Modern C++ Interfaces

Complexity, Emergent Simplicity, SFINAE, and Second Order Properties of Types

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About Steve Dewhurst

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Steve has consulted for projects in areas such as compiler design, embedded telecommunications, e-commerce, and derivative securities trading. He was programming track chair of *Embedded Systems*, a Visiting Scientist at CERT and a Visiting Professor of Computer Science at Jackson State University.

Steve was a contributing editor for *The C/C++ User's Journal*, an editorial board member for *The C++ Report*, and a cofounder and editorial board member of *The C++ Journal*.

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Outline

- Some years ago, Policy-Based Design techniques devolved implementation decisions to users of interfaces.
- More recently, interfaces seem to prefer to move such decisions away from users of interfaces to their implementers.
- Lately, there seems to be a great increase in use of SFINAE-based techniques in tandem with Modern C++. Why?
  - Increased complexity implies need for more nuanced interfaces.
  - Increased interface complexity implies that we are now embedding not just our experience in implementations, we're embedding our judgement in our interfaces.
  - New language features and libraries make it feasible.

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Outline

✓ *Hypothesis: We've hit a cusp such that C++ is complex enough that it's use is actually becoming simpler due to the necessity of using*
  - convention,
  - idiom,
  - embedded experience,
  - and "Do What I Mean" interfaces.

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Wishful Thinking…

- Recently, our code has evolved in the direction of relieving the user from, well, knowing much of anything.
- We've gone from comments…

```
// DO NOT EVEN THINK OF PASSING AN ARRAY OF COMPLEX
// TYPES TO THIS FUNCTION!!!
template <typename T>
T *copy_it(T const *src, size_t n) {
    ~~~
}
```

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Totalitarianism…

- …to enforcing our will for their own good…

```
template <typename T>
T *copy_it(T const *src, size_t n) {
    static_assert(
        is_trivially_copyable<T>::value,
        "array type must be memcopy-able"
    );
    ~~~
}
```

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Embedding Experience

- ...to embedding our design experience directly in self-maintaining code.

```
template <typename T>
inline T *copy_array(T const *s, size_t n) {
    size_t const amt = sizeof(T) * n;
    T *d = static_cast<T *>(::operator new(amt));
    if (is_trivially_copyable<T>::value)
        d = static_cast<T *>(memcpy(d, s, amt));
    else if (has_nothrow_copy_constructor<T>::value)
        for (size_t i = 0; i != n; ++i) {
            new (&d[i]) T (s[i]);
        }
    else ...
```

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Embedding Experience in C++17

- Moving faster than is typical, this idiom has made its way into the C++ standard.

```
template <typename T>
inline T *copy_array(T const *s, size_t n) {
    size_t const amt = sizeof(T) * n;
    T *d = static_cast<T *>(::operator new(amt));
    if constexpr (is_trivially_copyable<T>::value)
        d = static_cast<T *>(memcpy(d, s, amt));
    else if
       constexpr (has_nothrow_copy_constructor<T>::value)
        for (size_t i = 0; i != n; ++i) {
            new (&d[i]) T (s[i]);
        }
    else ...
```

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Embedding Judgment

- We've simplified maintenance and use of implementations by embedding our experience.
- As implementations become more complex, some of that complexity inevitably leaks out into interfaces.
- As a result, designers have been embedding their judgement into interfaces.
- This has the effect of simplifying use of the interface, even if the actual interface is more complex due to its inflection by the nuanced implementation.

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Language Changes That Impelled

- Increasing complexity in stating what your intentions are:
  - Preferential treatment of initializer-list arguments in overload resolution
  - Greedy universal references
  - Need to extend functionality in a backward-compatible way
  - Increasingly fine-grain distinguishability in overloaded function templates
  - None of these individually caused the shift, but the language complexity reached a tipping point, where designers could no longer trust that their interfaces would allow the compiler and user to interpret an interface in the same way.

✓ *To be clear: Increased language complexity is not an advantage in itself. However, it leads to greater expressiveness than would a less complex language. Simplicity is an emergent property.*

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Language Changes That Enabled

- Templated using declarations
- Default template arguments for function templates
- `constexpr`
- <type_traits>, in particular those aspects that require participation by the compiler.
- …and some assistance from variadic templates.

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SFINAE is Simple

- "***S***ubstitution ***F***ailure ***I***s ***N***ot ***A***n ***E***rror" in template argument deduction.
- That is, if argument deduction finds at least one match, the failed matches aren't errors, as in:

```
template <typename T> void f(T);
template <typename T> void f(T *);
~~~
f(1729);        // no error, specializes first f
```

- The call `f(1729)` can match `f(T)`, but not `f(T *)`.
- The failure to match `f(T *)` is not an error.
- If `f(T)` were not present, it would be an error.

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SFINAE in C++03 Was a Pain in the Neck

- Unlike a constraint implemented with a static assertion, SFINAE must be applied to an interface, before a decision is made.
- In the template parameter list,

```
template <typename T>
void                          in the return type,
munge_shape(T const &a) {
    ~~~                       or in the argument list.
}
                 It's too late here, although we can static_assert.
```

- In C++03, function templates could not have default template parameters.
- This typically left us to apply SFINAE to return types and argument lists. With unfortunate syntactic results.

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SFINAE in Modern C++

- The augmented language makes it necessary to ask more compile-time questions.
  - We have more choices, and with great power comes great responsibility.
- Happily, the augmented language provides facilities to help us to ask the questions.

✓ *One major piece: the fully-standard <type_traits> header file provides a collection of useful predicates (some of which are compiler intrinsics) and a syntactic model on which to build more complex predicates.*

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Default Function Template Arguments

✓ *In C++11, function templates may have default template arguments.*

- This permits syntactic improvement because we no longer have to hide a constraint within some other facet of the declaration.

```
template <
    typename T,
    typename = enable_if_t<is_base_of<Shape, T>::value>
>
void munge_shape(T const &a) { ~~~ }
```

- Now substitution will fail if it can't determine the type of the default template parameter.

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Template Typedef

✓ *In syntactic situations like this, use of using is of use:*

```
template <typename T>
using IsShape = typename
    enable_if<is_base_of<Shape, T>::value>::type;
```

- Our snobby function template is now fairly readable:

```
template <typename T, typename = IsShape<T>>
void munge_shape(T const &a);
```

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A Constructor Overload Issue

- Let's look at a sporadic problem with constructor overloading:

```
template <typename T>
class Heap {
public:
    ~~~
    Heap(size_t n, T const &v);
    template <typename In>
    Heap(In b, In e);              // range init
    ~~~
};
```

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Constructor Overload Code Smell

- Interference by the range initialization member template may give surprising results:

```
Heap<int> h (5, 0);    // range initialization!
```

- The member template is a better match than the non-template two-argument constructor.
- Why?
  - The template is an exact match; `In` is deduced to be `int`.
  - The non-template requires a conversion on the first argument from `int` to `size_t`.

✓ *I intended that constructor for input iterators only! Do what I mean!*

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Syntactic Difficulties

- Older template metaprogramming features of the standard library can be syntactically challenging:

```
is_same<    // is this a random access STL iterator?
    typename iterator_traits<Iter>::iterator_category,
    random_access_iterator_tag
>::value
```

- The expression uses long identifiers.
- It also requires explicit use of the keyword `typename` to identify the nested name `iterator_category` as a type.
- A “template typedef” alias can simplify the syntax…

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Simplifying With “Template Typedef”

- For example, these alias templates can categorize iterators:

```
template <typename It>
using Category
    = typename iterator_traits<It>::iterator_category;

template <typename It>
using is_exactly_rand
    = is_same<Category<It>, random_access_iterator_tag>;

~~~
```

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Simplifying With Alias Declarations

- This alias template can determine if an iterator is an STL input iterator:

```
template <typename It>
using is_in = is_true<
    is_exactly_in<It>::value || is_for<It>::value
>;
```

- The `is_true` template is non-standard.
- One last syntactic cleanup:

```
template <typename It>
using IsIn
    = typename enable_if<is_in<It>::value>::type;
```

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Disabling the Constructor with SFINAE

```
template <typename T>
class Heap {
public:
    ~~~
    template <typename In, typename = IsIn<In>>
    Heap(In b, In e);
};
```

- Here, the required constraint is that `In` be an input iterator.

✓ *That's what I meant!*

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Greedy Universal Members

- Universal references are *very* accommodating:

```
template <typename T>
class X {
public:
    void operation(T const &);  // #1: lvalue version
    void operation(T &&);       // #2: rvalue version
    template <typename S>
    void operation(S &&);       // #3: universal version
    ~~~
};
```

- They often provide somewhat surprising better matches than functions without universal reference arguments.

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Similar in Decay

- The `std::decay` type trait models the conversions and decay that occur when passing by value.
- We can use mutual decay to decide whether two types are "pretty much" the same:

```
template <typename S, typename T>
using similar = is_same<decay_t<S>, decay_t<T>>;

template <typename S, typename T>
using NotSimilar = enable_if_t<!similar<S, T>::value>;
```

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Limiting Greediness

- Now we can use SFINAE to limit the use of the universal version of `operation` to types that are “not similar to” the type used to specialize `X`:

```
template <typename T>
class X {
public:
  void operation(T const &);  // #1: lvalue version
  void operation(T &&);       // #2: rvalue version
  template <typename S,
            typename = NotSimilar<S, T>>
  void operation(S &&);      // #3: universal version
                             // Do What I Mean:
};                           // OK as long as S is not
                             // "similar" to T
```

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Self-Identification for SFINAE

- SFINAE for interface design is so effective, that some types are designed to facilitate it by making complex properties easy to determine.
- For example, complete specializations of standard function objects identify themselves as “transparent.”

```
template <>
struct less<void> {
    template <class T, class U>
    constexpr auto operator()(T &&t, U &&u) const {
        return std::forward<T>(t)
             < std::forward<U>(u);
    }
    using is_transparent = void;
};
```

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SFINAE, Again

- Standard `set` has members that are considered only if the `set`'s comparator is transparent:

```
template <typename T, typename Comp ~~~>
class set {
public:
    ~~~
    iter lower_bound(const T &key);
    template <typename Key,
              typename = typename Comp::is_transparent>
    iter lower_bound(const Key &key);
};
```

- Effectively, the interface to `set` is modified based on self-identified properties of its comparator.

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Self-Identification

- For another example, consider a scoped enum that has been tricked up to act like a container of enumerators:*

```
enum class bits {
  begin = 0x01,
  one = begin, two = 0X02, three = 0X04,
  four = 0X08, five = 0X10, six = 0X20, seven = 0X40,
  end = 0X80,
  is_enum_container
};
~~~
template <typename E>
using IsEnumContainer =
    std::enable_if_t<sizeof(E::is_enum_container)>;
```

* Thanks to Dan Saks for the example.

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Volunteering

- Only enums that self-identify as enum containers have container-like operations on their enumerators:

```
template <
    typename T,
    T(&next)(T) = next_enum,
    T(&prev)(T) = prev_enum,
    typename = IsEnumContainer<T>>
class enum_iterator {
    ~~~
};
```

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Predicate Composition

- Compile time predicates like those in `<type_traits>` are often composed to test complex type properties.
- We can simplify the composition through use of a variadic template template parameter pack:

```
template <template <typename...> class... Preds>
struct Compose;
```

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Using Composed Predicates

- We can use composition like this:

```
using Happy = Compose<is_class, is_transparent, is_big>;
~~~
static_assert(Happy::eval<T>(), "Unhappy, I am.");
~~~
template <typename T>
using IsHappy = enable_if_t<Happy::eval<T>()>;
~~~
template <typename T, typename = IsHappy<T>>
void pursuit_of_happyness() { ~~~ }
```

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Traditional First/Rest Implementation

```
template <template <typename...> class First,
          template <typename...> class... Rest>
struct Compose<First, Rest...> {
    template <typename T>
    static constexpr auto eval() {
        return First<T>::value &&
               Compose<Rest...>::template eval<T>();
    }
};

template <>
struct Compose<> {
    template <typename>
    static constexpr auto eval()
        { return true; }
};
```

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Simpler Non-Recursive Implementation

- A C++14 constexpr function can simplify the implementation:

```
template <template <typename...> class... Preds>
struct Compose {
    template <typename T>
    static constexpr auto eval() {
        auto results = { Preds<T>::value... };
        auto result = true;
        for (auto el : results)
            result &= el;
        return result;
    }
};
```

- ...and a C++17 fold operation could simplify even further.

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Dealing With Complex Constraints

- We've seen a number of reasonably complex constraints so far.
- In such situations, it can help to have a framework available to automate away some of the complexity.
- Luckily, C++ has a rich collection of idioms to deal with complexity.
- We'll reuse some of these traditional idioms to write a framework:
  - Represent a compile-time data structure as a complex, nested type.
  - Use "expression template" operators to generate the complex type.
- We'll write a constraint expression template language and parser that can handle the usual `and`, `or`, `xor`, and `not` operators.

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Template Trees

- Rather than use a simple linear template template predicate list, we'll use a template template predicate tree structure.
  - Represent a compile-time data structure as a complex, nested type.
  - Use "expression template" operators to generate the complex type.
- We'll write a constraint expression template language and parser that can handle the usual and, or, xor, and not operators.

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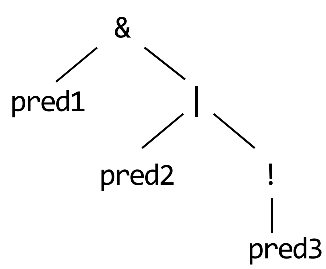
Abstract Syntax Trees

- A type predicate expression like

```
pred1 & (pred2 | !pred3)
```

- Should generate a parse tree like



where the leaves of the AST are templates.

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Idiomatic Blast From The Past

- Actually, we don't really want a parse tree, *per se*, but a (compile time) type that contains the information from the parse tree, similar to the use of a type list to represent a linear sequence of types.
- The leaves of the expression tree are values of the form

```
template <typename> class Pred; // a type predicate
```

- For example, most of the predicates in `<type_traits>` qualify.
- We'll employ a compile-time-only version of the venerable Expression Template idiom in the implementation.
- Here's the root type of the AST that will come in handy later:

```
struct E {};  // every node type is an E of some sort
```

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And/Or...

- We'll implement binary operators like this:

```
template <typename P1, typename P2>
struct And : E {
    template <typename T>
    static constexpr bool eval()
       { return P1::template eval<T>()
              & P2::template eval<T>(); }
};

template <typename P1, typename P2>
struct Or : E {
    ~~~
};
```

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&/|…

- For clarity and convenience, we'll use an infix operator interface to generate the type.

```
template <typename P1, typename P2>
constexpr And<P1, P2> operator &(P1, P2)
    { return And<P1, P2>(); }
```

- Note that we're interested entirely in the (compile time) return *type* of the function rather than the (runtime) return *value*.

✓ *Note the value of leveraging function template argument deduction to perform compile-time type algebra.*

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!

- Unary operators are even easier:

```
template <typename P>
struct Not : E {
    template <typename T>
    static constexpr bool eval()
        { return !P::template eval<T>(); }
};

template <typename P>
constexpr Not<P> operator !(P)
    { return Not<P>(); }
```

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Leaves

- The leaves in our compile time AST are unary type predicates.

```
template <template <typename> class Pred>
struct Id : E {
    template <typename T>
    static constexpr bool eval()
        { return Pred<T>::value; }
};

template <template <typename> class Pred>
constexpr Id<Pred> pred()
    { return Id<Pred>(); }
```

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<type_traits>

- It's convenient to provide versions of standard unary type traits as leaves:

```
constexpr auto isTriviallyCopyable
    = pred<std::is_trivially_copyable>();
constexpr auto isStandardLayout
    = pred<std::is_standard_layout>();
constexpr auto isPod
    = pred<std::is_pod>();
constexpr auto isLiteralType
    = pred<std::is_literal_type>();
// ad infinitum...
```

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Constructing Complex Predicates

- We perform a compile time traversal of the type representation of the AST with a type argument:

```
constexpr auto my_needs              // build an AST
    = isClass & (isPod | !isPolymorphic) ^ isShape;

constexpr auto your_needs            // build another
    = isClass & hasVirtualDestructor
              ^ !isNothrowCopyAssignable;
```

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Compile Time Evaluation

- We can evaluate an AST directly:

```
my_needs.eval<T>()
```

- ...but a little syntactic sugar is always in good taste:

```
template <typename T, typename AST> // get a bool
constexpr bool constraint(AST)
    { return AST().template eval<T>(); }

template <typename T, typename AST> // get a type...maybe
using Constraint =
    std::enable_if_t<constraint<T>(AST())>;
```

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Using the Predicate

- Sometimes we need a Boolean constraint:

```
static_assert(constraint<T>(my_needs),
              "My idiosyncratic needs are unmet.");
```

- Sometimes we're in SFINAE mode:

```
template <typename Me, typename You,
          typename = Constraint<Me, my_needs>,
          typename = Constraint<You, your_needs>>
void oy_vey(Me &&me, You &&you) { ~~~ }
```

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That's Not What I Meant!

- Unfortunately, this implementation—intended to simplify our use of SFINAE—causes sporadic compilation errors.
- The overloaded operators are too accommodating.

```
template <typename P1, typename P2>
constexpr And<P1, P2> operator &(P1, P2)
    { return And<P1, P2>(); }
```

- This overload will be considered for any & that accepts at least one class argument…

✓ *…which is not what I meant.*

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What I Mean Is...

- We'll call in SFINAE to rescue our SFINAE toolkit:

```
template <typename... Ps>
using all_E_t = enable_if_t<all_E<Ps...>::value>;
~~~
template <typename P1, typename P2,   // I meant...
          typename = all_E_t<P1, P2>> // ...only ASTs!
constexpr And<P1, P2> operator &(P1, P2)
    { return And<P1, P2>(); }
```

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What I Mean To Say Is...

- Increasingly our designs require us to distinguish not only among predefined and user-defined conversions, but to include arbitrary constraints and properties in making compile time decisions.
- One way to look at the situation is that we're no longer writing code just in terms of "first order" properties of types, but on design-specific, *ad hoc* "second order" properties.
- Some of these properties are extracted from types by the interface, some are offered to the interface by the type.

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An Emergent Property of C++'s Complexity

- SFINAE is increasingly employed in modern C++ to make these decisions, and the result is that interfaces are—or can be—simpler and more natural.
- This simplicity is an emergent property of C++'s complexity.
- Newer features of the C++ language and standard library provide straightforward ways to apply SFINAE to our designs.

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The End

Thanks for Coming!

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