

Meeting C++ 2017

Concepts Driven Design

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Agenda

- Concepts
 - Motivation / History
- Type constraints (C++20)
 - Requirements
 - Design by introspection
 - Named concepts
 - Optional interfaces
- Concepts emulation (C++17)
- Concepts based design
 - Static polymorphism
 - Dynamic polymorphism
 - Virtual concepts (C++2?)
 - Dependency Injection
 - Mocking (testing)
- Future of concepts (C++2X)

Disclaimer

Concepts, although, merged into C++20 draft, are still a subject for future changes.

Compiler	Version	Notes
GCC	6.1+	Requires <code>-fconcepts</code> flag
MSVC	VS2017 15.5	-
Clang	In progress...	It had C++0x concepts support

Examples in this talk were compiled using

```
g++7.2 -std=c++2a -fconcepts
```

Motivation - Error Novel

```
int main() {  
    auto list = std::list{1, 2, 3};  
    std::sort(std::begin(list), std::end(list));  
}
```

<https://godbolt.org/g/RTRgg2>

Motivation - Improve error messages

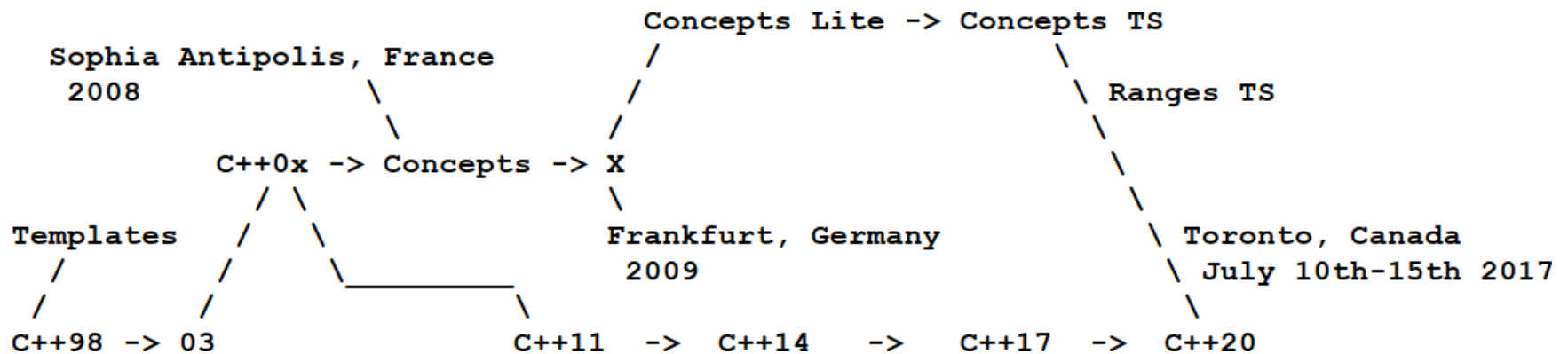
Without concepts

```
invalid operands to binary expression
  ('std::_List_iterator<int>' and
   'std::_List_iterator<int>')
std::__lg(__last - __first) * 2);
          ~~~~~ ^ ~~~~~
...many lines of output f<- library side
```

With concepts

```
error: cannot call std::sort
note: concept RandomAccessIterator was not satisfied
since: expression (b-a) will be ill formed
```

Concepts - History



Concepts Lite - <https://wg21.link/n3701>

Andrew Sutton, Bjarne Stroustrup, Gabriel Dos Reis

Concepts TS - <https://wg21.link/P0734R0>

Andrew Sutton, Bjarne Stroustrup

Concepts - C++20 draft

<http://eel.is/c++draft/temp.constr>

17.4	Template constraints	[temp.constr]
17.4.1	Constraints	[temp.constr.constr]
17.4.1.1	Logical operations	[temp.constr.op]
17.4.1.2	Atomic constraints	[temp.constr.atomic]
17.4.2	Constrained declarations	[temp.constr.decl]
17.4.3	Constraint normalization	[temp.constr.normal]
17.4.4	Partial ordering by constraints	[temp.constr.order]

- Requirements
 - `requires-clause` , `requires-expression`
- Constraints
 - `predicates`, `conjunctions`, `disjunctions`
- Named concepts
 - `placeholders` , `abbreviated templates`

Requirements

Requires-clause

Specifies constraints on template arguments or on a function declaration

`std::enable_if` on steroids

```
template<bool Value>
void foo() requires Value {}
```

```
int main() {
    foo<true>(); // Okay
    foo<false>(); // Error: constraints not satisfied
}
```

Note: requires-clause is part of the function signature

Requires-expression

prvalue expression of type bool

```
requires ( [parameters] ) { requirements }
```

```
// type requirement  
requires(T) { typename T::value_type; };
```

```
// simple requirement  
requires(T t) { t[typename T::value_type{}]; };
```

```
// compound requirement  
requires(T t) { { t.empty() } -> bool; };
```

```
// nested requirement  
requires(T t) {  
    requires std::is_integral_v<typename T::value_type>;  
};
```

Requires-clause/Requires-expression

```
template<class T>
constexpr auto foo(T&& x)
    requires requires(T t) { t.bar(); }
{ return x.bar(); }
```

```
struct { void bar() {} } bar;
foo(bar); // Okay
foo(42);  // Error: constraints not satisfied
           // note: the required expression
           //       't.bar()' would be ill-formed
```

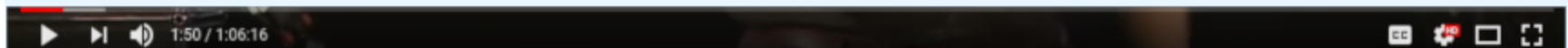
Note: `requires requires` -> `requires-clause` followed by `requires-expression`

Design by introspection

Design by Introspection DConf 2017

Andrei Alexandrescu, Ph.D.

2017-05-06



<https://www.youtube.com/watch?v=29h6jGtZD-U>

Design by introspection - D lang

<https://dlang.org/spec/traits.html>

```
auto foo(T)(T x) {
    static if(__traits(hasMember, x, "bar")) {
        return x.bar;
    } else {
        return 0;
    }
}

void main() {
    assert(0 == foo(42));

    struct Bar { int bar = 42; }
    Bar bar;
    assert(42 == foo(bar));
}
```

<https://godbolt.org/g/wpLXzV>

Design by introspection - C++20

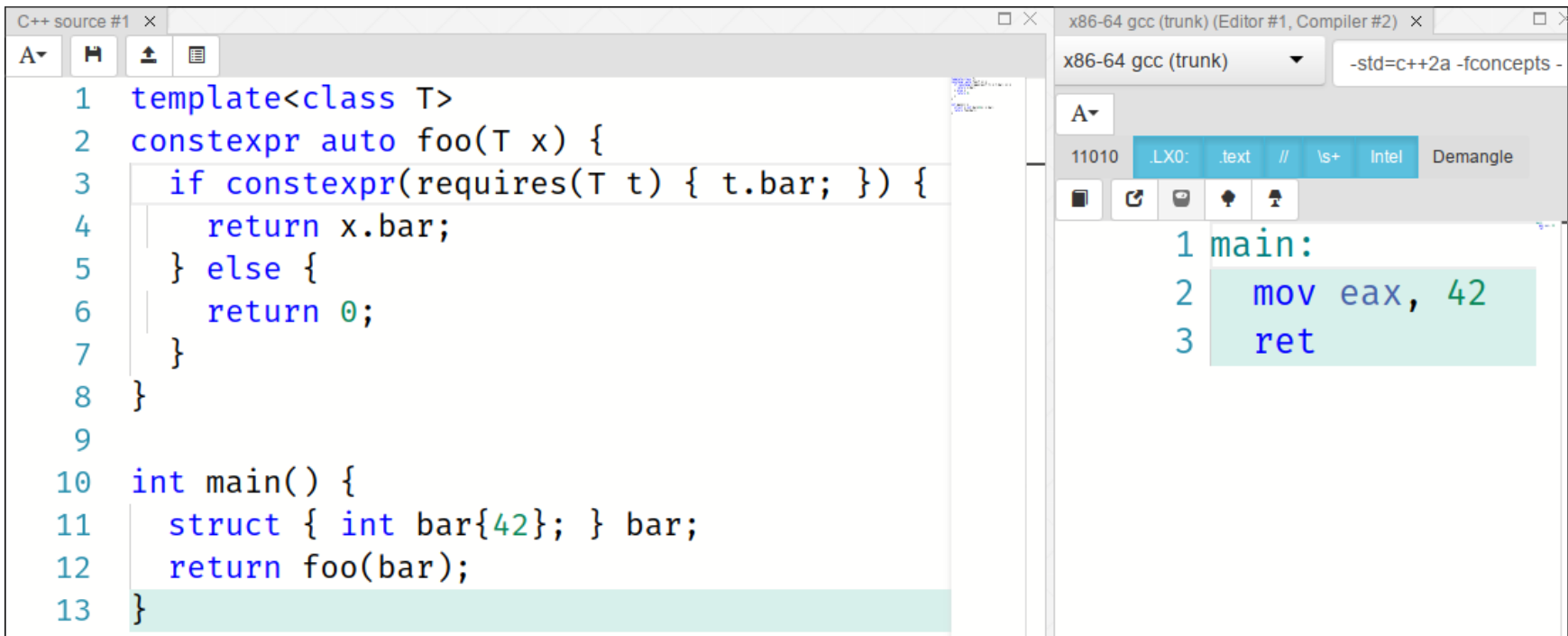
```
template<class T>
constexpr auto foo(T x) {
    if constexpr(requires(T t) { t.bar; }) { // compile-
        return x.bar; // time if
    } else {
        return 0;
    }
}

int main() {
    assert(0 == foo(42));

    struct { int bar{42}; } bar;
    assert(42 == foo(bar));
}
```

<https://godbolt.org/g/uot6Bv>

Design by introspection - C++



The image shows a screenshot of a C++ IDE with two panes. The left pane, titled 'C++ source #1', contains the following C++ code:

```
1  template<class T>
2  constexpr auto foo(T x) {
3      if constexpr(requires(T t) { t.bar; }) {
4          return x.bar;
5      } else {
6          return 0;
7      }
8  }
9
10 int main() {
11     struct { int bar{42}; } bar;
12     return foo(bar);
13 }
```

The right pane, titled 'x86-64 gcc (trunk) (Editor #1, Compiler #2)', shows the assembly output for the same code. The assembly is in Intel syntax and shows the `main` function:

```
1  main:
2      mov     eax, 42
3      ret
```

The assembly output is highlighted in a light blue box.

<https://godbolt.org/g/MFxqWu>

Named concepts

A collection of requirements on a type (variable template)

```
template<template-parameters>  
concept concept-name = constraint-expression;
```

"If you like it then you should have put a name on it", Beyonce rule

Named concepts

Predicate constraints

```
template<class>  
concept Always = true; // always satisfied
```

```
template<class T>  
concept Size32 = sizeof(T) == 4;
```

Conjunctions, Disjunctions

```
template<class T>  
concept SignedIntegral = std::is_integral<T>{} and  
                           std::is_signed<T>{};
```

Named concepts

Requirements

```
template<class T>
concept Fooable =                // named concept
    requires(T t) {              // collection of
        typename T::type;        // type requirement
        { t.foo() } -> void;      // compound requirement
        requires Movable<T> or    // nested requirement
            Same<T, int>;
    };
```

Named concepts

Unconstrained class definition

```
template<class> class Bar {};
```

Requires expression

```
template<class T> class Bar  
    requires Fooable<T> {}; // requires-expression
```

Abbreviated templates

```
template<Fooable T> // Fooable instead of  
class Bar {}; // typename/class
```

Note: C++17 - Non-type template arguments

```
template<auto T> class Bar {}; // For values -> Bar<42>
```

Named concepts

Example

```
struct tcp_socket { void send(std::string_view); };  
struct udp_socket { void send(std::string_view); };  
struct file       { void write(std::string_view); };
```

Everything Cpp

<https://www.youtube.com/watch?v=xsSYPD0v5Mg>

Named concepts

Concept definition

```
template<class T> concept Socket =  
    requires(T t, std::string_view data) {  
        { t.send(data) } -> void; // compound requirement  
    };
```

```
template<class T> concept File =  
    requires(T t, std::string_view data) {  
        { t.write(data) } -> void; // compound requirement  
    };
```

Named concepts

Concept overloading

```
template<Socket T> // requires Socket<T>  
/*1*/ void forward(T& t, std::string_view data) {  
    t.send(data);  
}
```

```
template<File T> // requires File<T>  
/*2*/ void forward(T& t, std::string_view data) {  
    t.write(data);  
}
```

```
int main() {  
    tcp_socket tcp; forward(tcp, "tcp data"sv); // calls 1  
    udp_socket udp; forward(udp, "udp data"sv); // calls 1  
    file file; forward(file, "file data"sv); // calls 2  
}
```

Named concepts

Concepts overloading

if constexpr (C++17)

```
template<class T>
void forward(T& t, std::string_view data) {
    if constexpr(Socket<T>) { // compile-time
        t.send(data);
    } else if constexpr(File<T>) {
        t.write(data);
    }
}
```

Note: Branch which is not taken is discarded

----- Statement may not compile but syntax has to be valid

Named concepts

Lambdas

```
constexpr auto forward =  
    [](auto& t, std::string_view data) {  
        using type = std::decay_t<decltype(t)>;  
        if constexpr(Socket<type>) { t.send(data); } else  
        if constexpr(File<type>)    { t.write(data); }  
    };
```

Generic lambdas (C++17) - <https://wg21.link/P0428r2>

```
constexpr auto forward =  
    [<class T>(T& t, std::string_view data) {  
        if constexpr(Socket<T>) { t.send(data); } else  
        if constexpr(File<T>)    { t.write(data); }  
    };
```


Named concepts

Optional interfaces

Example -> `Stream<T>`

- Copy constructible
- Callable member function `write` which takes type T
- Callable member function `read` which returns type T
- Callable **optional** member function `read_complete`
- Printable

Named concepts

Optional interfaces : Virtual functions (not expressive enough)

```
/**
 * Implementation requires to be printable and
 * copy constructible
 */
template<class T>
class istream {
public:
    virtual ~istream() noexcept = default;
    virtual void write(T) = 0;
    virtual T read() = 0;

    // ??? [[optional]] ???
    virtual void read_complete() = 0;
};
```

Named concepts

Optional interfaces : Concepts

```
template<class T, class TData>
concept Streamable =
    CopyConstructible<T> and // CopyConstructible
    requires(T t, std::ostream& out, TData& data) {
        out << t; // Printable
        t.write(data); // Writable
        { t.read() } -> TData // Readable
    } or requires(T t, std::ostream& out, TData& data) {
        out << t; // Printable
        t.write(data); // Writable
        { t.read() } -> TData // Readable 1/2
        t.read_complete(); // Readable 2/2
    }
};
```

Named concepts

Optional interfaces : Usage

```
using data_t = std::array<std::byte, 1024>;
```

```
class FileStream {  
public:  
    void write(data_t&);  
    data_t read();  
    void read_complete();  
};
```

```
int main() {  
    Streamable<data_t> stream = FileStream{};  
    const auto data = stream.read();  
    ...  
    stream.read_complete();  
}
```

Placeholders

Placeholder	Synopsis
Unconstrained	<code>auto</code>
Constrained	<code>concept-name<[template-argument-list]></code>

```
template<class T> class Foo {};  
template<class T> concept Fooable = true;
```

```
// auto - weakest placeholder  
auto    foo1 = Foo<int>{};  
// C++17 - Constructor Template Argument Deduction  
Foo     foo2 = Foo<int>{};  
// C++20 - placeholder  
Fooable foo3 = Foo<int>{};
```

Note: Placeholders can be used for functions `void f(auto);`

Concepts and the C++ ISO standard

18	EqualityComparable requirements	467
19	LessThanComparable requirements	467
20	DefaultConstructible requirements	467
21	MoveConstructible requirements	468
22	CopyConstructible requirements (in addition to MoveConstructible)	468
23	MoveAssignable requirements	468
24	CopyAssignable requirements (in addition to MoveAssignable)	468
25	Destructible requirements	468
26	NullablePointer requirements	470
27	Hash requirements	471
28	Descriptive variable definitions	471
29	Allocator requirements	472

Note: More concepts to come with Ranges TS

Concepts and the C++ ISO standard

Table 18 — EqualityComparable requirements [equalitycomparable]

Expression	Return type	Requirement
<code>a == b</code>	convertible to <code>bool</code>	<code>==</code> is an equivalence relation, that is, it has the following properties: <ul style="list-style-type: none">— For all <code>a</code>, <code>a == a</code>.— If <code>a == b</code>, then <code>b == a</code>.— If <code>a == b</code> and <code>b == c</code>, then <code>a == c</code>.

```
template<class T> // C++20 concepts
concept EqualityComparable = requires(T a, T b) {
    { a == b } -> bool;
};
```

```
class EqualityComparable a where // Haskell typeclasses
    (==) :: a -> a -> Bool
```

Concepts - Ranges TS

```
template <class I>
concept InputIterator =
    Iterator<I> &&
    Readable<I> &&
    requires(I& i, const I& ci) {
        typename iterator_category_t<I>;
        DerivedFrom<
            iterator_category_t<I>, input_iterator_tag>;
        i++;
    };
```

<https://github.com/CaseyCarter/cmcstl2>

Concepts emulation (C++17)

Concepts emulation (C++17)

Substitution Failure Is Not An Error (SFINAE)

```
template<bool, class = void>
struct enable_if {};

template<class T>
struct enable_if<true, T> { using type = T; };
```

- `false` predicates lead to ill-formed code that's discarded

Concepts emulation (C++17)

Dedection idiom (C++20)

```
template<class T>  
using Fooable = decltype(std::declval<T>().foo());
```

```
struct Foo { void foo(); };  
struct Bar { };
```

```
static_assert(not std::is_detected<Fooable, Bar>{});  
static_assert( std::is_detected<Fooable, Foo>{});
```

Note: Under the hood, it uses

```
template<class...> using void_t = void;
```

<https://wg21.link/n4436>

Concepts emulation (C++17)

Does the Concepts TS Improve on C++17?

```
template <class F, class... Args, class = decltype(
    std::declval<F&&>()(std::declval<Args&&>()...))>
constexpr auto requires_impl(int) { return true; }

template <class F, class... Args>
constexpr auto requires_impl(...) { return false; }

template <class... Args, class F>
constexpr auto requires(F&&) {
    return requires_impl<F&&, Args&&...>(int{});
}
```

<https://wg21.link/P0726R0>

Concepts emulation (C++17)

Error message

```
template<class T, class = std::enable_if_t<Socket<T>>>
void forward(T& t, std::string_view data) {
    t.send(data);
}
```

```
int main() {
    tcp_socket tcp; forward(tcp, "tcp data"sv); // Okay
    file file; forward(file, "file data"sv);
    // error: no matching function for call to 'forward'
    // possibly many lines of output <- library side
}
```

Note: No details why function couldn't be called

Concepts emulation (C++17)

requires-clause

```
struct Foo { void foo(); };  
struct Bar {};
```

```
static_assert(  
    requires<Foo>([](auto&& t) -> decltype(t.foo()) {})  
);
```

```
static_assert(  
    !requires<Bar>([](auto&& t) -> decltype(t.foo()) {})  
);
```

Concepts emulation (C++17)

Design by introspection - C++17

```
template<class T> constexpr auto foo(T x) {  
    if constexpr(requires<T>( // compile-time if  
        [](auto&& t) -> decltype(t.bar) {})) {  
        return x.bar;  
    } else {  
        return 0;  
    }  
}
```

Note: Workaround for expression is not a constant expression

```
if constexpr(  
    auto bar = [](auto&& t) -> decltype(t.bar) {};  
    requires<T>(bar)  
)
```

Concepts emulation (C++17)

Named concept

```
template<class T> constexpr auto Socket =  
    requires<T>([](auto&& t, std::string_view data)->  
        decltype(t.send(data)) {}  
    );
```

```
template<class T> constexpr auto File =  
    requires<T>([](auto&& t, std::string_view data) ->  
        decltype(t.write(data)) {}  
    );
```


Concepts emulation (C++17)

Concepts overloading

```
template<class T,  
    std::enable_if_t<Socket<T>, int> = 0>  
/*1*/ void forward(T& t, std::string_view data) {  
    t.send(data);  
}
```

```
template<class T,  
    std::enable_if_t<File<T>, int> = 0>  
/*2*/ void forward(T& t, std::string_view data) {  
    t.write(data);  
}
```

```
int main() {  
    tcp_socket tcp; forward(tcp, "tcp data"sv); // calls 1  
    udp_socket udp; forward(udp, "udp data"sv); // calls 1  
    file file; forward(file, "file data"sv); // calls 2  
}
```

Concepts emulation (C++17)

Concept overloading

`if constexpr` (C++17)

```
template<class T>
void forward(T& t, std::string_view data) {
    if constexpr(Socket<T>) { // compile-time
        t.send(data);
    } else if constexpr(File<T>) {
        t.write(data);
    }
}
```

Note: Exactly the same way as with C++20 concepts

Concepts based design

Concepts based design

Goals

Expressiveness	Type constraints for better error messages (Design by Introspection)
Loosely coupeled design	Inject all the things! (Policy Design)
Performance	Static dispatch by default (based on concepts)
Flexibility	Dynamic dispatch using type erasure (based on the same concepts)
Testability	Automatic mocks injection (based on the same concepts)

Concepts based design

Static polymorphism

```
template<class T> concept Drawable = requires
(T t, std::ostream& out) { { t.draw(out) } -> void; };
```

```
struct Square {
    void draw(std::ostream& out) { out << "Square"; } };

struct Circle {
    void draw(std::ostream& out) { out << "Circle"; } };

template<Drawable T>
void f(T& d) { d.draw(std::cout); }

int main() {
    f(Square{}); // prints Square
    f(Circle{}); // prints Circle
}
```

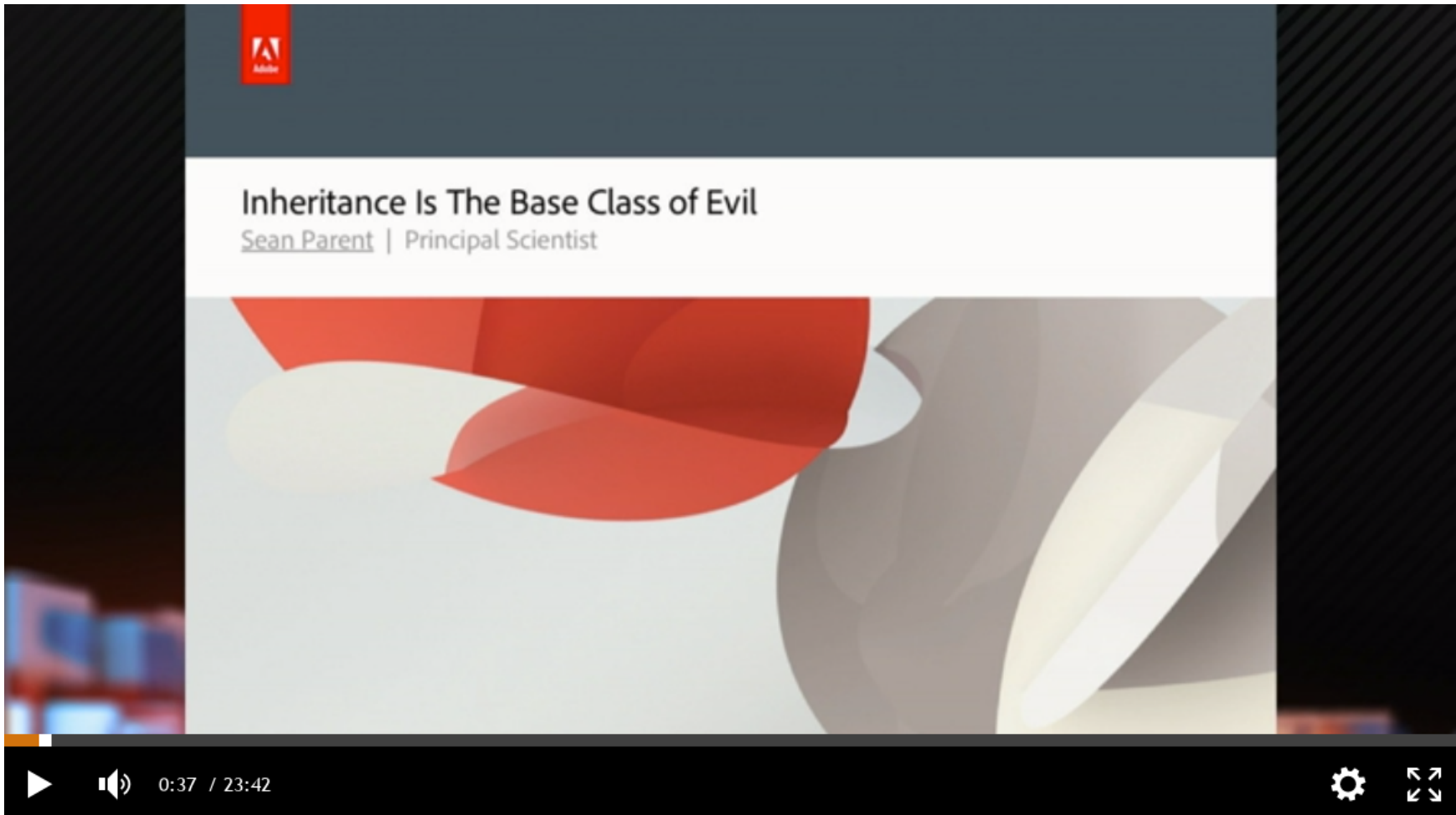
Concepts based design

Static polymorphism

```
std::vector v1 = { Square{}, Circle{} };  
// ERROR: class template argument deduction failed  
  
std::vector<auto> v2 = { Square{}, Circle{} };  
// ERROR: couldn't deduce template parameter  
  
std::vector<Drawable> v3 = { Square{}, Circle{} };  
// ERROR: couldn't deduce template parameter
```

Concepts based design

Concepts based polymorphism / Dynamic polymorphism



Inheritance-Is-The-Base-Class-of-Evil

Meeting C++ 2017 | Concepts Driven Design | Kris Jusiak

Concepts based design

Dynamic polymorphism / Virtual concepts (C++2?)

```
template<class T> concept Drawable =  
    requires() { auto T::draw(std::ostream&) -> void; };  
    // Signature requirement
```

```
struct Square {  
    void draw(std::ostream& out) { out << "Square"; } };  
  
struct Circle {  
    void draw(std::ostream& out) { out << "Circle"; } };  
  
void f(virtual Drawable& d) { d.draw(std::cout); }  
    // Type erasure  
  
int main() {  
    f(Square{}); // prints Square  
    f(Circle{}); // prints Circle  
}
```


Concepts based design

Dynamic polymorphism / Virtual concepts (C++2?)

Signature requirement

```
template<class T>
concept Fooable = requires() {
    auto T::foo() -> void; // NOT C++20!
};
```

Dynamic Generic Programming with Virtual Concepts

Note: Virtual concepts aren't part of C++20

Concepts based design

Dynamic polymorphism / Virtual concepts (C++2?)

```
std::vector<virtual Drawable> v; // okay (type erasure)
v.push_back(Square{});           // okay
v.push_back(Circle{});           // okay
```

100% value semantics / Stack based / Small buffer optimization (SBO)

Note: Might be also generated with Metaclasses (C++2?)

```
template<class T>
any Foo
    auto foo() -> void;
};
```

```
template<class T>
$any { // metaclass
    constexpr { ... }
};
```

<https://wg21.link/p0707r0>

Concepts based design

Dynamic polymorphism / Virtual concepts emulation (C++17)

```
template<class T> constexpr auto Drawable =  
    Callable<void(T::*)(std::ostream&)>( $(draw) );
```

```
struct Square {  
    void draw(std::ostream& out) { out << "Square"; } };  
  
struct Circle {  
    void draw(std::ostream& out) { out << "Circle"; } };  
  
void f(any<Drawable>& d) { d.draw(std::cout); }  
  
int main() {  
    f(Square{}); // prints Square  
    f(Circle{}); // prints Circle  
}
```

Concepts based design

Virtual concepts emulation (C++17)

```
Callable<void(T::*)(std::ostream&)>( $((draw)) ]  
    \_      \__   \_____          \___-> name  
    \_      \_     \         \  
  
$((name)) [](auto&& r, auto&& t, auto&&... args) {  
    struct { // base class  
        auto name(declype(args)... args) ->  
            declype(self.name(args...)){ } {  
                // static polymorphism  
                return static_cast<declype(t) *>(this)->template  
                    call<name, typename declype(r)::type>(args...);  
            }  
    } _; return _;  
}
```

```
$ (type) decltype (type<...>)
```

<https://github.com/boost-experimental/vc>

Concepts based design

Dependency Injection (policy design) / concepts

```
template<class T>
concept ErrorPolicy =
    requires(T t, std::string_view msg) {
        requires CopyConstructible<T>;
        { t.onError(msg) } -> void;
    };
```

```
struct ThrowPolicy {
    void onError(std::string_view msg) { throw T{msg}; }
};

struct LogPolicy {
    void onError(std::string_view msg) {
        std::clog << T{msg} << '\n';
    }
};
```

Concepts based design

Dependency Injection (policy design) / concepts

```
template<ErrorPolicy TPolicy = class Policy>
class App {
    public: explicit App(TPolicy policy):policy{policy} {}
    void run() {
        if (...) { policy.onError("error!"); }
    }
    private: TPolicy policy{};
};
```

```
int main() {
    const auto injector = di::make_injector(
        di::bind<class Policy>.to<ThrowPolicy>()
    );
    injector.create<App>().run();
}
```

<https://github.com/boost-experimental/di>

Concepts based design

Dependency Injection (policy design) / virtual concepts
(C++2?)

```
class App {  
public:  
    explicit App(virtual ErrorPolicy policy)  
        : policy{policy}  
    { }  
  
    void run() {  
        if (...) { policy.onError("error!"); }  
    }  
  
private:  
    virtual ErrorPolicy policy{};  
};
```

Concepts based design

Dependency Injection (policy design) / virtual concepts
(C++2?)

```
int main() {  
    const auto injector = di::make_injector(  
        di::bind<virtual ErrorPolicy>.to<LogPolicy>()  
    );  
    injector.create<App>().run();  
}
```


Concepts based design

Dependency Injection (policy design) / virtual concepts
emulation (C++17)

```
template<class T>
constexpr auto ErrorPolicy =
    CopyConstructible<T> and           // exposed by
    Callable<void(T::*)()>( $(onError) ); // reflection
```

```
class App {
public:
    explicit App(any<$(ErrorPolicy)> policy)
        : policy{policy} {}
    void run() {
        if (...) { policy.onError("error!"); }
    }
private:
    any<$(ErrorPolicy)> policy{};
};
```

Concepts based design

Dependency Injection (`policy design`) / `virtual concepts emulation` (C++17)

```
int main() {  
    const auto injector = di::make_injector(  
        di::bind<$(ErrorPolicy)>.to<LogPolicy>()  
    );  
    injector.create<App>().run();  
}
```

Note: Same wiring for dynamic/static polymorphism

Concepts based design

Mocking (testing)

Interface based mocking

```
struct ErrorPolicy {  
    virtual ~ErrorPolicy() = default;  
    virtual void onError(std::string_view) = 0;  
};  
GMock<ErrorPolicy> mock{};  
EXPECT_CALL(mock, onError("interface!")).Times(1);  
mock.onError("interface!");
```

Concepts based mocking

```
GMock<$(ErrorPolicy)> mock{};  
EXPECT_CALL(mock, onError("concept!")).Times(1);  
object(mock).onError("concept!");
```

Concepts based design

Mocking (testing)

automatic mocks injection

```
"should print read text"_test = [] {  
    auto [app, mocks] = testing::make<App>();  
  
    EXPECT_CALL(mocks<$(ErrorPolicy)>, onError("error!"));  
  
    app.run();  
};
```

Note: `make` creates mocks based on concepts requirements (reflection)

<https://github.com/cpp-testing/gunit>

Future of concepts (C++2X)

Future of concepts (C++2X)

Terse template syntax

```
void forward(Socket& socket, std::string_view data);
```

same as...

```
template<Socket T>  
void forward(T& socket, std::string_view data);
```

same as...

```
template<class T> requires Socket<T>  
void forward(T& socket, std::string_view data);
```

Note: Problem `f(auto, auto)` vs `f(Socket, Socket)`

<https://wg21.link/p0696r1>

Future of concepts (C++2X)

Template-introduction syntax

```
Concept{A, B, C} void f(A a, B b, C c);
```

or

```
template<Concept [A, B, C]> void f(A a, B b, C c);
```

same as...

```
template<class A, class B, class C>  
void f(A a, B b, C c) requires Concept<A, B, C>;
```

Future of concepts (C++2X)

Metaclasses syntax

```
template<class T>  
Fooable Foo { }; // static_assert(Fooable<Foo>);
```

<https://wg21.link/p0707r0>

Concepts: Summary

Provides better diagnostics

Simplify usage of SFINAE / `enable_if`

- Introspection by design / Optional interfaces

Allows better design

Can be emulated in C++14/C++17

- `variable templates` / `constexpr` / `constexpr if`

C++20 is just the beginning

- `syntax improvements` / `requirements improvements`
- `virtual concepts` / `metaclasses` / `static reflection`

Questions?



	
Concepts	https://wg21.link/P0734R0
Virtual Concepts	https://github.com/andyprowl/virtual-concepts/blob/master/draft/Dynamic Generic Programming with Virtual Concepts.pdf