 8 9     int create_number() const; 10 11     template&lt;typename T, 12         typename = std::enable_if&lt; 13             std::is_floating_point_v&lt;T&gt;&gt;&gt; 14     NumberFactory(T) : number_type { FLOATING } {} 15 }; </pre>		
<pre> 1 struct NumberFactory { 2     enum { INTEGRAL, FLOATING } number_type; 3 4     template&lt;int&gt; struct dummy { dummy(int) {} }; 5 </pre>		

```

6   template<typename T,
7           typename = std::enable_if<
8               std::is_integral_v<T>>>
9   NumberFactory(T, dummy<0>=0) : number_type { INTEGRAL } {}
10
11   int create_number() const;
12
13   template<typename T,
14           typename = std::enable_if<
15               std::is_floating_point_v<T>>>
16   NumberFactory(T, dummy<1>=0) : number_type { FLOATING } {}
17 };

```

---

```

1 struct NumberFactory {
2     enum { INTEGRAL, FLOATING } number_type;
3
4     template<typename T>
5         requires std::is_integral_v<T>
6     NumberFactory(T) : number_type { INTEGRAL } {}
7
8     int create_number() const;
9
10    template<typename T>
11        requires std::is_floating_point_v<T>
12    NumberFactory(T) : number_type { FLOATING } {}
13 };

```

---

## 2.3 Tag Dispatching

```

1 template<typename T, typename U>
2 void tagged_advance(T& iterator, U distance,
3                    std::forward_iterator_tag) {
4     while (distance-->0)
5         iterator++;
6 }
7
8 template<typename T, typename U>
9 void tagged_advance(T& iterator, U distance,
10                    std::bidirectional_iterator_tag) {
11     std::forward_iterator_tag hack_category;
12     tagged_advance(iterator, distance, hack_category);
13 }
14
15 template<typename T, typename U>
16 void tagged_advance(T& iterator, const U distance,
17                    std::random_access_iterator_tag) {
18     iterator += distance;
19 }

```

---

---

```
1 template<typename T, typename U>
2 void advance(T& iterator, U distance) {
3     typename std::iterator_traits<T>::category category;
4     tagged_advance(iterator, distance, category);
5 }
```

---

---

```
1 template<typename T, typename U>
2     requires ForwardIterator<T> &&
3         Unsigned<U> && Integral<U>
4 void advance(T& iterator, U distance) {
5     while (distance-->
6         ++iterator;
7 }
8
9 template<typename T, typename U>
10    requires RandomAccessIterator<T> &&
11        Unsigned<U> && Integral<U>
12 void advance(T& iterator, U distance) {
13     iterator += distance;
14 }
```

---

## 3 Concepts

### 3.1 Applying Constraints

#### 3.1.1 Requires Clauses

---

```
1 template<template<class> typename C, typename T>
2     requires Summable<T>
3 T sum(const C<T>& container) {
4     T total_sum { };
5     for (auto value : container)
6         total_sum += value;
7     return total_sum;
8 }
```

---

---

```
1 []<typename T>(T x, T y) requires EqualityComparable<T> {
2     return x == y;
3 };
```

---

---

```
1 template<typename T, std::size_t R,
2         std::size_t C = R>
3     requires Number<T>
4 class Matrix {
5 public:
6     template<typename U>
7         requires ScalableWith<T, U> && Number<U>
8     Matrix<T, R, C>& operator*=(U scalar) {
9         std::for_each(data.begin(), data.end(),
10             [scalar](T& element) {
11                 element *= scalar;
12             });
13
14         return *this;
15     }
16 };
```

---

---

```
1 template<auto N>
2     requires Even<N>
3 int square_even() {
4     return N*N;
5 }
```

---

---

```
1 // Just read The Hitchhiker's Guide!
2 constexpr bool the_answer(int value) {
3     return value == 42;
4 }
5
```

---



```

6 template<auto N>
7     requires the_answer(N)
8 void check_with_deep_thought() {
9     std::cout << "good guess!"
10             << std::endl;
11 }

```

---

### 3.1.2 Overload Resolution

```

1 template<typename T, typename U>
2     requires ForwardIterator<T> &&
3             Unsigned<U> && Integral<U>
4 void advance(T& iterator, U distance) {
5     while (distance-->
6         ++iterator;
7 }
8
9 template<typename T, typename U>
10     requires RandomAccessIterator<T> &&
11             Unsigned<U> && Integral<U>
12 void advance(T& iterator, U distance) {
13     iterator += distance;
14 }

```

---

### 3.1.3 Logical Operations

#### Conjunctions

```

1 template<auto N>
2     requires Even<N> &&
3             Number<decltype(N)>
4 int square_only_even_numbers() {
5     return N*N;
6 }

```

---

#### Disjunctions

```

1 template<template<class> typename C, typename T>
2     requires Integral<T> || Floating<T>
3 T sum_numbers(const C<T>& container) requires Summable<T> {
4     T total_sum { };
5     for (auto value : container)
6         total_sum += value;
7     return total_sum;
8 }

```

---

## 3.2 Defining Requirements

### 3.2.1 Requires Expressions

---

```
1 template<typename T>
2 concept ForwardIterator = requires {
3     T();
4     T{};
5 } && requires {
6     typename std::iterator_traits<T>::value_type;
7     typename std::iterator_traits<T>::difference_type;
8     typename std::iterator_traits<T>::reference;
9     typename std::iterator_traits<T>::pointer;
10    typename std::iterator_traits<T>::iterator_category;
11 } && requires(T x) {
12     { *x } -> typename std::iterator_traits<T>::reference;
13     { ++x } -> T&;
14     { x++ } -> T;
15 } && requires(T x, T y) {
16     { std::swap(x, y) } noexcept;
17     { std::swap(y, x) } noexcept;
18 } && EqualityComparable<T>;
```

---

#### Simple Requirements

---

```
1 template<typename T>
2 concept ForwardIterator = requires {
3     T();
4     T{};
5 };
```

---

#### Type Requirements

---

```
1 template<typename T>
2 concept ForwardIterator = requires {
3     typename std::iterator_traits<T>::value_type;
4     typename std::iterator_traits<T>::difference_type;
5     typename std::iterator_traits<T>::reference;
6     typename std::iterator_traits<T>::pointer;
7     typename std::iterator_traits<T>::iterator_category;
8 };
```

---

#### Compound Requirements

---

```

1 template<typename T>
2 concept ForwardIterator = requires(T x) {
3     { *x } -> typename std::iterator_traits<T>::reference;
4     { ++x } -> T&;
5     { x++ } -> T;
6 } && requires(T x, T y) {
7     { std::swap(x, y) } noexcept;
8     { std::swap(y, x) } noexcept;
9 };

```

---

## Nested Requirements

---

```

1 template<typename T>
2 concept Allocatable = requires(T x, std::size_t n) {
3     requires Same<T*, decltype(&x)>;
4     { x.~T } noexcept;
5     requires Same<T*, decltype(new T)>;
6     requires Same<T*, decltype(new T[n])>;
7     { delete new T[n] };
8     { delete new T };
9 };

```

---

## 3.3 Giving Names to Concepts

---

```

1 template<typename T>
2 concept ForwardIterator = DefaultConstructible<T> &&
3                             IteratorTraits<T> &&
4                             ReadableIterator<T> &&
5                             WeaklyIncrementable<T> &&
6                             Swappable<T>;

```

---



---

```

1 template<typename T>
2 concept BidirectionalIterator = ForwardIterator<T> &&
3                                 WeaklyDecrementable<T>;
4 template<typename T>
5 concept RandomAccessIterator = BidirectionalIterator<T> &&
6                                 WeaklyRandomAccess<T>;

```

---

### 3.3.1 “Good” Concepts

## 4 Terse Syntax

### 4.1 Natural Syntax

### 4.2 Concepts In-Place Syntax

### 4.3 Constrained **auto** Syntax

## 5 Standard Library Concepts

### 5.1 The Ranges Library

---

```
1 std::vector v { 10, 2, 6, 10, 4, 1, 9, 5, 8, 3 };
2 v = std::move(v) | action::sort | action::unique;
```

---

---

```
1 auto r = v | view::remove_if([](int i){ return (i % 2) == 1; })
2           | view::transform([](int i){ return to_string(i); })
3           | view::take(4);
```

---

## 6 Summary

## References

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- **Andrew Sutton:** for another great [talk](#): “*Generic Programming with Concepts*” at C++Now 2015. Many of the early examples in this primer are based from that talk (with some modifications); consent acquired.
- **Peter Sommerlad:** and the rest of the committee, for allowing me to participate in the discussion on Concepts, Modules and Contracts in the *Rapperswil* 2018 EWG meeting. It was great fun, and it was very interesting to get a perspective on how the committee operates; while the work was tiring (reading so many papers...), it was very rewarding!
- **Tobias Lasser:** and the rest of the teachers/participants in the course seminar “*Discovering and Teaching Modern C++*”, for very interesting talks and for providing a platform where like-minded people can discuss and teach modern C++ to each other. It forced me (being really lazy), to write something that might (?) be useful (I hope?) to others as well.

You may find the short [presentation](#) for the seminar above, useful as well.