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 `-fconcepts` 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

```
 Sophia Antipolis, France   Concepts Lite -> Concepts TS
        2008  \             /                    \
               \           /                      \ Ranges TS
    Aims for  C++0x -> Concepts -> X               \
    / \            /  \             \               \
   /  Templates   /    \      Frankfurt, Germany   Toronto, Canada
  /     /        /      \___        2009         July 10th-15th 2017
 /     /        /           \                                 \
1987  C++98 -> 03          C++11  ->  C++14   ->   C++17  ->  C++20
```

> Requirements analysis
>
> Concepts Lite - https://wg21.link/n3701
>
> Concepts TS - https://wg21.link/P0734R0

> Alex Stepanow, Andrew Lumsdaine, Sean Parent,
>
> Andrew Sutton, Bjarne Stroustrup, Gabriel Dos Reis

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>;
};
```

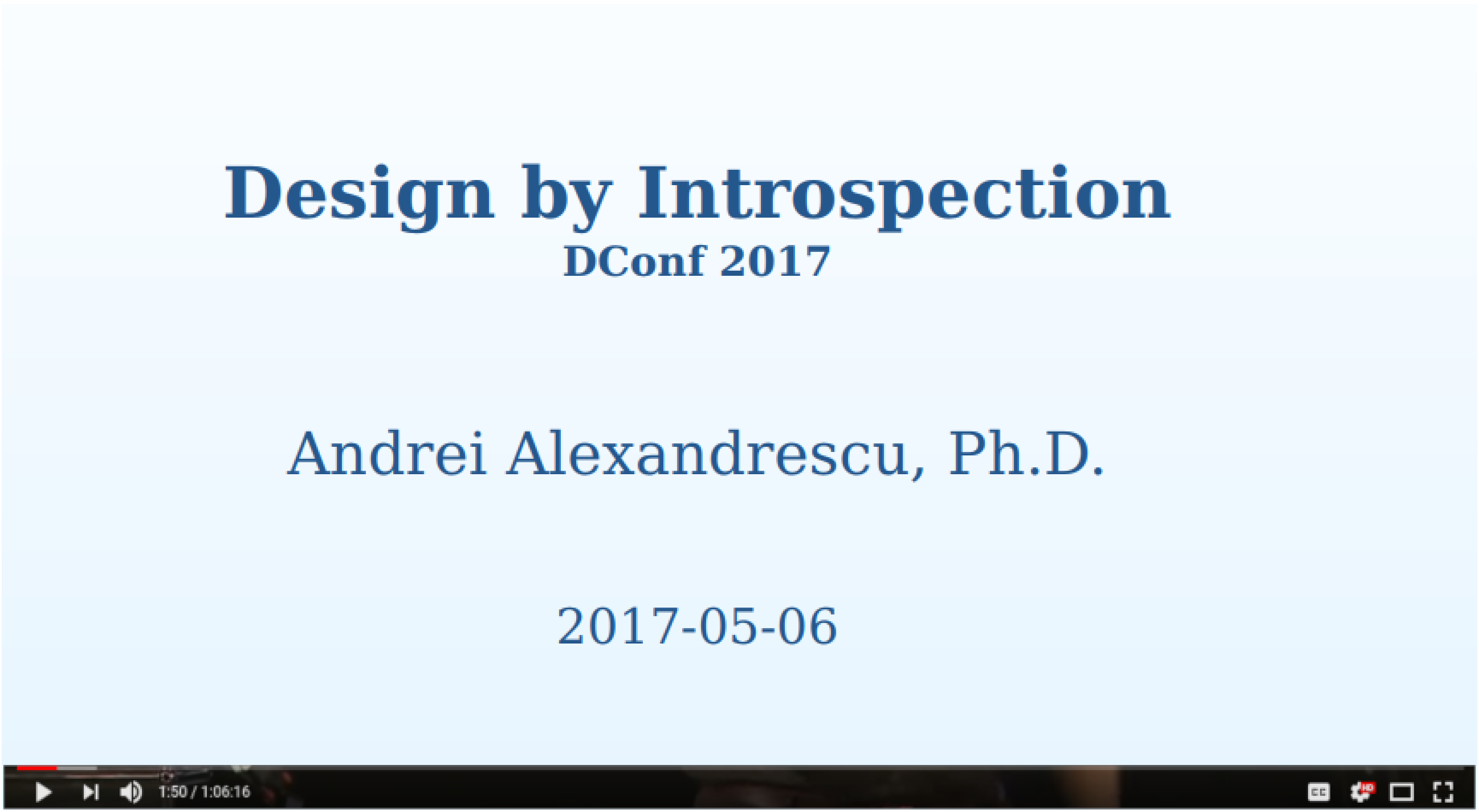
Requires-clause/Requires-expression

```
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



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

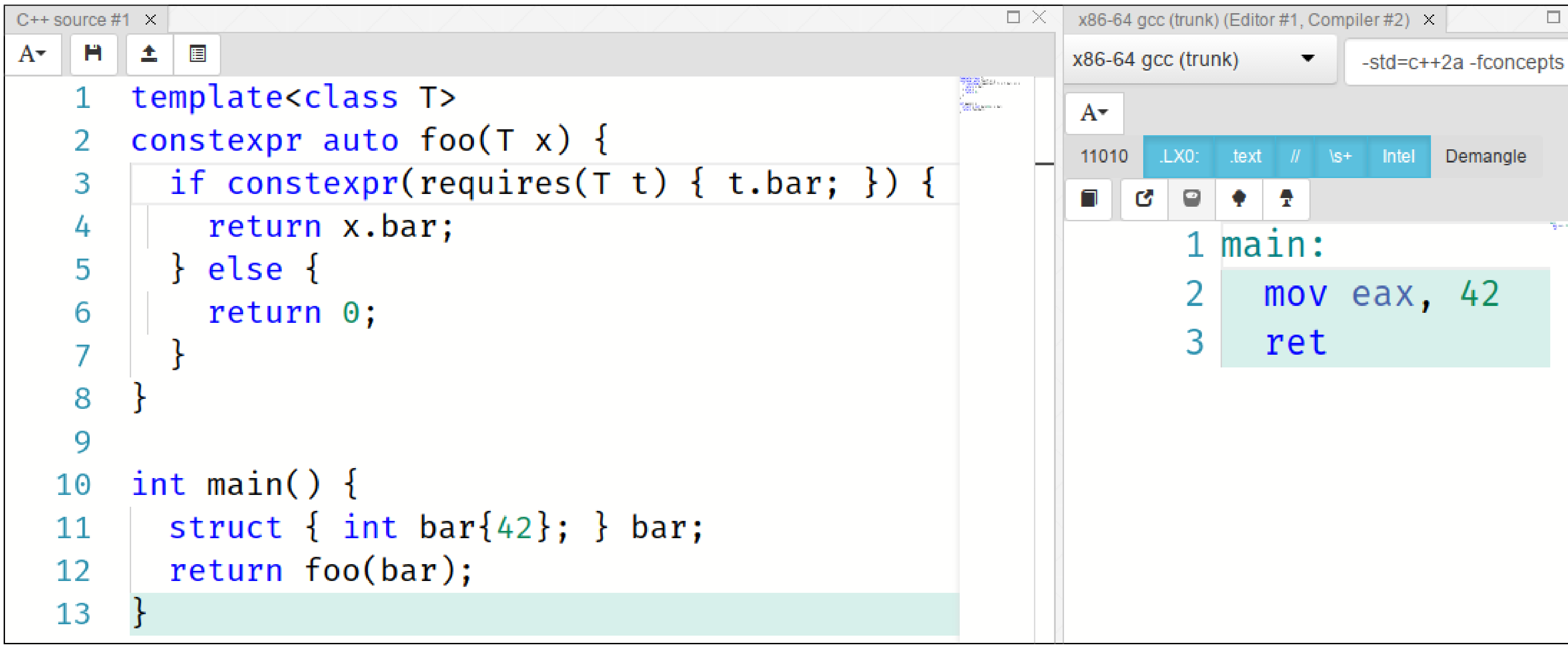
```cpp
template<class T>
constexpr auto foo(T x) {
  if constexpr(requires(T t) { t.bar; }) { // compile-
    return x.bar;                          // time if
  } else {
    return 0;
  }
}

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

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

https://godbolt.org/g/uot6Bv

Design by introspection - C++



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 satisified
```

```
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	`auto`
Constrained	`concept-name<[template-argument-list]>`

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

```
// auto - least constrained concept
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
`a == b`	convertible to `bool`	`==` is an equivalence relation, that is, it has the following properties: — For all `a`, `a == a`. — If `a == b`, then `b == a`. — If `a == b` and `b == c`, then `a == c`.

```
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)

> Substituation 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)
Flexiblity	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

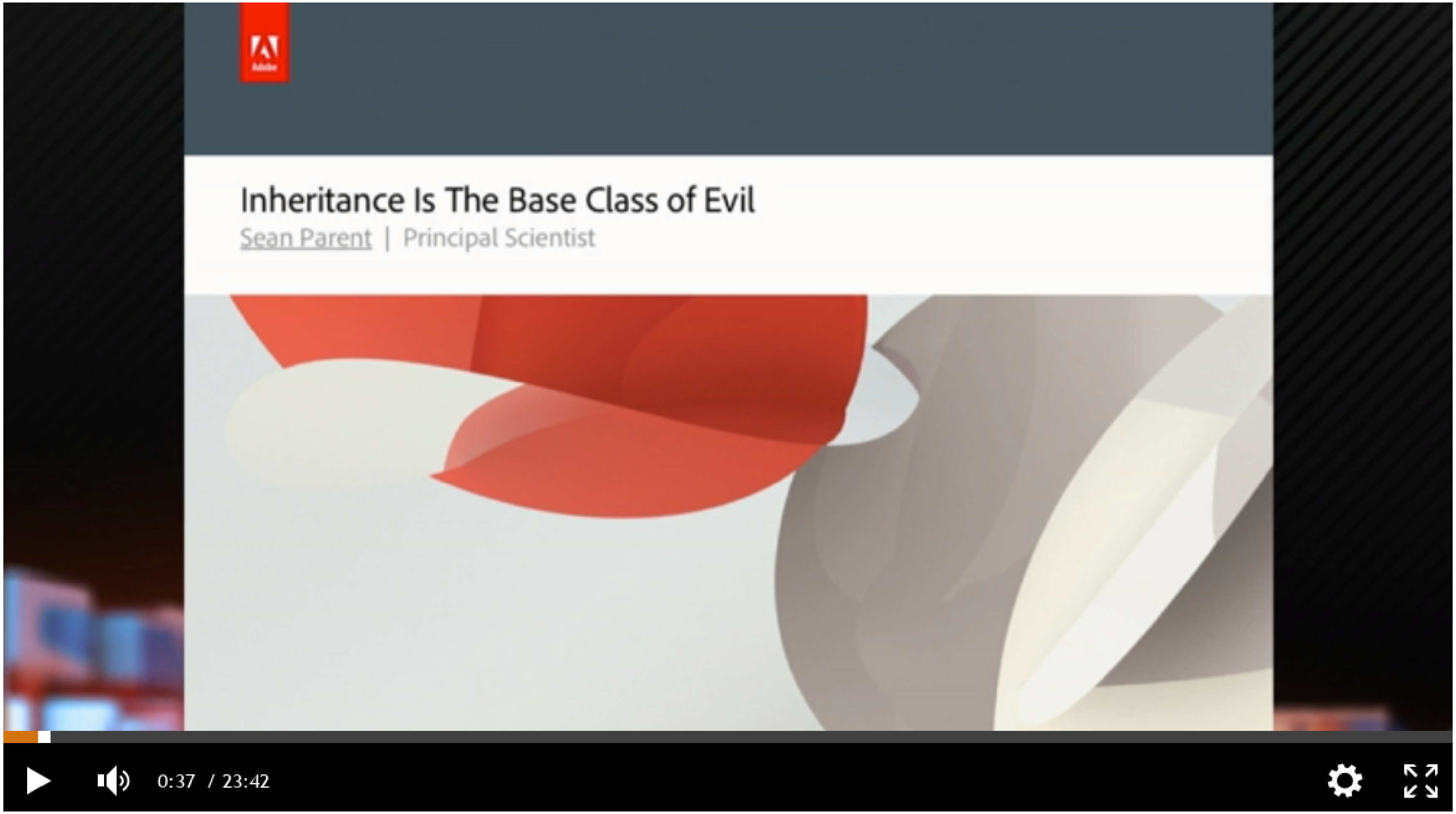
```
std::vector v1 = { Square{}, Circle{} };
 // ERROR: class template argument deduction failed

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

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>               template<class T>
any Foo                         $any { // metaclass
  auto foo() -> void;             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(decltype(args)... args)  ->
    decltype(self.name(args...)){} {
   // static polymorphism
   return static_cast<decltype(t) *>(this)->template
     call<name, typename decltype(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