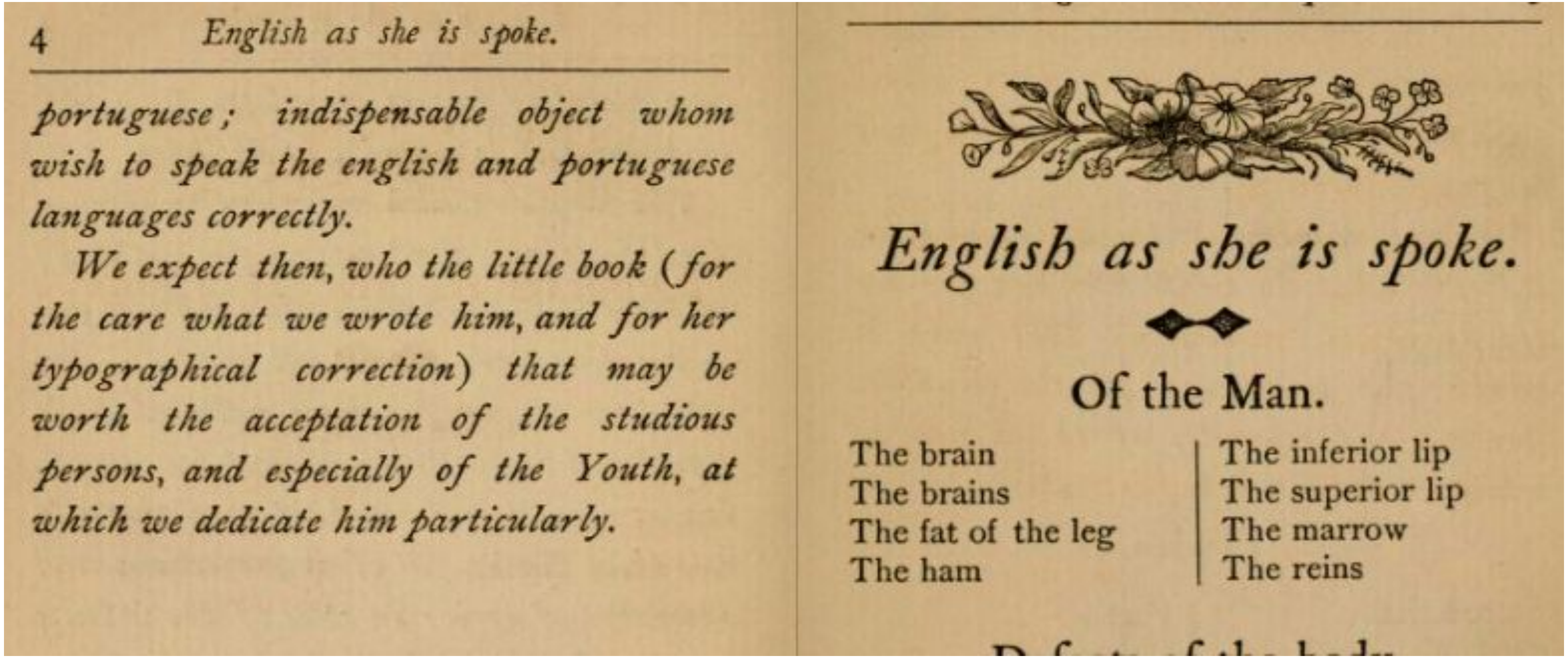
Concepts as she is spoke

Concepts in the C++2a Working Draft

Arthur O'Dwyer
2018-09-27

What’s with the title?



4 *English as she is spoke.*

portuguese; indispensable object whom wish to speak the english and portuguese languages correctly.

We expect then, who the little book (for the care what we wrote him, and for her typographical correction) that may be worth the acceptation of the studious persons, and especially of the Youth, at which we dedicate him particularly.

English as she is spoke.

Of the Man.

The brain	The inferior lip
The brains	The superior lip
The fat of the leg	The marrow
The ham	The reins

https://publicdomainreview.org/collections/english-as-she-is-spoke-1884/

What’s with the title?

Apprêndi ô francêz.	*I have learned the french language.*
Dôe-me à cabêça.	*My head is sick.*
Não tênho têmpo.	*I have no time.*
Não pósso demorár-me.	*I cannot to stayme.*
Conhêço-o dê vísta.	*I know him by sight.*
Tênho dê *ôu* dêvo sahír.	*I have to go out.*
Tênho dê *ôu* dêvo recebêr dinhêiro nô fím dô mêz.	*I have any money to receive at last month.*
Dár-vôs-hêi *ôu* dár-lhê-hêi ó sêu endc-rêço.	*I will give you on's adress.*
Refíro-me âo què dizèis *ôu* díz.	*I report me at this you tell me.*
Não sôu tôlo.	*I am not to silly.*
Não entêndo *ôu* intendo isso.	*I not understand that*

https://books.google.com/books?id=lUd5AAAAIAAJ&pg=PA75

Outline

- Why requires-clauses? [9–17]
    - What's a concept anyway?
    - What's wrong with good old-fashioned `enable_if`?
- The *requires-expression* as she is spoke [18–24]
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- The *requires-clause* as she is spoke [57–73]
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Hey look!
Slide numbers!

What's the state of Concepts?

There's the "Concepts Technical Specification (Concepts TS)," and then there's the part of it that has been merged into the C++2a working draft.

GCC supports (almost all of) Concepts TS.

```
g++ -std=c++2a -fconcepts -Dconcept="concept bool" test.cc
```

Saar Raz's fork of Clang supports (almost all of) C++2a Concepts.

```
clang++* -std=c++2a test.cc
```

MSVC 2018 can kinda parse Concepts TS syntax but basically treats it as whitespace; it doesn't "support" Concepts in any meaningful sense.

```
cl -std:c++latest -experimental:concepts test.cc
```

https://godbolt.org

What’s the state of Concepts?

	Concepts TS	g++ -fconcepts	C++2a (so far)	clang++ (Saar Raz)	MSVC 2018 with -experimental:concepts
`template<class T> concept Foo = ...;`	N	N	Y	Y	N
`template<class T> concept bool Foo = ...;`	Y	Y	N	N	IGN
`template<class T> concept bool Foo() { return ...; }`	Y	ICE	N	N	IGN
`template<int I> concept ...;`	Y	Y	Y	Y	IGN
`bool b = SomeConcept<int>;`	Y	Y	Y	Y	ICE
`template<class T> requires SomeConcept<T> void f();`	Y	Y	Y	Y	IGN
`template<SomeConcept T> void f();`	Y	Y	Y	Y	N
`void f(SomeConcept x); void f(auto x);`	Y	Y	N	N	N

What’s the state of Concepts?

This is a very silly diagram.

	Concepts TS	g++ -fconcepts	C++2a (so far)	clang++ (Saar Raz)	MSVC 2018 with -experimental:concepts
`template<class T> concept Foo = ...;`	N	N	Y	Y	N
`template<class T> concept bool Foo = ...;`	Y	Y	N	N	IGN
`template<class T> concept bool Foo() { return ...; }`	Y	ICE	N	N	IGN
`template<int I> concept ...;`	Y	Y	Y	Y	IGN
`bool b = SomeConcept<int>;`	Y	Y	Y	Y	ICE
`template<class T> requires SomeConcept<T> void f();`	Y	Y	Y	Y	IGN
`template<SomeConcept T> void f();`	Y	Y	Y	Y	N
`void f(SomeConcept x); void f(auto x);`	Y	Y	N	N	N

What is a *concept*, anyway?

```
template<class T>
std::string stringify(const T& t) {
    std::ostringstream oss;
    oss << t;
    return std::move(oss).str();
}
```

What *kinds* of arguments can we pass to this function?

- “Anything with an << operator”
- Just that one requirement? Probably doesn’t need Concepts.

What is a *concept*, anyway?

```
template<class Body>
struct http_request {
    int version;
    string method, target;
    map<string, string> fields;
    Body::value_type body;

    void read(istream& is) {
        read_header(is, *this);
        Body::read(is, this->body);
    }
    void write(ostream& os) const {
        write_header(os, *this);
        Body::write(os, this->body);
    }
};
```

This example comes from
Vinnie Falco's CppCon 2017 session
"Make Classes Great Again"
https://youtu.be/WsUnnYEKPnI

What is a *concept*, anyway?

```
template<class Body>
struct http_request {
    int version;
    string method, target;
    map<string, string> fields;
    Body::value_type body;

    void read(istream& is) {
        read_header(is, *this);
        Body::read(is, this->body);
    }
    void write(ostream& os) const {
        write_header(os, *this);
        Body::write(os, this->body);
    }
};
```

Many requirements:

- `Body::value_type`
- `Body::read`
- `Body::write`

Let's also say we want to prevent callers from using `http_request` with a "half-implemented" Body type. Implementing `Body::write()` but not `Body::read()`, for example. Let's forbid that.

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Vinnie Falco's CppCon 2017 session
"Make Classes Great Again"
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Defining a concept (old-school)

```
template<class B, class = void> struct is_body : false_type;

template<class B>
struct is_body<B, void_t<
  typename B::value_type,
  decltype(
    B::read(declval<istream&>(), declval<typename B::value_type&>())
  ),
  decltype(
    B::write(declval<ostream&>(), declval<typename B::value_type const&>())
  )
>> : true_type {};

static_assert(is_body<file_body>::value);
static_assert(is_body<string_body>::value);
static_assert(not is_body<int>::value);
```

This example again comes from Vinnie Falco's CppCon 2017 session "Make Classes Great Again"
https://youtu.be/WsUnnYEKPnI

Defining a concept (C++2a)

```
template<class B>
concept Body = requires(
    istream& is,
    ostream& os,
    typename B::value_type& b,
    typename B::value_type const& cb)
{
    typename B::value_type;  // redundant
    B::read(is, b);
    B::write(is, cb);
};

static_assert(Body<file_body>);
static_assert(Body<string_body>);
static_assert(not Body<int>);
```

Asserting and SFINAEing (old-school)

```
template<class Body>
struct http_request {
    static_assert(is_body<Body>::value, "Body requirements are not satisfied");
};

template<class Body, class = enable_if_t<is_body<Body>::value>>
void do_something() { puts("yes"); }

template<class NonBody, class = enable_if_t<not is_body<NonBody>::value>>
void do_something() { puts("no"); }


do_something<file_body>();  // prints "yes"
do_something<int>();        // prints "no"
```

This `enable_if` prevents ambiguity during the overload resolution of `do_something<file_body>()`.

Asserting and SFINAEing (C++2a)

```
template<class B>
struct http_request {
    static_assert(Body<B>, "Body requirements are not satisfied");
};

template<class B> requires Body<B>
void do_something() { puts("yes"); }

template<class B>
void do_something() { puts("no"); }


do_something<file_body>();  // prints "yes"
do_something<int>();        // prints "no"
```

This template is "constrained."

This template is "unconstrained," and therefore a "less good" match during overload resolution.

Something else about the old way...

```
template<class Body, class = enable_if_t<is_body<Body>::value>>
void do_something() { puts("yes"); }
```

We’re basically abusing template parameters here — we have a template type *parameter* that is not being used to *parameterize!*
A caller who knows we’re doing this can “hijack” our implementation.

```
do_something<int>();             // correctly does not compile

do_something<int, char**>();  // prints "yes" (yikes!)
```

`requires` clauses aren't template parameters

```
template<class Body> requires is_body<Body>::value
void do_something() { puts("yes"); }
```

The constraint is properly relegated to a `requires` clause, which is not a template parameter and thus cannot be hijacked.

```
do_something<int>();            // correctly does not compile

do_something<int, char**>();  // also does not compile
```

Q: How do `requires`-clauses interact with name-mangling?

A: They don't. (Yet.)

requires doesn't affect mangling*

```
template<class T, class = enable_if_t<is_integral_v<T>>>
T foo(T t) { return t + 1; }

template int foo<int>(int);          // _Z3fooIivET_S0_
template short foo<short>(short);    // _Z3fooIsvET_S0_
template float foo<float>(float);    // does not compile
```

} old-school enable_if

```
template<class T> requires is_integral_v<T>
T bar(T t) { return t + 1; }

template int bar<int>(int);          // _Z3barIiET_S0_
template short bar<short>(short);    // _Z3barIsET_S0_
template float bar<float>(float);    // does not compile
```

} new-school requires

requires doesn't affect mangling*

```
template<class T, enable_if_t<is_integral_v<T>, int> = 0>
T foo(T t) { return t + 1; }
template<class T, enable_if_t<not is_integral_v<T>, int> = 0>
T foo(T t) { return t + 2; }

template int foo<int>(int);           // _Z3fooIiLi0EET_S0_
template short foo<short>(short);     // _Z3fooIsLi0EET_S0_
template float foo<float>(float);     // _Z3fooIfLi0EET_S0_
```

old-school
enable_if

```
template<class T> requires is_integral_v<T>
T bar(T t) { return t + 1; }
template<class T> requires not is_integral_v<T>
T bar(T t) { return t + 2; }

template int bar<int>(int);           // _Z3barIiET_S0_
template short bar<short>(short);     // _Z3barIsET_S0_
template float bar<float>(float);     // _Z3barIfET_S0_
```

new-school
requires

Duplicate function templates are OK

We need a uniquely mangled name for each ***template function***, but not necessarily for each ***function template***.

```
template<class T> requires is_integral_v<T>
T bar(T t) { return t + 1; }                       // "A"

template<class T>  // unconstrained
T bar(T t) { return t + 2; }                       // "B"

template int bar<int>(int);             // _Z3barIiET_S0_ specializes template "A"
template short bar<short>(short);       // _Z3barIsET_S0_ specializes template "A"
template float bar<float>(float);       // _Z3barIfET_S0_ specializes template "B"
```

Different story with class templates

A constraint on a class, variable, or alias template is forever.
But you can place different constraints on different partial specializations.

```
template<class T>
class Widget { ... };

template<class U> requires is_pointer_v<U>
class Widget { ... };      // Error: redefinition of class template "Widget"

template<class V> requires is_pointer_v<V>
class Widget<V> { ... };      // OK: constrained partial specialization
```

GCC doesn't fully support constrained alias templates.

Remember this old-school trap?

Recall a trap I discussed in “Template Normal Programming, Part 1.”

```
template<class T>
T baz(T t) { return t + 1; }                        // "A"

template<>
int *baz(int *t) { return t + 2; }   // _Z3bazIPiET_S1_ specializes template "A"

template<class T>  // "better match"
T *baz(T *t) { return t + 3; }                      // "B"
```

At this point, if we call `baz(&i)`, overload resolution will consider two candidates:

- the template function `baz<int*>(int*)` that could be instantiated from template "A"
- the template function `baz<int>(int*)` that could be instantiated from template "B"

"B" is a better match than "A".
So the compiler uses template "B" to instantiate `baz<int>(int*)` a.k.a. `_Z3bazIiEPT_S1_` ...
and our explicitly specialized `baz<int*>(int*)` a.k.a. `_Z3bazIPiET_S1_` is never called!

With `requires`, the stakes are higher*

```
template<class T>
T baz(T t) { return t + 1; }                // "A"

template<>
int *baz(int *t) { return t + 2; }   // _Z3bazIPiET_S1_ specializes template "A"

template<class T> requires is_pointer_v<T>   // "better match"
T baz(T t) { return t + 3; }                // "B"
```

At this point, if we call `baz(&i)`, overload resolution will consider two candidates:

- the template function `baz<int*>(int*)` that could be instantiated from template "A"
- the template function `baz<int*>(int*)` that could be instantiated from template "B"

"B" is a better match than "A", because "B" is constrained and "A" is not.
So the compiler uses template "B" to instantiate `baz<int*>(int*)` a.k.a. `_Z3bazIPiET_S1_` ...
which has exactly the same mangled name as our explicitly specialized `baz<int*>(int*)` a.k.a. `_Z3bazIPiET_S1_`! This is a violation of the One Definition Rule, and causes undefined behavior.

Two distinct “better match” criteria

```
template<class T>
T foo(T t) { return t + 1; }                      // "A"

template<class T> requires is_pointer_v<T>
T foo(T t) { return t + 2; }                      // "B"

template<class T>
T *foo(T *t) { return t + 3; }                    // "C"
```

When we call `foo(&i)`,

- "C" is a better match than "A" because its function parameter list is more highly specialized.
- "C" is a better match than "B" because its function parameter list is more highly specialized.
- "B" is a better match than "A" because it is more constrained.

Two distinct “better match” criteria

```
template<class T>
T foo(T t) { return t + 1; }                       // "A"

template<class T> requires is_pointer_v<T>
T foo(T t) { return t + 2; }                       // "B"

template<class T>
T *foo(T *t) { return t + 3; }                     // "C"
```

The old-school rule has highest priority! Look first at the parameter list; ***then*** (and only then) consider the `requires` clause.

When we call `foo(&i)`,

- "C" is a better match than "A" because its function parameter list is more highly specialized.
- "C" is a better match than "B" because its function parameter list is more highly specialized.
- "B" is a better match than "A" because it is more constrained.

What is “more constrained” exactly?

```
template<class T>
T foo(T t) { return t + 1; }                    // "A"

template<class T> requires is_integral_v<T>
T foo(T t) { return t + 2; }                    // "B"
```

- "B" is a better match than "A" because it is more constrained.

What is “more constrained” exactly?

```
template<class T>
T foo(T t) { return t + 1; }                    // "A"

template<class T> requires is_integral_v<T>
T foo(T t) { return t + 2; }                    // "B"
```

- "B" is a better match than "A" because it is more constrained.

```
template<class T> requires (sizeof(T) == 4)
T foo(T t) { return t + 3; }                    // "C"
```

- Intuitively, neither "B" nor "C" is “more constrained” than the other.

What is “more constrained” exactly?

```
template<class T>
T foo(T t) { return t + 1; }                    // "A"

template<class T> requires is_integral_v<T>
T foo(T t) { return t + 2; }                    // "B"
```

- "B" is a better match than "A" because it is more constrained.

```
template<class T> requires (sizeof(T) == 4)
T foo(T t) { return t + 3; }                    // "C"
```

- Intuitively, neither "B" nor "C" is “more constrained” than the other.

```
template<class T> requires (sizeof(T) != 0)
T foo(T t) { return t + 4; }                    // "D"
```

??

What is “more constrained” exactly?

```
template<class T>
T foo(T t) { return t + 1; }                    // "A"

template<class T> requires is_integral_v<T>
T foo(T t) { return t + 2; }                    // "B"
```

- "B" is a better match than "A" because it is more constrained.

```
template<class T> requires (sizeof(T) == 4)
T foo(T t) { return t + 3; }                    // "C"
```

- Intuitively, neither "B" nor "C" is “more constrained” than the other.

```
template<class T> requires (sizeof(T) != 0)
T foo(T t) { return t + 4; }                    // "D"
```

- Logically "D" is less constrained than "C", but we don’t seriously expect the compiler to realize that. So intuitively it makes sense that all of "B", "C", and "D" are *equally much* constrained.

What is “more constrained” exactly?

So do we only have two levels — “constrained” and “unconstrained”?
Let’s try some things we think the compiler might be able to figure out.

```
template<class T> requires is_integral_v<T>
T foo(T t) { return t + 6; }                    // "F"

template<class T> requires is_integral_v<T> && is_signed_v<T>
T foo(T t) { return t + 7; }                    // "G"

int x = foo(0);
```

What do we expect to happen here? Will the compiler pick "G", or say there’s an ambiguity?

https://concepts.godbolt.org/z/eIXttk

What is "more constrained" exactly?

So do we only have two levels — "constrained" and "unconstrained"?
Let's try some things we think the compiler might be able to figure out.

```
template<class T> requires is_integral_v<T>
T foo(T t) { return t + 6; }                    // "F"

template<class T> requires is_integral_v<T> && is_signed_v<T>
T foo(T t) { return t + 7; }                    // "G"

int x = foo(0);
```

Trick question! The Concepts TS (GCC) is actually happy with this. But the C++2a version of Concepts (Clang) says "no":

```
<source>:12:9: error: call to 'foo' is ambiguous
int x = foo(0);
        ^~~
```

https://concepts.godbolt.org/z/YLqK-S

What is “more constrained” exactly?

CONCEPTS ALERT!

```
template<class T>
concept Integral = is_integral_v<T>;

template<class T> requires Integral<T>
T foo(T t) { return t + 10; }                   // "J"

template<class T> requires Integral<T> && is_signed_v<T>
T foo(T t) { return t + 11; }                   // "K"

int x = foo(0);
```

What do we expect to happen **here**? Will the compiler pick "K", or say there’s an ambiguity?

https://concepts.godbolt.org/z/YLqK-S

What is “more constrained” exactly?

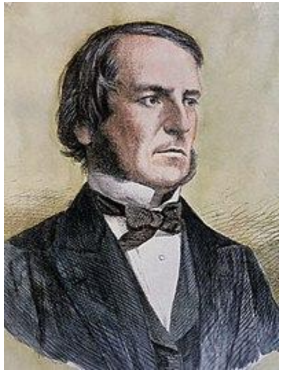
```
template<class T>
concept Integral = is_integral_v<T>;

template<class T> requires Integral<T>
T foo(T t) { return t + 10; }                    // "J"

template<class T> requires Integral<T> && is_signed_v<T>
T foo(T t) { return t + 11; }                    // "K"

int x = foo(0);
```

CONCEPTS ALERT!

The compiler picks "K"!

Subsumption

Constraints are logical formulas!



requires-clause :

`requires` *constraint-logical-or-expression*

constraint-logical-or-expression :

constraint-logical-and-expression

constraint-logical-or-expression `||` *constraint-logical-and-expression*

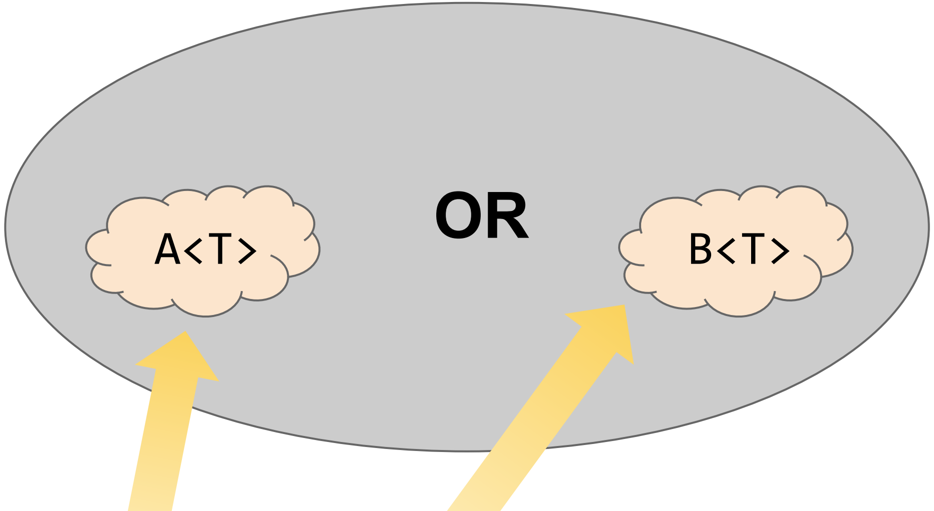
constraint-logical-and-expression :

primary-expression

constraint-logical-and-expression && *primary-expression*

Both Clang and GCC accept *inclusive-or-expression* where the wording currently says "*primary-expression*." I expect the wording to catch up soon.

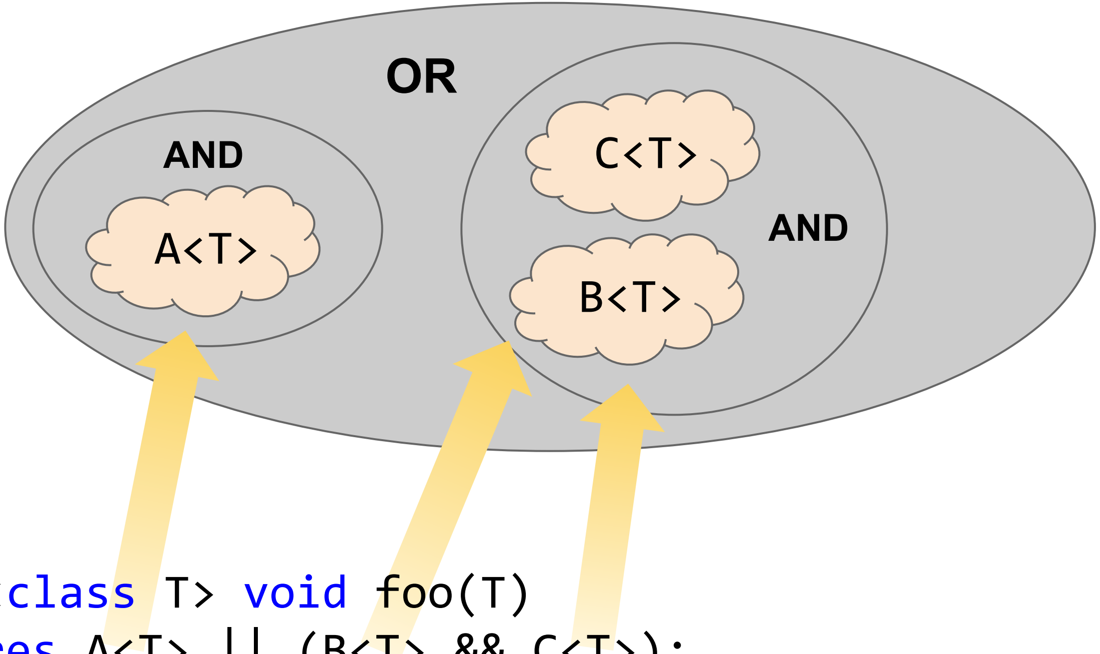
Normalization and normal form



This cloudy Platonic diagram is called the constraint's "normal form." It is a mathematical construct, not a C++ source code construct.

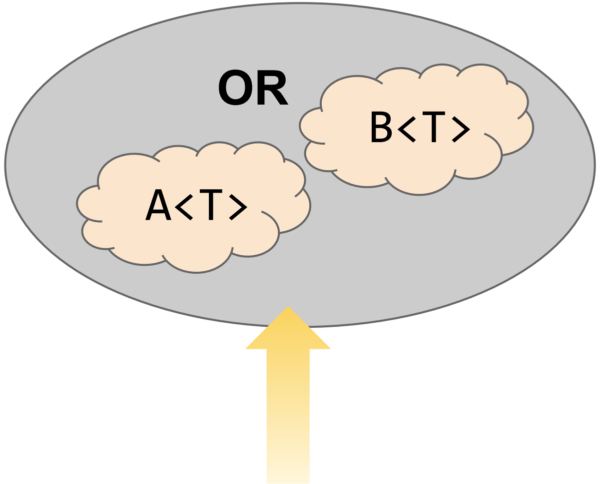
```
template<class T> void foo(T)
    requires A<T> || B<T>;
```

Normalization and normal form




```
template<class T> void foo(T)
   requires A<T> || (B<T> && C<T>);
```

Logical operations are commutative




```
template<class T> void foo(T)
   requires A<T> || B<T>;
template<class T> void foo(T)
   requires B<T> || A<T>;
```

These two requires-clauses have exactly the same *normal form*.

Non-atomic concepts

```
template<class T> concept AB =
    A<T> && B<T>;
```

Non-atomic concepts

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template<class T> concept AB =
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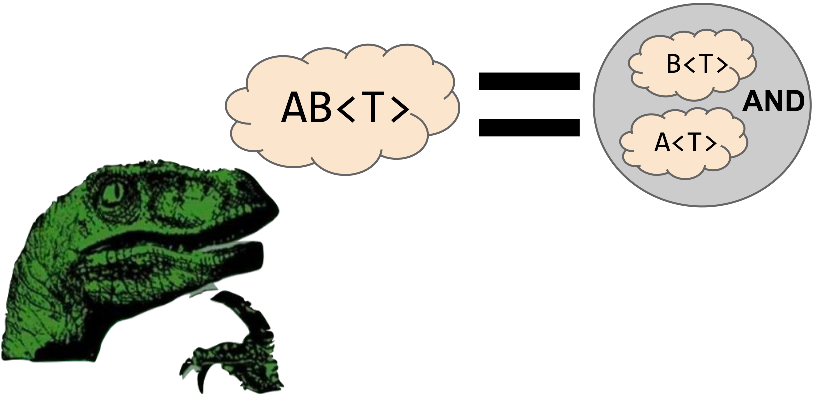
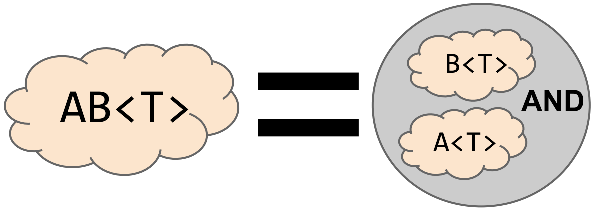
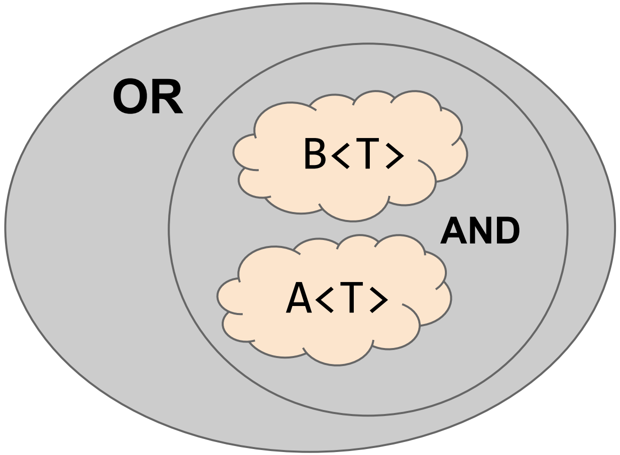


Non-atomic concepts

```
template<class T> concept AB =
   A<T> && B<T>;
```






```
template<class T> void foo(T)
   requires AB<T>;
template<class T> void foo(T)
   requires B<T> && A<T>;
```

These two requires-clauses have exactly the same *normal form*.

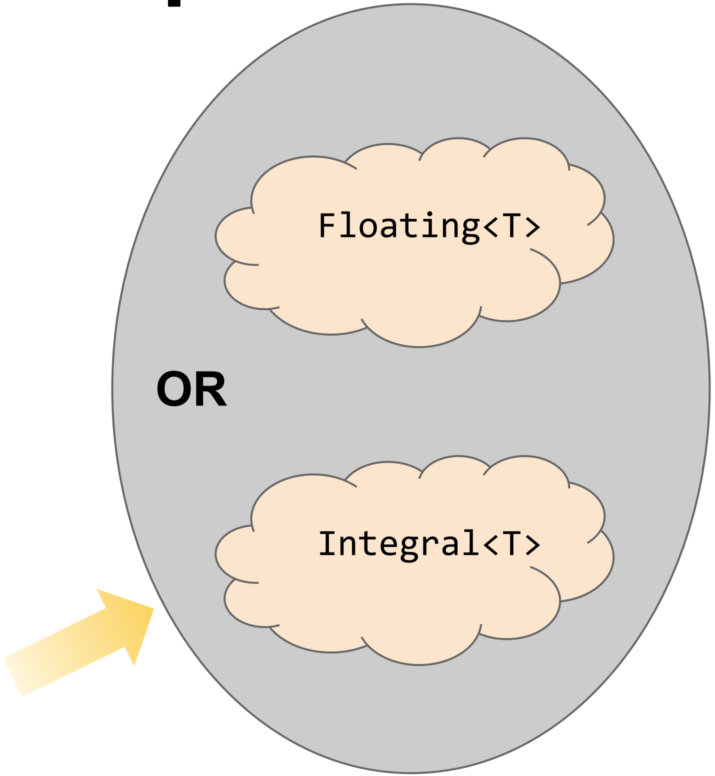
We always bottom out at expressions

```
template<class T> concept Scalar =
    is_scalar_v<T>;

template<class T> concept Integral =
    Scalar<T> && is_integral_v<T>;

template<class T> concept Floating =
    Scalar<T> && is_floating_point_v<T>;

template<class T> void foo(T)
    requires Integral<T> || Floating<T>;
```



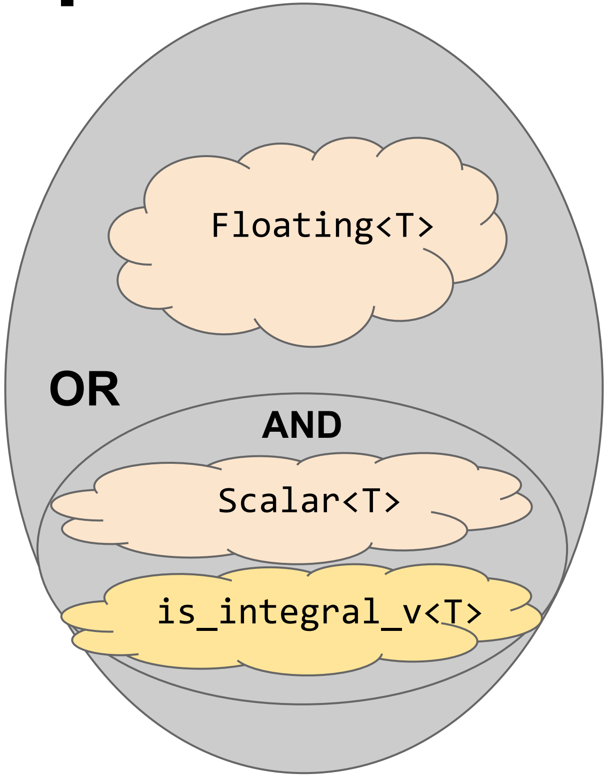
We always bottom out at expressions

```
template<class T> concept Scalar =
    is_scalar_v<T>;

template<class T> concept Integral =
    Scalar<T> && is_integral_v<T>;

template<class T> concept Floating =
    Scalar<T> && is_floating_point_v<T>;

template<class T> void foo(T)
    requires Integral<T> || Floating<T>;
```



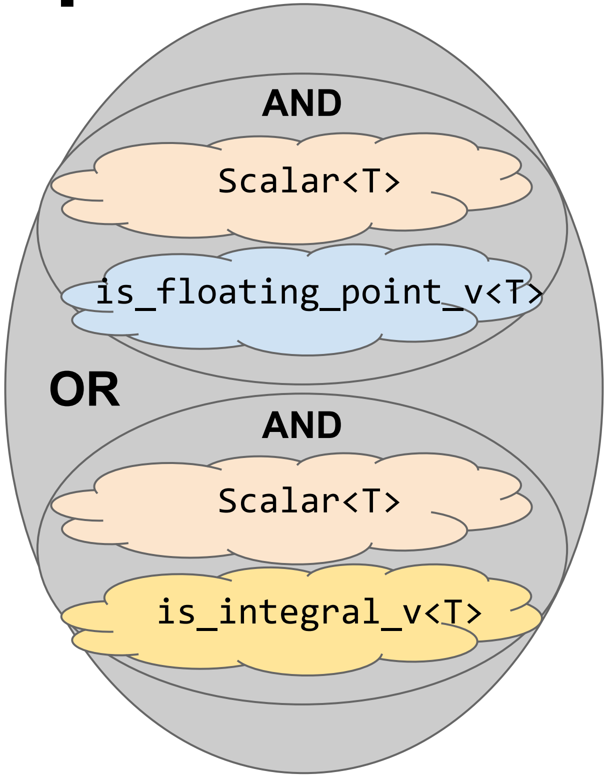
We always bottom out at expressions

```
template<class T> concept Scalar =
    is_scalar_v<T>;

template<class T> concept Integral =
    Scalar<T> && is_integral_v<T>;

template<class T> concept Floating =
    Scalar<T> && is_floating_point_v<T>;

template<class T> void foo(T)
    requires Integral<T> || Floating<T>;
```



We always bottom out at expressions

```
template<class T> concept Scalar =
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    Scalar<T> && is_floating_point_v<T>;

template<class T> void foo(T)
    requires Integral<T> || Floating<T>;
```
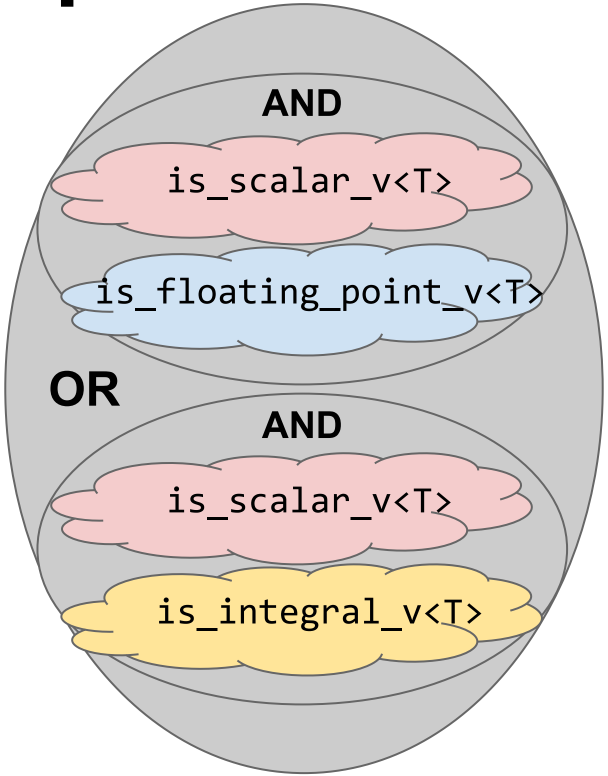
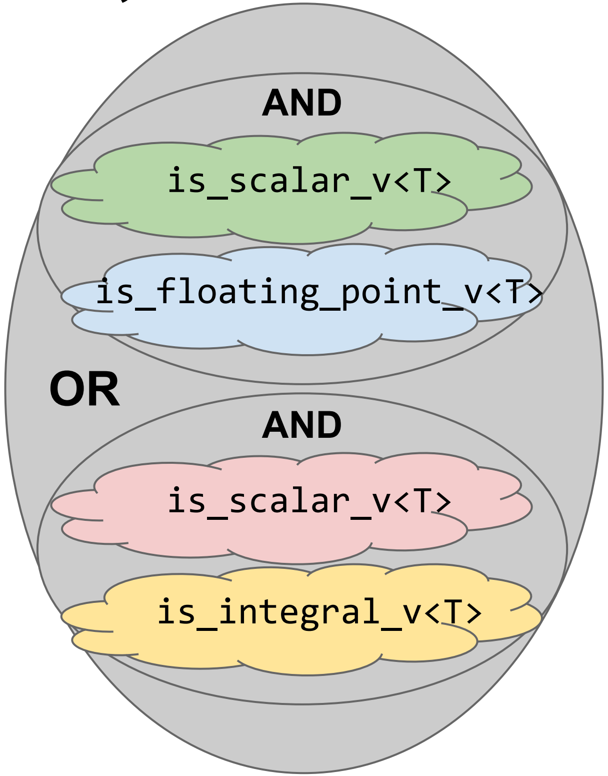



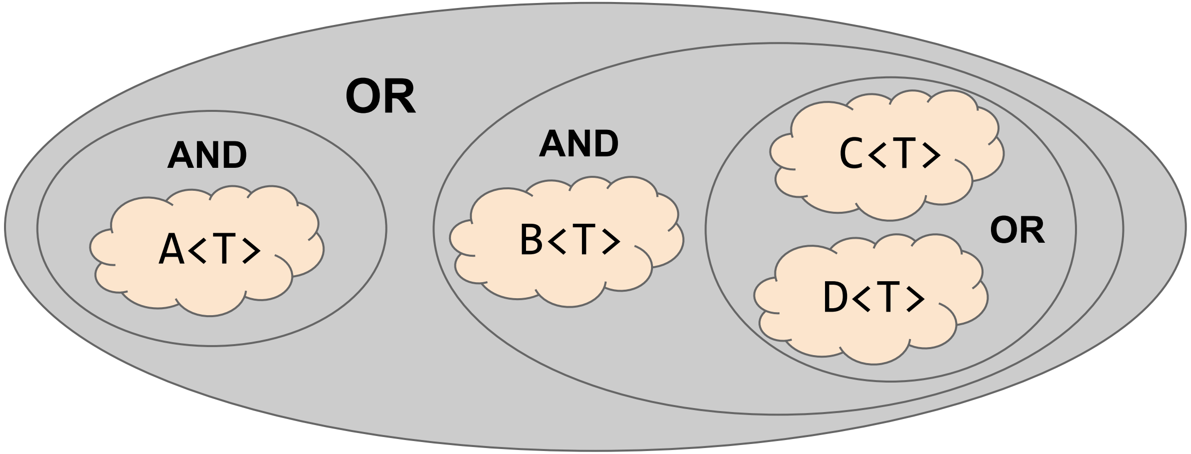
...indexed by source position, not text*

```
template<class T> concept Integral =
    is_scalar_v<T> &&
                   is_integral_v<T>;

template<class T> concept Floating =
    is_scalar_v<T> &&
                   is_floating_point_v<T>;

template<class T> void foo(T)
    requires Integral<T> || Floating<T>;
```



This is slide 31's trick question. The Concepts TS actually did try to deduplicate expressions based on textual spelling, not source position.

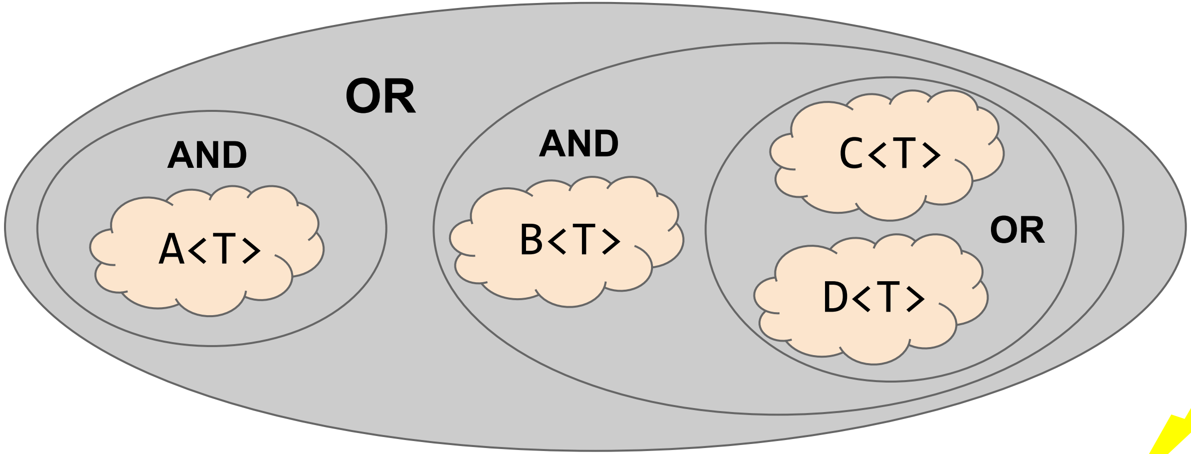
Only two levels are needed

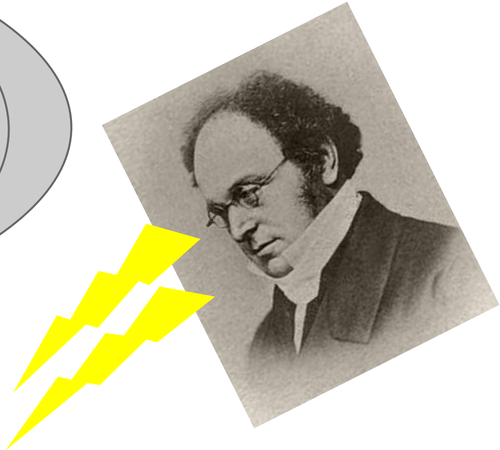



```
template<class T> void foo(T)
   requires A<T> || (B<T> && (C<T> || D<T>));
```

??

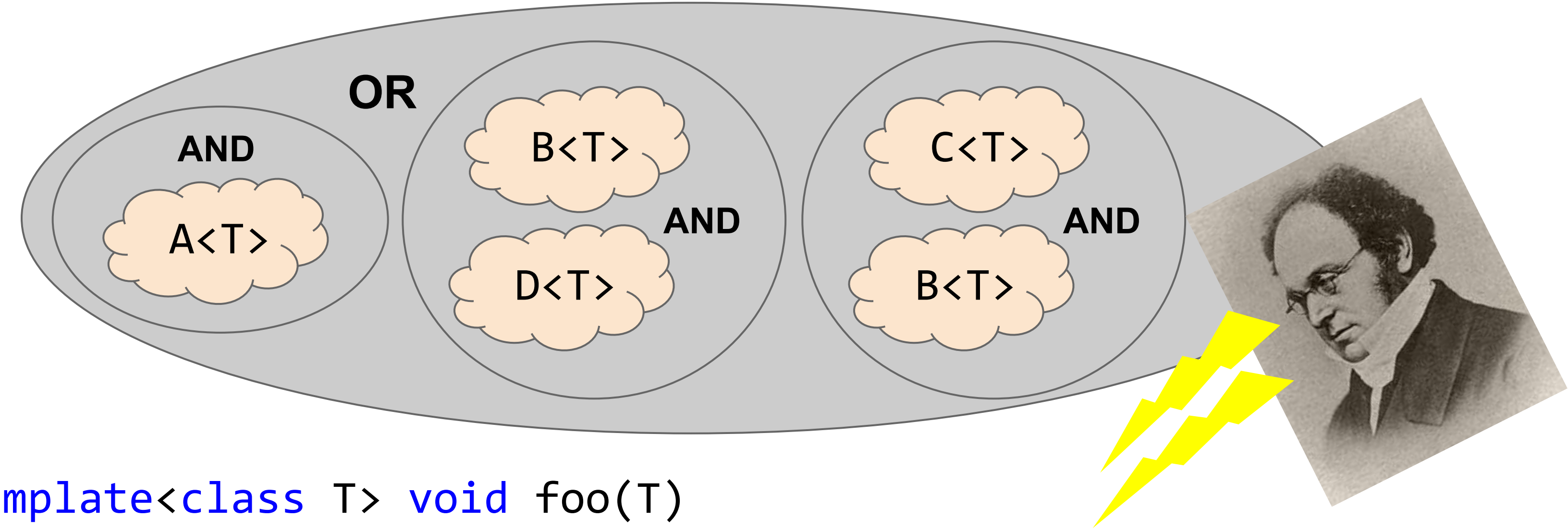
Only two levels are needed





```
template<class T> void foo(T)
   requires A<T> || (B<T> && (C<T> || D<T>));
```

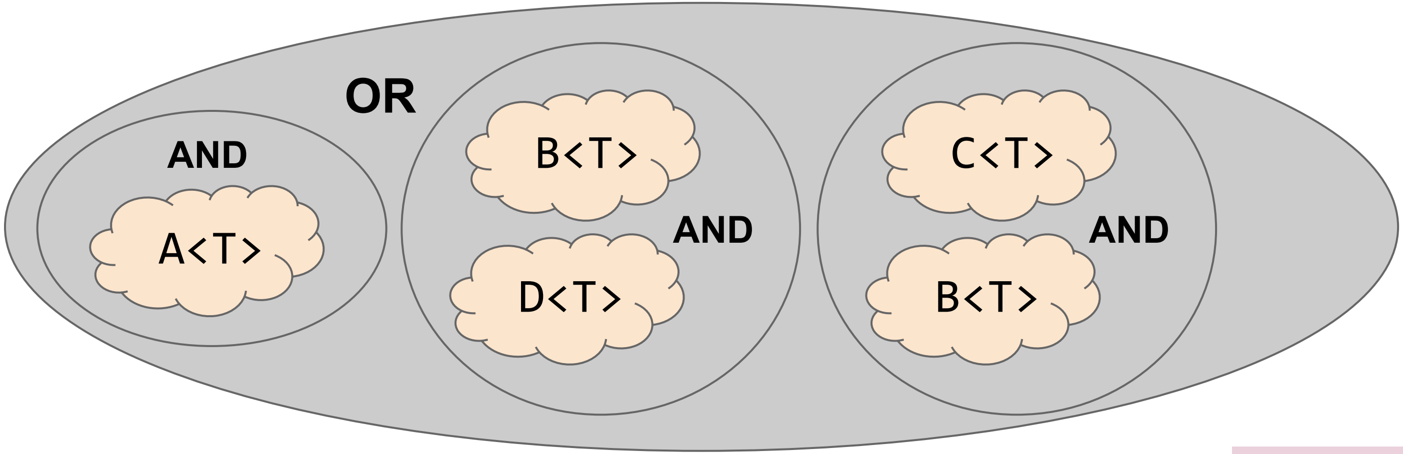
Only two levels are needed




```
template<class T> void foo(T)
   requires A<T> || (B<T> && (C<T> || D<T>));
```

```
template<class T> void foo(T)
   requires A<T> || (B<T> && C<T>) || (B<T> && D<T>);
```

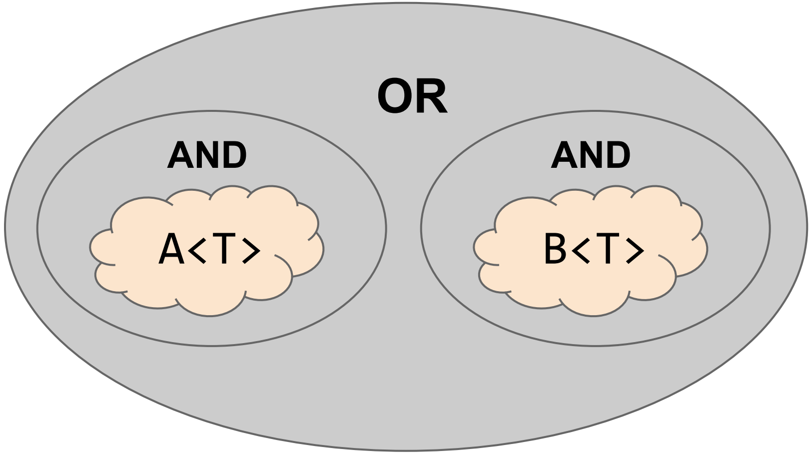
Only two levels are needed




```
template<class T> void foo(T)
   requires A<T> || (B<T> && (C<T> || D<T>));

template<class T> void foo(T)
   requires A<T> || (B<T> && C<T>) || (B<T> && D<T>);
```

These two requires-clauses have exactly the same *normal form*.

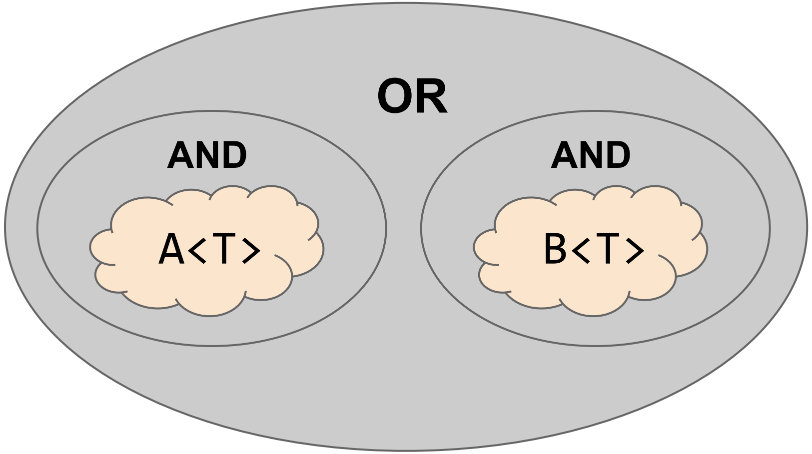
What about negation?



??

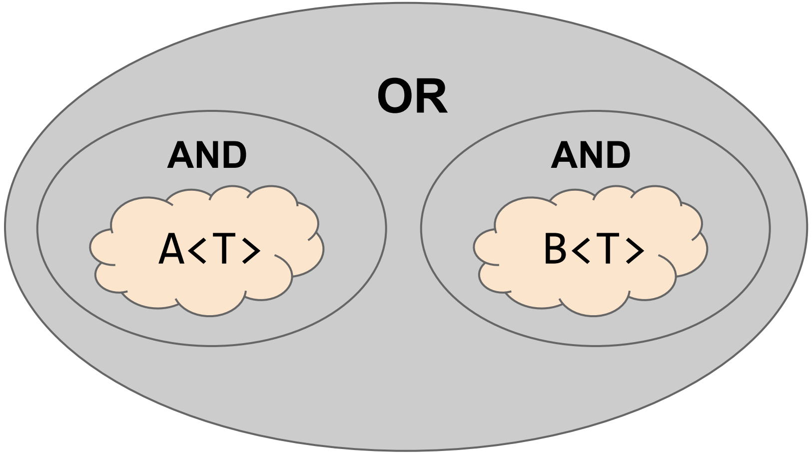
```
template<class T> void foo(T)
   requires not (not A<T> || not B<T>);

template<class T> void foo(T)
   requires (A<T> && B<T>);
```

What about negation?



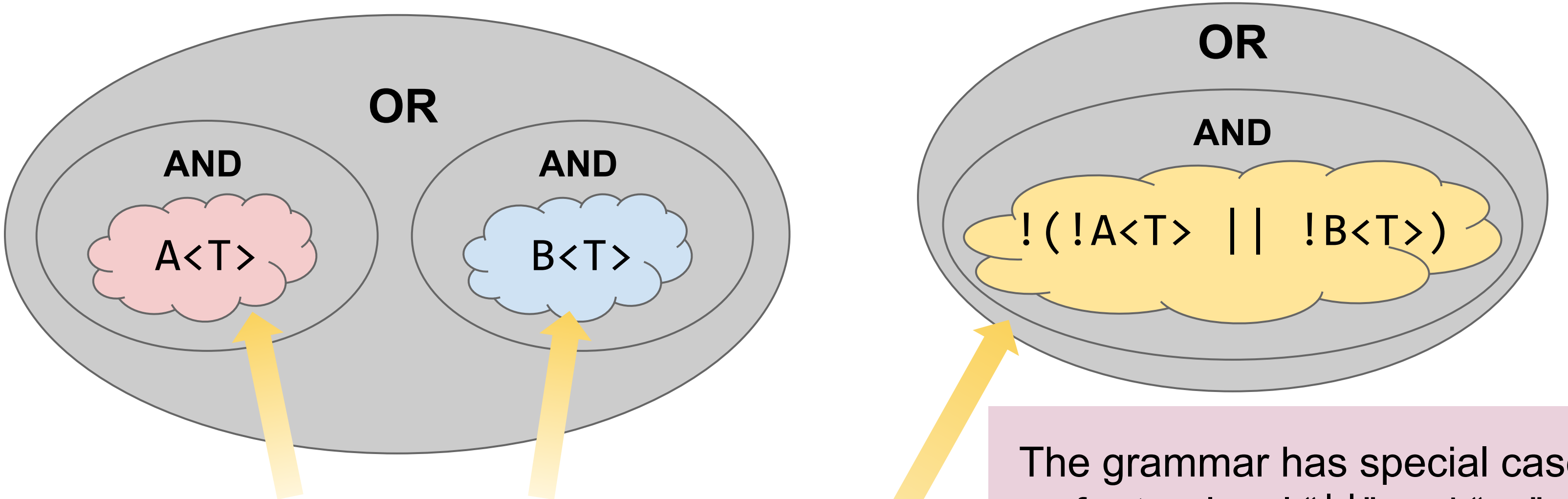
```
template<class T> void foo(T)
   requires not (not A<T> || not B<T>);

template<class T> void foo(T)
   requires (A<T> && B<T>);
```

What about negation? NO!



```
template<class T> void foo(T)
   requires not (not A<T> || not B<T>);

template<class T> void foo(T)
   requires (A<T> && B<T>);
```

What about negation? NO!




```
template<class T> void foo(T)
    requires (A<T> && B<T>);

template<class T> void foo(T)
    requires not (not A<T> || not B<T>);
```

The grammar has special cases for top-level "||" and "&&", but not for "!". These two requires-clauses are **functionally equivalent**, but neither one **subsumes** the other.

What about negation? NO!

The situation is similar to “covariance and contravariance” with virtual methods.
Just as in that case, C++2a supports covariance but not contravariance.

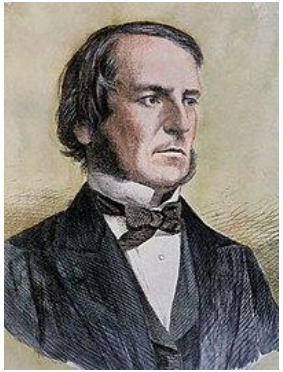
```
template<class T> void foo(T) requires Scalar<T>;
  // ...is subsumed by the more constrained template...
template<class T> void foo(T) requires Integral<T>;


template<class T> void foo(T) requires !Integral<T>;
  // ...has no subsumption relationship at all with...
template<class T> void foo(T) requires !Scalar<T>;
```

Defining a Concept

Defining a concept

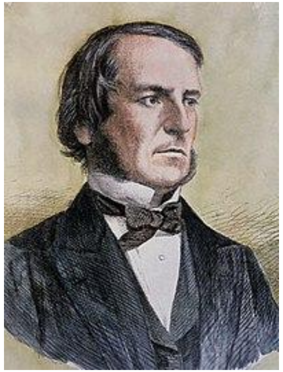
```
template <template-parameter-list>
concept concept-name = constraint-expression;
```

Kinds of *constraint-expressions*



- Disjunction — `a || b`
- Conjunction — `a && b`
- Primary expression of type `bool`
  - Type trait — `is_integral_v<T>`
  - A `requires`-expression

Kinds of *constraint-expressions*



- Disjunction — `a || b`
- Conjunction — `a && b`
- Primary expression of type `bool`
  - Type trait — `is_integral_v<T>`
  - A `requires`-expression

⚠️ A requires-expression is **not the same** as a requires-clause.

Noexcept-expression vs. clause

Noexcept-clause is part of a declaration:
“This is noexcept when...”

```
template<class T>
void xyzzy() noexcept ( boolean-expression );
```

Noexcept-expression is a constant expression of type `bool`:
“Is this expression noexcept?”

```
constexpr bool plugh =
    noexcept ( unevaluated-expression );
```

Requires-expression vs. clause

Requires-clause is part of a declaration:
“This participates in overload resolution when...”

```
template<class T>
void xyzzy() requires boolean-expression ;
```

Requires-expression is a constant expression of type `bool`:
“Is this (set of) requirement(s) satisfied?”

```
constexpr bool plugh =
    requires ( parameter-list ) { requirement-seq };
```

Noexcept-expression vs. clause

Noexcept-clause sometimes contains a noexcept-expression:

```
template<class T>
void xyzzy() noexcept(noexcept( unevaluated-expression ));
```

Or we separate the two:

```
template<class T>
bool is_nothrow_fooable =
    noexcept ( unevaluated-expression );

template<class T>
void xyzzy() noexcept( is_nothrow_fooable_v<T> );
```

Requires-expression vs. clause

Requires-clause sometimes contains a requires-expression:

```
template<class T>
void xyzzy()
    requires requires ( parameter-list ) { requirement-seq };
```

Or we separate the two:

```
template<class T>
concept Fooable =
    requires ( parameter-list ) { requirement-seq };

template<class T>
void xyzzy() requires Fooable<T>;
```

Requires-expression vs. clause

Requires-clause sometimes contains a requires-expression:

```
template<class T>
void xyzzy()
    requires requires ( parameter-list ) { requirement-seq };
```

Or we separate the two:

```
template<class T>
concept Fooable =
    requires ( parameter-list ) { requirement-seq };

template<class T>
void xyzzy() requires Fooable<T>;
```

Kinds of requirements

```
constexpr bool Fooable = requires ( parameter-list ) {

    typename type-expression ;

    { value-expression };

    { value-expression } noexcept ;

    { value-expression } -> type-or-concept ;

    requires constraint-expression ;
};
```

Kinds of requirements

```
template<class T>
concept Fooable = requires ( parameter-list ) {

    typename T::value_type;

    { value-expression };

    { value-expression } noexcept ;

    { value-expression } -> type-or-concept ;

    requires constraint-expression ;
};
```

Kinds of requirements

```
template<class T>
concept Fooable = requires (const T ct, int i) {

    typename T::value_type;

    { ct + i };

    { ct += i } noexcept;

    { ct += i } -> T&;

    { ct - ct } -> Integral;
};
```

Kinds of requirements

```
template<class T>
concept Fooable = requires (const T ct, int i) {

    typename T::value_type;

    { ct + i };

    { ct += i } noexcept;

    { ct -= i } -> T&;

    { ct - ct } -> Integral;
};
```

Exactly equivalent to

```
requires noexcept(ct += i);
```

Kinds of requirements

```
template<class T>
concept Fooable = requires (const T ct, int i) {

    typename T::value_type;

    { ct + i };

    { ct += i } noexcept;

    { ct += i } -> T&;

    { ct - ct } -> Integral;
};
```

Exactly equivalent to

```
  requires is_convertible_v<
    decltype(ct += i), T&
  >;
```

Kinds of requirements

```
template<class T>
concept Fooable = requires (const T ct, int i) {

    typename T::value_type;

    { ct + i };

    { ct += i } noexcept;

    { ct += i } -> T&;

    { ct - ct } -> Integral;
};
```

Exactly equivalent to*

```
requires Integral<decltype(ct - ct)>;
```

Kinds of requirements

Sometimes, requirements can be chained together on a single line of code.

```
template<class T>
concept Fooable = requires (const T ct, int i, T::value_type) {

    { ct += i } noexcept -> T&;

    { ct - ct } noexcept -> Integral;

};
```

GCC (not C++2a) supports auto

```
template<class T>
concept Fooable = requires (const T ct) {

    { *ct } -> auto&&;

    { +ct } -> auto*;

};
```

Equivalent to

```
requires !is_void_v<decltype(*ct)>;
```

Equivalent to

```
requires is_pointer_v<
  remove_reference_t<decltype(+ct)>>;
```

Fun traps for the unwary

```
template<class T>
concept Negatable = requires (T t) {

    -t -> T;

};

static_assert(Negatable<char>);  // FAILS
```

??

Fun traps for the unwary

```
template<class T>
concept Negatable = requires (T t) {

    -t -> T;

};

struct S {
    int T;
};
static_assert(Negatable<S*>);  // OK
```

??

Fun traps for the unwary

```
template<class T>
concept Negatable = requires (T t) {

    -t -> T;

};

struct S {
    int T;
};
static_assert(Negatable<S*>);  // OK
```

Forgot the curly braces!

Minor traps for the unwary

```
template<class T>
concept Negatable = requires (T t) {

    { -t } -> T;

};
```

Minor traps for the unwary

```
template<class T>
concept IntSized = requires {

    sizeof(T) == 4;

};

static_assert(IntSized<char>);  // OK
```

??

Minor traps for the unwary

```
template<class T>
concept IntSized = requires {

    sizeof(T) == 4;

};

static_assert(IntSized<char>);  // OK
```

Forgot the “`requires`” keyword!

Minor traps for the unwary

```
template<class T>
concept IntSized = requires {

    requires sizeof(T) == 4;

};


// Or even better...

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

Minor traps for the unwary

```
template<class T>
concept NothrowIncrementable = requires (T t) {

    noexcept ( ++t );

};
```

Forgot the “requires” keyword!

Minor traps for the unwary

```
template<class T>
concept NothrowIncrementable = requires (T t) {

    requires noexcept( ++t );

    // Or even better...

    { ++t } noexcept;

};
```

Terse syntax(es)

C++2a supports a terser syntax, but I currently recommend not to use it.

```
template<Integral T>
void foo(T t) {
    // ...
}
```

“Constrained parameter”

means the same thing as

```
template<class T> requires Integral<T>
void foo(T t) {
    // ...
}
```

Terse syntax(es)

C++2a supports a terser syntax, but I currently recommend not to use it.

```
template<class T> concept Reference = is_reference_v<T>;
template<class T> concept Function = is_function_v<T>;

template<Reference R>
void foo(R r) { ... }

template<Function F>
void foo(F f) { ... }
```

"My attitude is never to be satisfied." —Duke Ellington

Perfect forwarding?

```
template<class T> concept Integral = is_integral_v<T>;

template<class T> requires Integral<T>
void oops(T&& value) { ... }

int ie; oops(ie);  // does not compile
```

Perfect forwarding?

```
template<class T> concept Range = requires(T&& t) {
    ranges::begin(std::forward<T>(t)) -> Iterator;
    ranges::end(std::forward<T>(t)) -> Iterator;
};

template<class T> requires Range<T>
void okay(T&& range) { ... }
```

Oops! I fell into the exact trap identified on slide 74! I did not mean to do that.

Terse syntax(es)

Concepts TS supports an *even terser* syntax, commonly known as “*the* terse syntax.” This syntax was ***not*** adopted into C++2a.

```
void foo(Integral t) {    // look ma, no “template”!
    // ...
}
```

would mean the same thing as

```
template<class T> requires Integral<T>
void foo(T t) {
    // ...
}
```

Terse syntax(es)

The Concepts TS also extends *constrained return types* and variable type deduction.

```
template<class T>
Integral foo(T i) {  // if the deduced type is not Integral, static-assert
    Integral j = i;  // if the deduced type is not Integral, static-assert
    return j;
}
```

Exactly analogous to C++11’s constrained return types:

```
template<class T>
auto* foo(T i) {    // if the deduced type is not a pointer, static-assert
    auto* j = i;    // if the deduced type is not a pointer, static-assert
    return j;
}
```

Non-type concepts

C++2a rejects concepts that are ***not*** templates:

```
concept True = true;  // error
```

But C++2a permits concepts that are ***weird*** templates:

```
template<template<class...> class Ctr>
concept BigContainer = sizeof(Ctr<int>) >= 24;  // OK!
static_assert(BigContainer<vector>);

template<int I>
concept EvenValue = (I % 2 == 0);  // OK!
static_assert(EvenValue<42>);
```

Metaprogramming with concepts

Concepts can be nested inside namespaces.
Concepts ***cannot*** be nested inside classes or structs.
Concepts ***cannot*** be passed as template parameters.

```
namespace N { template<class T> concept NestedC = ...; }  // OK

struct S { template<class T> concept MemberC = ...; }  // ERROR

template <template<class T> concept ParamC>            // ERROR
struct ST { ... };
```

Multi-parameter concepts

C++2a permits concepts with multiple template parameters.

```
template<class A, class B, class C>
concept BiggerThan =
    sizeof(A) >= sizeof(B) && sizeof(B) >= sizeof(C);

static_assert(BiggerThan<int[3], int[2], int[1]>);
```

Multi-parameter concepts

C++2a permits concepts with multiple template parameters.

```
template<class A, class B, class C>
concept BiggerThan =
    sizeof(A) >= sizeof(B) && sizeof(B) >= sizeof(C);
```

Combined with C++2a's constrained-parameter syntax, this gets weird.

```
template<BiggerThan<int[2], int[1]> D>
void foo();
```

Equivalent to

```
template<class D> requires BiggerThan<D, int[2], int[1]>
void foo();
```

Multi-parameter concepts

Even though I say not to use constrained-parameter syntax, its existence suggests some style guidelines for naming of concepts:

- Your first template parameter is magic. Make sure your name reflects that.
  - `ConvertibleTo<Src, Dst>`
  - `GeneratorOf<F, ReturnType>`
- But don't strain yourself. Maybe this concept just doesn't ***need*** to play well with constrained-parameter syntax.
  - `requires Mergeable<InIter1, InIter2, OutIter>`
  - Does it even need to be a concept at all?
  - `requires is_mergeable<I1, I2, O>`

Concepts enable subsumption. We'll never use `Mergeable` in a context requiring subsumption. So it needn't be a concept.

Multi-parameter concepts

Even though I say not to use constrained-parameter syntax, its existence suggests some style guidelines for naming of concepts:

- Constrained-parameter syntax eliminates the visual distinction between type and non-type parameters. Make sure your concept's name is unambiguous.
- I strongly recommend the suffix `-Value` for non-type concepts!
  - `template<class T> concept Arithmetic = ...;`
  - `template<auto V> concept ArithmeticValue = ...;`

```
template<Arithmetic A> void foo();
template<ArithmeticValue B> void bar();
  ... foo<int>(); ... bar<42>(); ...
```

We already saw this convention with `concept EvenValue`.

Constrained non-template functions?

On the surface, constrained non-template functions seem to provide an alternative to `#ifdef` / `if constexpr`.
But neither Clang nor GCC supports this idiom. Don't try it.

```
unsigned byteswap(unsigned x) requires (sizeof(int) == 2) {
    return (x << 8) | (x >> 8);
}

unsigned byteswap(unsigned x)
                requires (sizeof(int) == 4) {
    return (x << 24) | (x >> 8 << 24 >> 8)
         | (x >> 16 << 24 >> 16) | (x >> 24);
}
```

Because name-mangling. `requires` means "does not participate in overload resolution"; it doesn't mean "does not get codegenned."

More information on Concepts

- “Constraints and concepts (since C++20)”
  `https://en.cppreference.com/w/cpp/language/constraints`
- Cpplang Slack channel #concepts
  `https://cpplang-inviter.cppalliance.org`
- For examples of usage in practice:
  P0896 “The One Ranges Proposal” — *warning! 233-page PDF alert!*
  `http://wg21.link/p0896`
- Herb Sutter’s P0745 “Concepts in-place syntax” `http://wg21.link/p0745`
- Corentin Jabot’s “The tightly-constrained design space of convenient syntaxes for generic programming” `https://cor3ntin.github.io/posts/concepts_syntax/`

Questions?

https://github.com/itanium-cxx-abi/cxx-abi/issues/{20,24}

Sidebar: Linkers hate return-type SFINAE

```
template<class T>
enable_if_t<is_integral_v<T>, T> foo(T t) { return t + 1; }
template<class T>
enable_if_t<not is_integral_v<T>, T> foo(T t) { return t + 2; }

template int foo<int>(int);         // _Z3fooIiENSt9enable_ifIX13is_integral_vIT_EES1_E4typeES1_
template short foo<short>(short);   // _Z3fooIsENSt9enable_ifIX13is_integral_vIT_EES1_E4typeES1_
template float foo<float>(float);   // _Z3fooIfENSt9enable_ifIXnt13is_integral_vIT_EES1_E4typeES1_
```

enable_if on the function's return type

```
template<class T> requires is_integral_v<T>
T bar(T t) { return t + 1; }
template<class T> requires not is_integral_v<T>
T bar(T t) { return t + 2; }

template int bar<int>(int);           // _Z3barIiET_S0_
template short bar<short>(short);     // _Z3barIsET_S0_
template float bar<float>(float);     // _Z3barIfET_S0_
```

new-school requires