Meeting C++ 2017

Concepts Driven Design

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Overview

- **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

> This talk is from user perspective
> See Andrew Sutton talks for more details about concepts!

> 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...	-

> Examples in this talk were compiled using
> `g++7.2 -std=c++2a -fconcepts`

Motivation - Well specified interfaces

```
template<class T>
const T& min(const T& a, const T& b) {
  return b < a ? b : a;
}
```

> Precise documentation

> - What's are the syntax requirements for `T`?
>   - compile-time / ***concepts***

> - What's are the semantics requirements for `min`?
>   - run-time / contracts, tests, manuals

Motivation - Compiler diagnostics

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

https://godbolt.org/g/RTRgg2

Motivation - Compiler diagnostics

> Without concepts

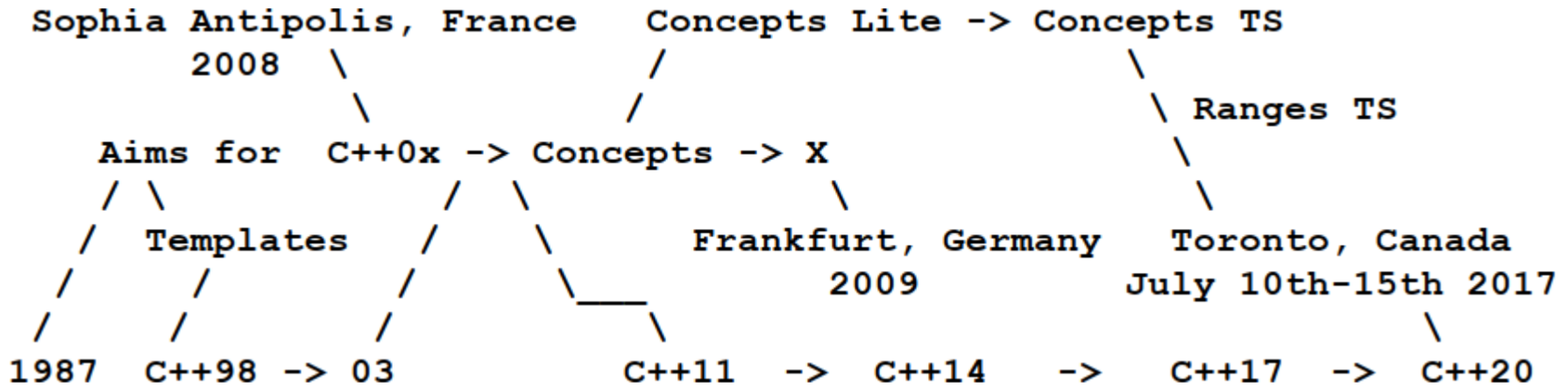
```
 invalid operands to binary expression
   ('std::_List_iterator<int>' and
    'std::_List_iterator<int>')
 std::__lg(__last - __first) * 2);
           ~~~~~~ ^ ~~~~~~~
...many lines of templates instantiation call stack...
```

> With concepts

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

> Note: Constraints are checked at the point of use

History



Requirements analysis	https://wg21.link/n3351
Concepts Lite	https://wg21.link/n3701
Concepts TS	https://wg21.link/P0734R0

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

C++20 draft

> Requirements
> Constraints
> Named concepts

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

Requirements

Requires-clause

> Specifies constraints on template arguments or on a function declaration
>
> `std::enable_if` on steroids

```
template<class> requires false
void foo() {}
```

```
foo<class AnyType>(); // Error: constraints not satisfied
```

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

```
bar<true>();  // Okay
bar<false>(); // Error: constraints not satisfied
```

> Note: requires-clause is part of the function signature

Requires-expression

> 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; }; // convertible to bool
```

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

> Note: Parameters -> `declvals`

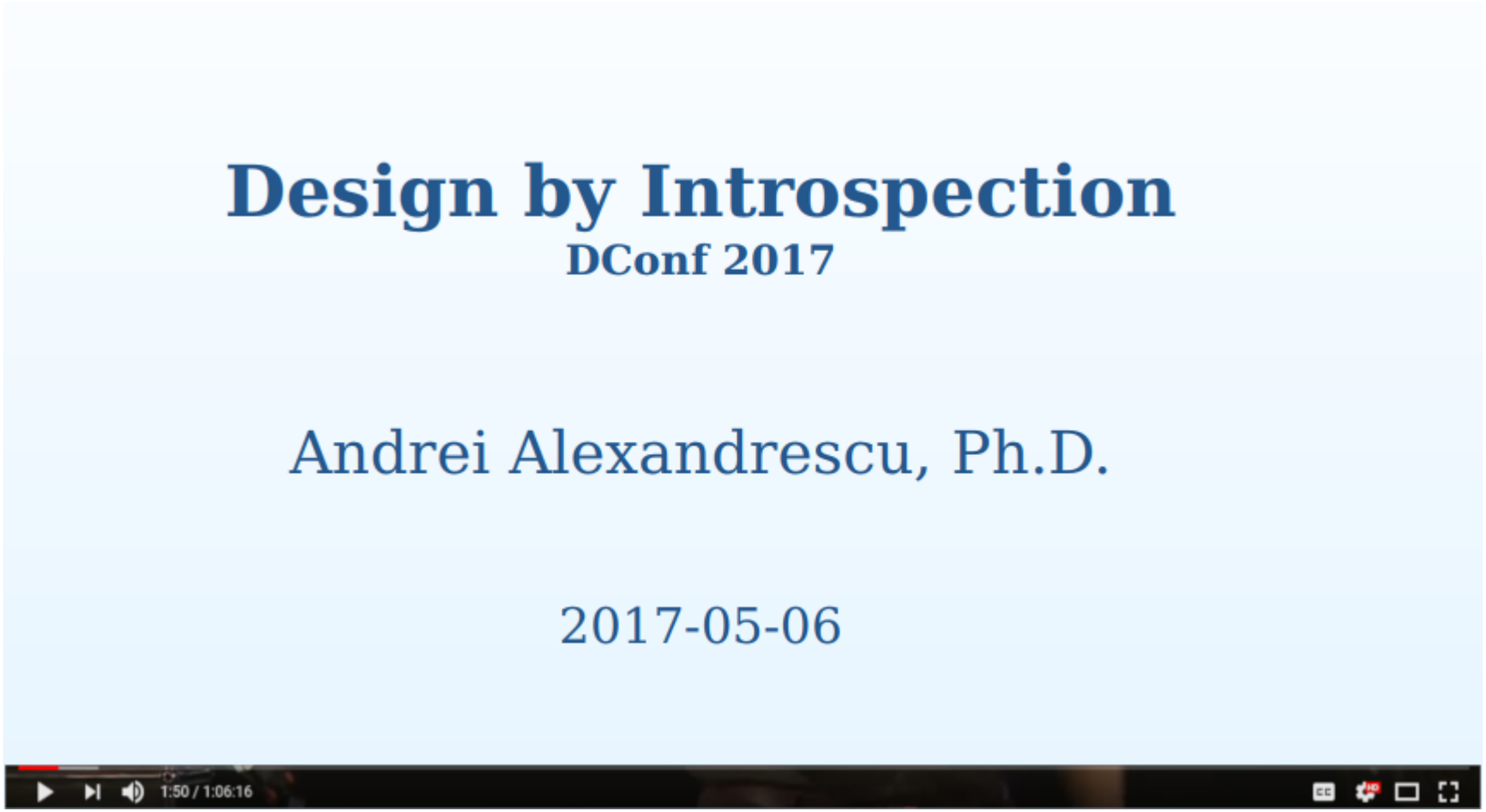
Requires-clause/Requires-expression

```
template<class T>
constexpr auto foo(T&& x) // immediate context (SFINAE friendly)
  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

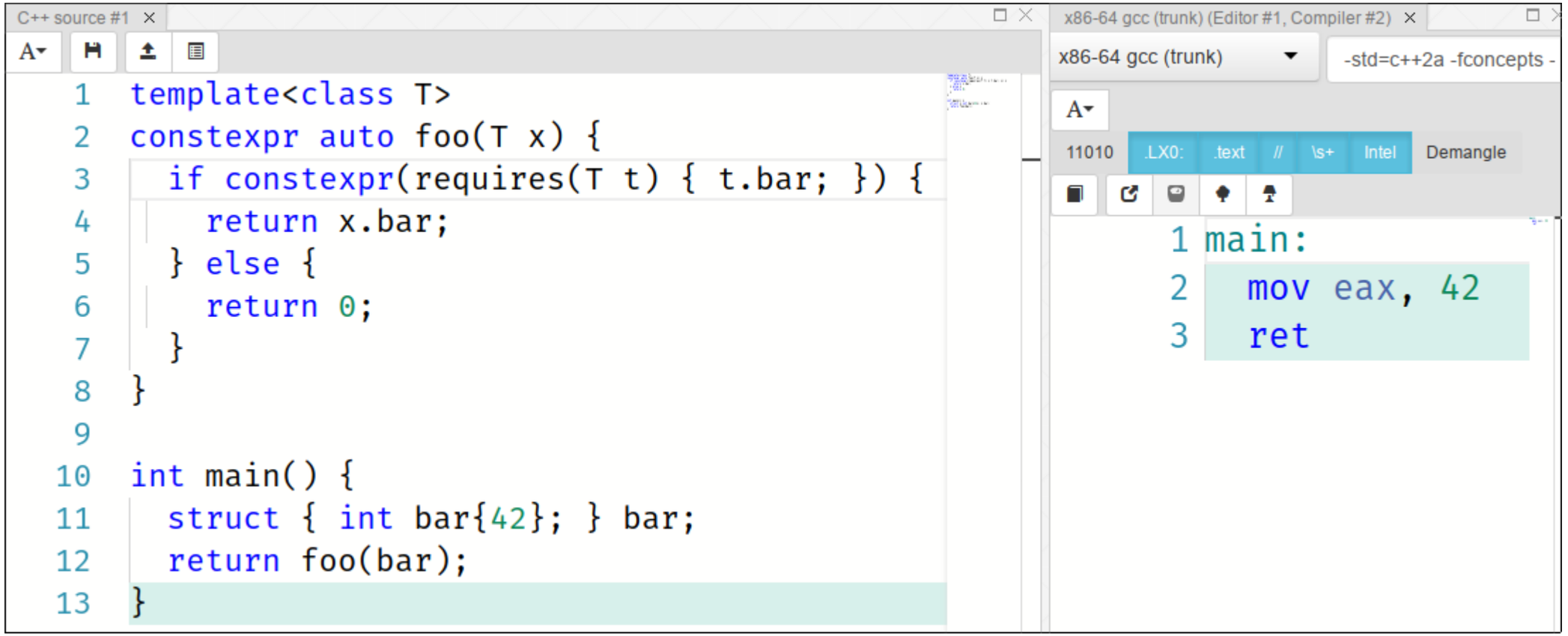
```
template<class T>
constexpr auto foo(T x) {
  if constexpr(requires(T t) { t.bar; }) { // immediate context
    return x.bar;
  } else {
    return 0;
  }
}

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

Requirements

> Readability?

```
template<class T>
auto bar(T& t)
  requires requires(T t) {
    typename T::type;
    { t.foo() } -> void;
    requires Movable<T> or Same<T, int>;
  } {
  return foo(t);
}
```

Named concepts

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_v<T> and std::is_signed_v<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>;
  };
```

> Note: Concepts are never instantiatied
>
> (therefore the `concept` keyword)

Named concepts

> Unconstrained class definition

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

> Requires expression (long form)

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

> Abbreviated templates

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

> 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); };
```

```
template<class T> void forward(T& t, std::string_view data) {
  t.???(data); // send/write
}
```

> 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
}
```

> Note: If multiple are satisifed the most constrainted is chosen

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 : Inheritance / 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 in the C++ ISO standard

> 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 {}; // no type alias

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)

> `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)

> 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)

> 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
}
```

> Note: Default template pramaters aren't part of the function signature (no SFINAE)

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
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

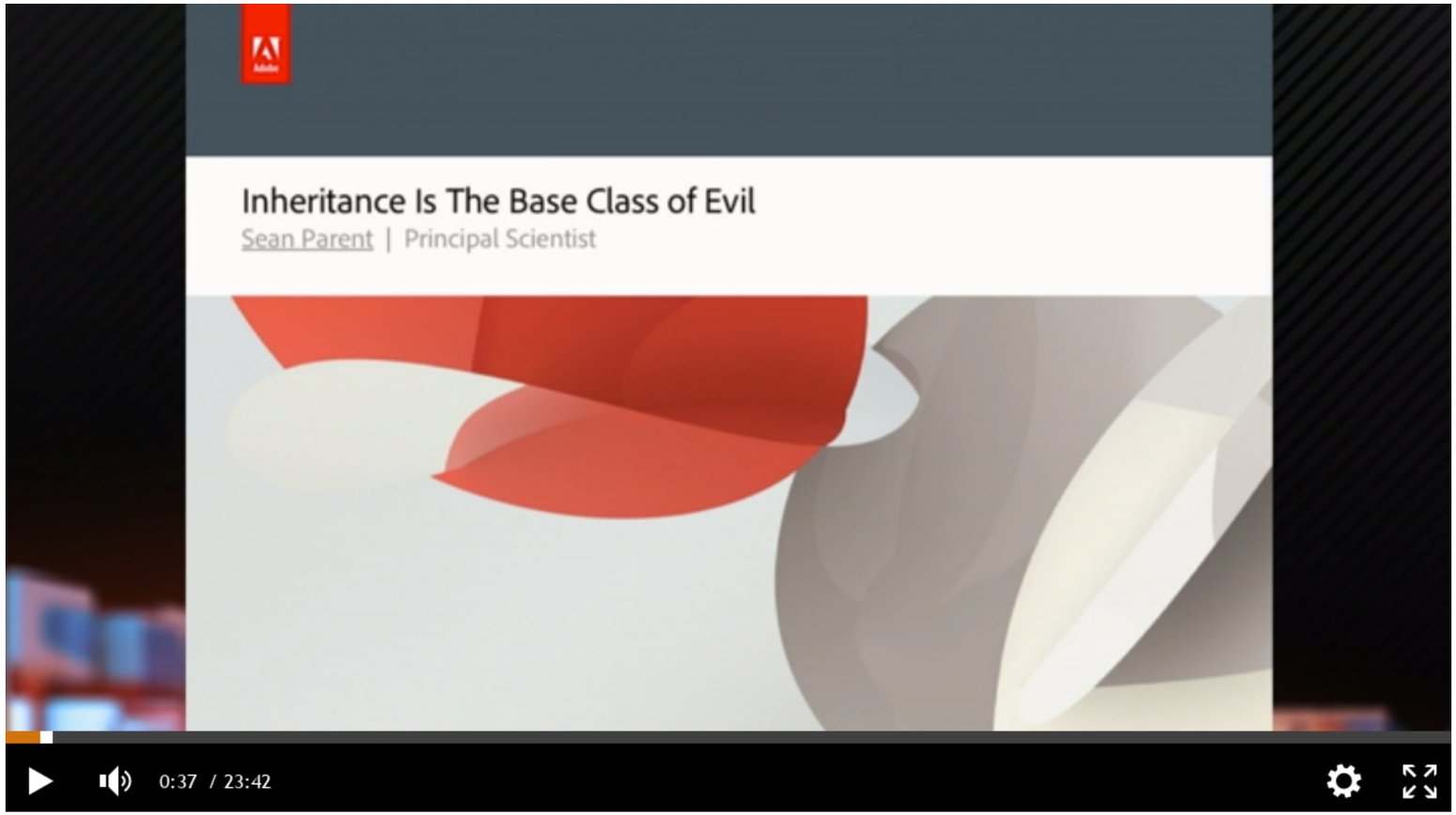
```
std::vector v1 = { Square{}, Circle{} };
 // ERROR: class template argument deduction failed

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 / type erasure

```
class Drawable {
  void* ptr_{}; // ??? Small Buffer Optimization (SBO)
  struct {
    void (*draw)(void*, std::ostream&);
    void (*delete_ptr)(void*);
  } const vptr_{}; // ??? Usually a pointer

public:
 template<class T> Drawable(T t) // non explicit
  : ptr_{new T{t}}, vptr_{
      [](void* self, std::ostream& os) { static_cast<T*>(self)->draw(os); },
      [](void* self) { delete static_cast<T*>(self); }
    } { }
 ~Drawable() { vptr_.delete_ptr(ptr_); }

 void draw(std::ostream& os) { vptr_.draw(ptr_, os); }
};
```

Concepts based design

> Dynamic polymorphism / type erasure

```
void f(Drawable d) { d.draw(std::cout); }

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

Concepts based design

> Dynamic polymorphism / Virtual concepts (C++2?) - Dynamic Generic Programming with Virtual Concepts

```
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?)

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

> No inheritance
>
> No heap
>
> 100% value semantics
>
> Might be inlined (Small buffer optimization - SBO)

Concepts based design

> Dynamic polymorphism / Metaclasses (C++2?) - https://wg21.link/p0707r0

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

```
$class any { // type-erasure metaclass
  void* ptr_{};
  struct {
    constexpr {
      void (*delete_ptr)(void*);
      for... (const auto f: $any.functions()) {
        -> {
          f.ret_type() (*f.name())(void*, f.args());
        }
      }
    }
  } const vptr_{};
  ...
};
```

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 (CRTP)
   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> // inject
struct App {
  TPolicy policy{};
  void run() { if (...) { policy.onError("error!"); } }
};
```

> Bindings / Injection

```
Creatable injector = di::injector{
  di::bind<class Policy>.to<ThrowPolicy>()
};
injector.create<App>().run();
```

> Same as...

```
App{ThrowPolicy{}}.run();
```

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?)`

```
Creatable injector = di::make_injector(
  di::bind<virtual ErrorPolicy>.to<LogPolicy>()
);
injector.create<App>().run();
```

> Same as...

```
App{LogPolicy{}}.run();
```

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

Concepts based design

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

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

```
struct App {
  any<$(ErrorPolicy)> policy{};
  void run() { if (...) { policy.onError("error!"); } }
};
```

Concepts based design

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

```
Creatable injector = di::make_injector(
  di::bind<$(ErrorPolicy)>.to<LogPolicy>()
);
injector.create<App>().run();
```

> Same as...

```
App{LogPolicy{}}.run();
```

> Note: Same wiring for static/dynamic 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);
```

> long form

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

> longer form

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

Future of concepts (C++2X)

> Terse template syntax - https://wg21.link/p0696r1

```
void forward(Socket, Socket);
```

> long form

```
template<class T> void forward(T, T);
```

> **vs**

```
void forward(auto, auto);
```

> long form

```
template<class T, class U> void forward(T, U);
```

Future of concepts (C++2X)

> Template-introduction syntax

```
Socket{T} void forward(T, auto);
```

> **or**

```
template<Socket [T]> void forward(T, auto);
```

> long form

```
template<class T, class U> void forward(T, U) requires Socket<T>;
```

Future of concepts (C++2X)

```
template<class T>
struct tcp_socket {
  static_assert(Socket<tcp_socket>); // always fail, tcp_socket is incomplete
};
```

> Metaclasses syntax

```
template<class T> Socket tcp_socket { };
```

https://wg21.link/p0707r0

Summary

> Provides better diagnostics

> Simplify usage of SFINAE / enable_if
>
> - Introspection by design / Optional interfaces

> Well specified interfaces (precised documentation)

> 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?

C++20 draft	http://eel.is/c++draft/temp.constr
Concepts	https://wg21.link/P0734R0
Virtual Concepts	https://github.com/andyprowl/virtual-concepts/blob/master/draft/Dynamic Generic Programming with Virtual Concepts.pdf