IN THIS TALK

1. Composability defined
2. Composable types
3. Objects and patterns
4. Composability at compile time
5. Hierarchies and computation
What does "composable" mean?
Composable, reusable, extensible, flexible…?
Simple?

Do we recognize composability when we see it?

- STL algorithms?
- ranges?
"When I am working on a problem, I never think about beauty. But when I have finished, if the solution is not beautiful, I know it is wrong."

-- R. Buckminster Fuller
"Understanding why software fails is important, but the real challenge is understanding why software works."

-- Alexander Stepanov (via Sean Parent)
WHY SOFTWARE WORKS

Software works because of properties we can reason about.

This is the root of composability:

- Alice writes some code
- Bob takes that code
- Bob puts it to a use that Alice didn’t foresee, and it works
WHAT COMPOSABILITY ISN'T

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• based on syntax
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Composability is not:

- based on syntax
- a product of test-driven development
- one particular pattern
- exclusive to one coding paradigm
NO, REALLY
NO, REALLY

Composability
NO, REALLY

Composability is NOT
NO, REALLY

Composability is NOT about syntax!
COMPOSABILITY IS JOB #1

"If you want to design an allocator, you gotta make composition the first thing in your design, the first concern.

Getting composition right is getting the allocators right."

-- Andrei Alexandrescu (CppCon 2015)

As for allocators, so for everything.
PART 1: FUNCTIONS

Starting at the bottom and working our way up:

Function-level composability
Choosing the wrong return type is one of the most common composability errors.

Often we don't even realise we’re choosing.
The simplest composable return type is `bool`.

```cpp
auto do_a_thing() -> void;
auto do_a_thing_more_composably() -> bool;
```

Simple, but important.
WHY IS \texttt{bool} COMPOSABLE?

The simplest form of composability stems from properties of boolean algebra.

```cpp
auto any_done = do_aThing(1) \texttt{or} do_aThing(2) \texttt{or} \ldots;
auto all_done = do_aThing(1) \texttt{and} do_aThing(2) \texttt{and} \ldots;
```
bool UNDERLIES SO MUCH

It seems so trivial that we often don't notice it.

Things that build on composability of bool:
It seems so trivial that we often don't notice it.

Things that build on composability of `bool`:

- `control flow`: almost all algorithms and loops, really
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- polling/non-blocking functions
- Chain of Responsibility pattern
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Things that build on composability of `bool`:

- control flow: almost all algorithms and loops, really
- a lot of caching schemes (or idempotent calculations)
- polling/non-blocking functions
- Chain of Responsibility pattern

Note: short-circuiting is not part of composability here; it's just a semantic nicety of the operators.
CHAIN OF RESPONSIBILITY

A design pattern that exploits bool’s composability to achieve prioritization.
CASE STUDY: LOGGING

From "Easy to Use, Hard to Misuse: Declarative Style in C++" (CppCon 2018)

```cpp
struct log_sink {
  virtual bool push(const log_entry&);
};
```

The `bool` return type is the key to composition here.
CASE STUDY: LOGGING

Given the `push` function, we can write various `log_sink` classes:
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- a sink that wraps several other sinks and:
  - sends a log_entry to all
  - sends a log_entry to the first one that accepts
CASE STUDY: LOGGING

Given the push function, we can write various log_sink classes:

• "ordinary" sinks that send entries to different places (file, output window, etc)
• a filter sink that runs a predicate on the entry and accepts it conditionally
• a sink that wraps another sink in an execution policy (e.g. for threaded logging)
• a sink that wraps several other sinks and:
  ▪ sends a log_entry to all
  ▪ sends a log_entry to the first one that accepts
• the null sink that accepts every entry and does nothing
Returning `void` gives no choice to the caller.

Returning `bool` gives one choice to the caller.

What can be returned to give more choices?
The next simplest composable return type is `int`. 

```
auto do_a_thing() -> void;
auto do_a_thing_more_composably() -> bool;
auto do_a_thing_even_more_composably() -> int;
```
The next simplest composable return type is `int`.

```cpp
auto do_a_thing() -> void;
auto do_a_thing_more_composably() -> bool;
auto do_a_thing_even_more_composably() -> int;
```

Spoiler: `bool` and `int` are in some sense the only two composable return types we need...
WHY int?

Of course, int can represent N (32?) bools, using bitand ( &) and bitor ( | ) operators.

That's sometimes useful, but really just an extension of the composability of bool...
WHY \texttt{int}?

With \texttt{int} we can say not just \textit{if} something happened, but \textit{how much} was taken care of.

Going from \texttt{bool} to \texttt{int} is like going from \texttt{find} to \texttt{accumulate}.

It also opens the door for more complex user-defined behaviour.
HOW MUCH WAS CALCULATED?

```c
auto do_calculation(float) -> float;
```

`bool` gives a binary choice (naturally).

An arithmetic type allows incremental progress.
CASE STUDY: STEERING BEHAVIOURS

a.k.a. "boids" (by Craig Reynolds)

Boids are defined quite simply:

- **mechanical parameters**: position, heading, velocity etc
- **a collection of behaviours**

The calculation of each behaviour returns a force (**arithmetic type**).

The sum of forces (**composition**) given by all behaviours is applied to the boid.
Classic boids flocking consists of three behaviours.

- separation
- alignment
- cohesion
MORE BEHAVIOURS

We can arbitrarily layer more behaviours into the calculation.

Obstacle avoidance, collision response, priority deferment, etc…
COMPOSABILITY FROM PRINCIPLES

At the core, steering behaviours is based on the *composability of arithmetic types*.

A single function returns a force *that can be accumulated* and applied.

The resulting framework has many uses:

- crowd simulations
- visualisations
- optimisation problems
- etc
MORE COMPOSABLE TYPES

So far we've seen `bool` and `int`.

The next step in composable types stems directly from here.

Instead of integral types, let's go to `T`.
MORE COMPOSABLE TYPES

bool is to int

as

optional<T> is to collection<T>
COMPOSING **optional**

**optional** can compose in the same way as **bool**. But it also has another trick.

```cpp
struct T { ... };  
auto combine(T x, T y) -> T;
```

When you have a `T` that has no "default value" for some combining operation, you can use **optional** to provide that value.

```cpp
auto combine(optional<T> x, optional<T> y) -> optional<T> {  
  if (x.has_value() and y.has_value()) {  
    return combine(*x, *y);  
  }  
  return {};
}
```
COMPOSING `vector`

`optional` is like `bool`: we get presence or absence.

`vector` is like `int`: we get to combine quantities.

(It's been suggested that `optional` is just a `vector` with max size 1)
A COMMON PROBLEM

Many calculations are most simply formulated as recursive calculations. Interesting variations often include mutual recursion.

```cpp
auto calculate_recursively(const collection&) -> collection;
```

The most common inhibitor of recursive beauty is mixed up return types.
When solving any kind of interesting recursive problem, the highest probability of confusion occurs from failing to keep return types uniform.
MATCH RETURN TYPE WITH PARAMETERS

Functions whose return type is the same as (one of) their parameter type(s) are the most composable.

```cpp
auto do_calculation(float) -> float;
auto combine(T x, T y) -> T;
auto combine(optional<T> x, optional<T> y) -> optional<T>;
auto calculate_recursively(const collection&) -> collection;
```

And one of the easiest ways to make code ugly, if we don't line up types properly.
MATCH RETURN TYPE WITH PARAMETERS

Put more simply:

When working with a container, stay in the container!

e.g. if you're returning a `vector`, write your function to take a `vector`.

There is always a cost to exiting container-world.

- checking whether an `optional` is engaged
- checking whether a `vector` is empty
- waiting for a `future` value to materialize
Composable functions stem from composable properties of their return types. We can:

- use `and` and `or` with `bool`
- use `arithmetic`, `ordering operations`, etc with numbers
- concatenate or merge collections

And we can take the output of a function and feed it back to another.

Almost all composability in object-pattern land builds on such type composability.
PART 2: OBJECTS & PATTERNS

The next rung on the ladder:

Object-level composability
What classes should we write to this interface, to enable higher-level composability?

```cpp
struct thing_doer {
  virtual auto frob(const widget&) -> composable_type_t;
};
```
FIRST: ZERO

The first object to write is the one that does nothing, composably.
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- the logger that accepts an entry and produces no log
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- the visitor that uses the identity operation
The first object to write is the one that does nothing, composably.

- the logger that accepts an entry and produces no log
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- the parser or validator that fails
- the visitor that uses the identity operation
- the request that does nothing
THE ZERO OBJECT

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Solutions:
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If writing this is difficult, it's a good sign our composability abstraction is not right.

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- no default state
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Solutions:

- use composable types
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- no default state
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Solutions:

- use composable types
- apply SOLID principles
THE ZERO OBJECT

If writing this is difficult, it's a good sign our composability abstraction is not right.

Possible problems:

- no default state
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- side-effectful behaviour
- world-switching

Solutions:

- use composable types
- apply SOLID principles
- avoid world-switching
THE ZERO OBJECT

If writing this is difficult, it's a good sign our composability abstraction is not right.

Possible problems:

- no default state
- coupled actions or state
- side-effectful behaviour
- world-switching

Solutions:

- use composable types
- apply SOLID principles
- avoid world-switching
- find a better abstraction?
SECOND: PASSTHROUGH

The second object to think about is the one that delegates to another presumed object in some way.

If your return type is bool or optional, you can write the "if-else" object: try option A, and if it fails, employ option B.

At this point, the "if-else" object may extend to the "any-of" and "all-of" objects.
CASE STUDY: ALLOCATORS

std::allocator is to Allocation
what std::vector is to Vexation

-- Andrei Alexandrescu, CppCon 2015

```cpp
struct Allocator {
    auto allocate(size_t) -> B1k;
    auto owns(B1k) const -> bool;
    auto deallocate(B1k) -> void;
};
```

B1k contains pointer (=> bool) and size.
CASE STUDY: ALLOCATORS

With just that interface, we can implement:
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- fallback allocator (try A, if it fails, try B)
CASE STUDY: ALLOCATORS

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- fallback allocator (try A, if it fails, try B)
- stack allocator
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With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
CASE STUDY: ALLOCATORS

With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
- slab/arena allocators
CASE STUDY: ALLOCATORS

With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
- slab/arena allocators
- freelist based allocators
CASE STUDY: ALLOCATORS

With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
- slab/arena allocators
- freelist based allocators
- affix allocator (metadata prefix/suffix)
CASE STUDY: ALLOCATORS

With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
- slab/arena allocators
- freelist based allocators
- affix allocator (metadata prefix/suffix)
- hi/lo allocator, bucket allocator, etc
CASE STUDY: ALLOCATORS

With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
- slab/arena allocators
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- mallocator
CASE STUDY: ALLOCATORS

With just that interface, we can implement:

- fallback allocator (try A, if it fails, try B)
- stack allocator
- fixed size allocators (chunks of N bytes)
- slab/arena allocators
- freelist based allocators
- affix allocator (metadata prefix/suffix)
- hi/lo allocator, bucket allocator, etc
- mallocator
- compositions of all of the above (powered by fallback allocator)
COMPOSABILITY IN THE FALLBACK ALLOCATOR

The fallback allocator first tries a primary; if that fails, it *falls back* to the other.

```cpp
template <class Primary, class Fallback>
struct FallbackAllocator : Primary, Fallback {
    auto allocate(size_t n) -> Blk {
        if (const auto r = Primary::allocate(n); r.ptr) {
            return r;
        }
        return Fallback::allocate(n);
    }
};
```

This relies on the composable properties of `bool`. 

We can turn a binary pattern into an n-ary pattern:

```cpp
template <class... As>
struct FallbackAllocator : As... {
    auto allocate(size_t n) -> Blk {
        Blk r{};
        auto alloc = [&] <class A> () -> bool {
            r = static_cast<A*>(this)->allocate(n);
            return r.ptr;
        };
        (... or alloc.template operator()<As>();
        return r;
    }
};
```
"FUNCTIONAL PROGRAMMING"

Functional programming in C++? Polarising?

Higher order functions that take functions as arguments and return functions.

"A m**** is just a m***** in the c******* of..."
auto compose(auto f1, auto f2) {
    return [f1, f2] (auto arg) {
        if (auto result = f1(arg); result) {
            return result;
        }
        return f2(arg);
    };
}
Who writes code like this?

```cpp
auto compose(auto f1, auto f2) {
    return [f1, f2] (auto arg) {
        if (auto result = f1(arg); result) {
            return result;
        }
        return f2(arg);
    };
}
```

Who *writes* code like this?

We. All. Do.
"Composite lets clients treat individual objects and compositions of objects uniformly."

In classical OO-style, this is done with an abstract base class that declares operations on both composite and leaf classes.

```cpp
struct graphic {
    virtual auto draw() -> void = 0;
    virtual auto add(graphic&) -> void = 0;
    virtual auto remove(graphic&) -> void = 0;
};

struct leaf : graphic { ... };
struct collection : graphic { ... };`
PATTERNS: COMPOSITE

Composite is a useful pattern because it allows us to compose structure directly without conditions in the handling code.

We don't have a dichotomy between a leaf and a collection.

This means we can write functions against one interface that work with both.
WHAT IS THE LEARNING HERE?

Q. What makes composite nice to use?
WHAT IS THE LEARNING HERE?

Q. What makes composite nice to use?

A. We don't have to put conditions in the calling code.
A raw condition is any binary condition that doesn't serve one of two purposes:

- intrinsic optionality present inside a data type
- a configuration or construction-time choice

Notice this includes:

- regular if
- the conditional operator
- if constexpr
BRIEF ASIDE

Remember "C++ Seasoning"?

Of course. We all remember "no raw loops".

I suggest watching that talk again. (For the rest of it.)
NO RAW CONDITIONS

Put another way -

We should strive to put *if* statements in two places only:

- at the bottom of the stack (built into data structure)
- at the top of the stack (construction time)
THE SECRET OF UNIFORMITY

Good composition happens when functions across the object space:

- take the same types
- return the same types
- take the same types as they return (or related ones)
WELL-BEHAVED FUNCTIONS

Functions or methods with the following signatures usually make good compositional sense:

```plaintext
auto func() -> bool;
auto func(T) -> collection<T>;
auto func(collection<T>) -> collection<T>;
```
PROBLEMATIC FUNCTIONS

Functions or methods with the following signatures are often problematic:

```cpp
auto func(int) -> bool;
auto func(optional<T>) -> T;
auto func(collection<T>) -> T;
```

As well as mixing functions that return `T` and `collection<T>`.
INTERLUDE: COMPILE-TIME

So far we've seen everything in value-space.

The *same principles apply* (perhaps even more so) to *type-space*.
COMPILE-TIME TYPE CALCULATIONS

In this form of compile-time programming:

- values become types
- functions become templates (usually class/alias)
- data structures are typically type lists or pairs
We have pretty much one data structure: the type list.

The same problematic function signatures apply.

```cpp
// auto func(collection<T>) -> T;
template<typename... Ts>
struct func {
    using type = some_T;
};
```
WE WOULDN'T WRITE THIS CODE

```java
if (conditionA) {
    if (subConditionX) {
    } else if (subConditionY) {
    } else {
    }
} else if (conditionB and conditionC) {
    if (not subConditionZ) {
    }
}
```

If we saw this structure in code review, we'd balk.
BUT WE CAN END UP WITH THIS

"At least it's better than SFINAE."

```cpp
if constexpr (conditionA) {
    if constexpr (subConditionX) {
    } else if constexpr (subConditionY) {
    } else {
    }
} else if constexpr (conditionB and conditionC) {
    if constexpr (not subConditionZ) {
    }
}
```
REFLECTION IS COMING

Maybe for some of you, it's already here in some form.

We are going to get a lot of metafunctions building on the following general form:

```cpp
template <typename T>
auto members_of(T) -> type_list<T Members...>;
```

What should happen if T is an int? What does that mean for when T is a struct?
REFLECTION IS COMING

We are going to get a lot of metafunctions in the following pattern:

```cpp
template <typename T>
auto for_each_member_recursively(T) -> /* what? */;
```

What should this function return?
How can we compose functionality like this?
PART 3: STRUCTURES

The top rung on the ladder (for this talk):

Structural composability
FIRST PROBLEM

Many languages have object-oriented features.

They make it easy to add new types.

It's difficult to add new behaviour though.

This is (half of) the expression problem.
WHAT SOLVES THIS PROBLEM?

Another pattern, of course.

The visitor pattern.
VISITOR PATTERN

"The Visitor pattern is the most widely misunderstood pattern in all of Design Patterns, which is really saying something [...] The pattern isn't about "visiting", [... it's] really about approximating the functional style within an OOP language."

-- Bob Nystrom, Crafting Interpreters
VISITOR PATTERN

In an OO language, **types (classes) are easy** to add, but adding behaviour (methods) require touching the world.

In a functional language, it's the other way around: **functions are easy** to add, but adding types requires updating pattern matching everywhere.

The visitor pattern approximates the functional experience in an OO language.
Fundamentally that's still a choice of one way or the other. And that's fine for some problems (like representing expressions).

The expression problem always remains to some degree.

We have another problem - composability means:

- structured hierarchies
- hierarchical composition and extension
- run computations over hierarchies
When structures are flat, we're already good at separating computation and traversal.

```cpp
auto total_length(const vector<string>& v) -> int {
    return transform_reduce(begin(v), end(v),
                            0, plus{},
                            [] (const auto& s) { return size(s); });
}

vector<string> v = {"Hello", "CppCon", "2021"};
std::cout << total_length(v); // 15
```

We have lots of algorithms that separate where (traversal with iterators) from what (the operation passed in).
When structures are hierarchical, we're much less good at separating computation and traversal.

Consider how to sum the lengths in a rose tree.

```cpp
template <typename T>
struct rose_tree : variant<T, vector<rose_tree<T>>> {
    using variant<T, vector<rose_tree<T>>>::_variant;
};
```
HIERARCHICAL COMPUTATION

auto total_length(const rose_tree<string>& t) -> int {
    return visit(
        overloaded{
            [] (const string& leaf) -> int { return size(leaf); },
            [] (const auto& branch) -> int {
                return transform_reduce(
                    begin(branch), end(branch),
                    0, plus{},
                    [] (const auto& t) -> int { return total_length(t); });
            },
            t);
        }
    );
}

The traversal is mixed with the operation.
Here is the "where": `reduce_tree` embodies the traversal.
Here is the "what": how to treat a branch and a leaf.

```cpp
auto total_length(const rose_tree<string>& t) -> int {
    return reduce_tree(t, 0, plus{},
        [] (const auto& leaf) -> int { return size(leaf); });
}
```
C++ IN FLATLAND

When all you have is iterators/ranges, everything looks flat.

Every standard structure is flat... many non-standard structures are not.
But they are amenable to the same kind of abstraction that leads to composability!
FROM FLATLAND TO HIGHER DIMENSIONS

// this is not possible in C++ but a useful structure to imagine...
struct nil{}

template <typename T>
struct vector : variant<nil, pair<T, vector<T>>> {
    using variant<nil, pair<T, vector<T>>>::variant;
};

template <typename T, typename TInit, typename Op>
auto reduce(const T& t, TInit i, Op op) {
    return visit(overloaded{
        [&] (nil) { return i; },
        [&] (const auto& v) {
            return op(v.first, reduce(v.second, i, op));
        },
        t);
    }
By applying a functional lens, we can see how to traverse hierarchies in higher dimensions.

This unlocks structural and computational composition by separating what from where.

We can go a little further though…
WHAT, WHERE - AND WHEN?

template <typename T, typename TInit, typename Op>
auto reduce(const T& t, TInit i, Op op) {
    return visit(overloaded{
        [&] (nil) { return i; },
        [&] (const auto& v) {
            return op(v.first, reduce(v.second, i, op)); }
    },
    t);
}
WHY IS ANY OF THIS IMPORTANT?

- Alice writes some code
- Bob takes that code
- Bob puts it to a use that Alice didn't foresee, and it works

This. This is only possible with a principled approach to composability.

- types
- functions
- objects
- structures
- computation
CONCLUSIONS

- Composability is **not about syntax**, it's **about semantics**.
- Pattern/object-level composability stems from function-level composability, stems from **type-level composability**.
- When working in a collection, **stay in the collection**.
- **Conditions inhibit composition**: avoid raw `if` statements.
- Compile-time capability is **still in its infancy** (`if constexpr` is **not** better than SFINAE).
- The key to structural composition is breaking out of flatland and **separating what, where and when**.