

# A little about me B.A. (math's); M.S., Ph.D. (computer science). Professional programmer for over 50 years, programming in C++ since 1982. Experienced in industry, academia, consulting, and research: Founded a Computer Science Dept.; served as Professor and Dept. Head; taught and mentored at all levels. Managed and mentored the programming staff for a reseller. Lectured internationally as a software consultant and commercial trainer. Retired from the Scientific Computing Division at Fermilab, specializing in C++ programming and in-house consulting. Not dead — still doing training & consulting. (Email me!)

### Emeritus participant in C++ standardization

 Written 125+ papers for WG21, proposing such now-standard C++ library features as gcd/lcm, cbegin/cend, and common\_type, as well as the entirety of headers <random> and <ratio>.



- Influenced such core language features as *alias templates*, *contextual conversions*, and *variable templates*; working on *requires-expressions*, comparison operators, and more!
- Conceived and served as Project Editor for Int'l Standard on Mathematical Special Functions in C++ (ISO/IEC 29124), now incorporated into C++17's <cmath>.
- Be forewarned: Based on my training and experience,
   I hold some rather strong opinions about computer software and programming methodology these opinions are not shared by all programmers, but they should be!

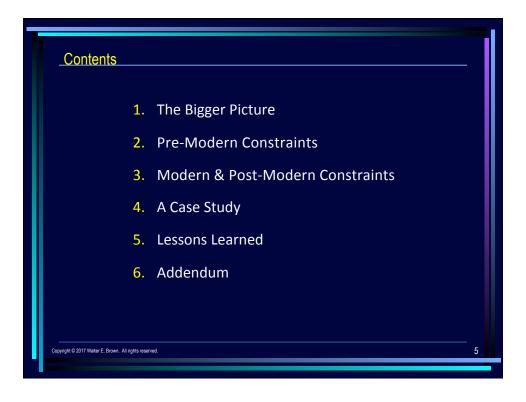
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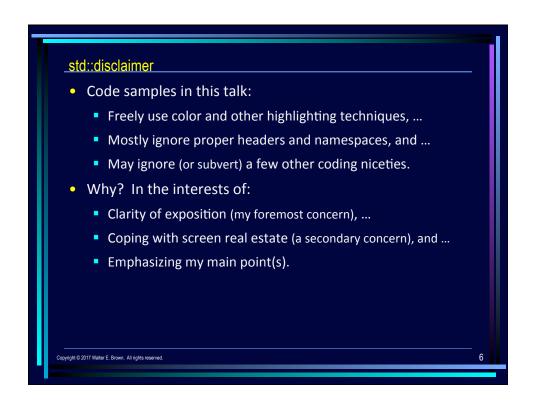
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- Compile-time constraints will soon be part of our routine
   C++ programming vocabulary:
  - Mainly due to requires, an expected new C++20 keyword ...
  - That introduces *requires-clauses* and *requires-expressions*.
- While this syntax is new to C++, the ideas are not, so ...
- This talk will explore:
  - What these ideas mean for us at a technical level, and ...
  - How they affect our past, present, and future C++ code.
  - (Some material is adapted from my recent WG21 paper "enable if vs. requires: A Case Study" [wg21.link/p0552].)

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# Nomenclature • What's common to these terms? • Precondition • Constraint • Narrow contract • requires-clause • Wide contract • requires-expression • All deal with requirements: • That a function or other component imposes, and ... • That are expected/assumed to be met before use. • How do they differ? • Some requirements affect a component's correct use. • Other requirements affect a component's very existence.

### Preconditions and contracts

- A function's precondition is a predicate:
  - Expected/assumed true each time the function is called:
    - Typically at run time, but at compile time if constexpr applies.
    - A function that checks its precondition doesn't really have one.
  - If its precondition is false, a function's behavior is undefined;
     the program (by definition) has a bug (see [res.on.required]/1).
- Preconditions are part of a function's contract with clients:
  - No preconditions ⇒ wide contract.
  - Any preconditions ⇒ narrow contract.
- Tangential to constraints, so not further discussed today:
  - (But keep an eye out for [[expects: ]], etc., in a future C++.)

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### How are constraints different?

- A constraint is a compile-time predicate associated with some program component (e.g., a function or a template):
  - The constraint must be satisfied (evaluated as true), or else!
  - Else the associated component won't/MUSTN'T BE COMPILED:
    - But that doesn't always imply that something is wrong!
    - Like preprocessor directives #if, #ifdef, etc., in this regard.
- C++ has always had certain innate constraints:
  - Types impose constraints: e.g., arg's must initialize parm's.
  - Template specialization imposes constraints on its arg's.
- The C++98 era limited us to such implicit techniques.

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### Newer technologies C++11 gave us tools for explicit constraint programming: Via static\_assert to force a diagnostic when constraint is false. Via std::enable\_if metafunction in a SFINAE context to prevent a template's instantiation (and thus to prevent its compilation). Via expression SFINAE, additional contexts in which deduction failures do not result in hard errors. Most recently, WG21 added: C++17: std::void\_t to support the detection idiom. C++17: constexpr if and discarded statements. C++20 WD: the Concepts [Lite] TS requires keyword.



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Statically asserting à la C++98

Declare something that might, but needn't, be valid:

Let the validity depend on the truth of the constraint.

Guarantees a diagnostic when the constraint isn't satisfied.

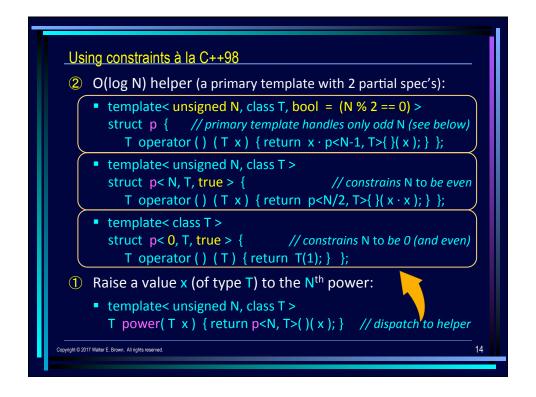
Example: int ensure[2 · int(constraint) - 1];

Or can apply tag dispatch for this purpose:

template < bool b > struct ensure { };

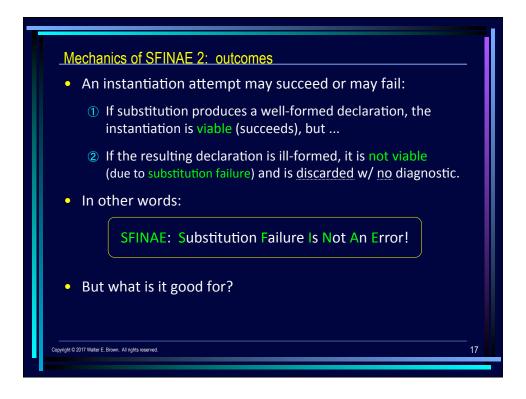
int g_impl(Tx, ensure<true>) { return ···; }

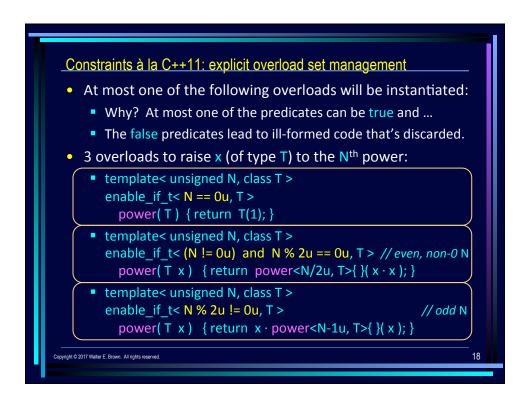
int g(Tx) { return g_impl(x, ensure<constraint>()); }
```



# Constraints à la C++11: the enable\_if type trait metafunction • If true, alias a given type; otherwise, provide no alias: • // primary template assumes the bool value is true: template< bool, class T = void > // default is useful, not essential struct enable\_if { using type = T; }; • // partial specialization recognizes a false value, so no alias: template< class T > struct enable\_if<false, T> { }; // no member named type! • Now consider a meta-call enable\_if< false, ... >::type: • Refers to a non-existent member named type. • Always an error, right? • No, only sometimes an error: SFINAE!

### Mechanics of SFINAE 1: instantiation • To instantiate a template's declaration, the compiler: ① Obtains (or figures out) each template argument: a) Take verbatim if explicitly supplied at template's point of use. b) Else deduce from function arguments, if any, at point of call. c) Else rely on (C++17) class template's deduction guide(s), if any. d) Else take from the declaration's default template arguments, if any. ② Replaces each occurrence of a template parameter by its corresponding template argument. (Substitution step.) • This process has one of two possible outcomes.





# What's wrong with enable\_if and SFINAE? Nothing at all. But ... The idiom does have limitations: It requires a template context. It's more challenging to use when a constructor is involved. And the resulting code tends to be verbose/wordy: It's often not very transparent to read/understand. Newer techniques for expressing constraints can be both easier to write and easier to read.



# Constraints à la C++17: constexpr if • An ordinary if, but evaluated at compile-time: • Branches not taken become discarded statements. • Each branch, even if discarded, must be parsable. • Raise x to the N<sup>th</sup> power — no dispatching, no overloading: • template< unsigned N, class T > T power(T x) { if constexpr(N == 0u) return T(1); else if constexpr(N % 2u == 0u) return power<N/2>(x · x ); // O(log N) multiplications else // N is odd return x · power<N-1>(x); } • While very useful, constexpr if doesn't fit all situations.

# Constraints à la Concepts [Lite] Concepts [Lite] TS was published in late 2015: Concepts parts weren't quite ready for C++17 integration. Other parts specify syntax/semantics for a requires-clause. A requires-clause may be applied: To any kind of template declaration, but ... Also to an ordinary (non-template) function declaration: In which case it's termed a trailing requires-clause.

### Technical details of requires

- A requires-clause induces constraints on its component:
  - These must be satisfied (true at compile time) ...
  - To permit the component to be (instantiated and) compiled.
  - An unsatisfied constraint causes its associated component (an instantiation or a function) to be ignored à la SFINAE.
  - Mustn't use any component whose constraint is unsatisfied.
- Subsumption is a new consideration:
  - Applies when one constraint subsumes a second constraint.
  - Gives us the notion of more constrained.
  - Akin to templates' notion of more specialized.
- None of this machinery depends on any concept keyword.

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### Constraints are useful even without templates

- E.g., overloaded functions:
  - void xmit(char buffer[]) requires local == endian::big;
  - void xmit(char buffer[]) requires local == endian::little;
  - void xmit(char buffer[]) requires local == endian::native;
  - Each function implements, say, the transmission protocol appropriate to its supported environment.
- How can overloading work with identical argument lists?
  - The requires-clause is now part of the signature, so that ...
  - Only declarations whose constraint is satisfied will go into a call's set of viable candidates, and ...
  - As usual, the other declarations won't be further considered.

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### A requires-clause has several forms

- Can take any compile-time predicate, e.g., a type trait.
- Or can refer to a named set of requirements (a concept):
  - E.g., using a concept C, can write requires C<T> .
  - The assoc. constraint is satisfied iff T meets C's specification.
- Or can use an equivalent shorter form:
  - Instead of template< class T > requires C<T> ... ,
  - Can write template< C T > ... (Stepanov/Concepts TS syntax).
- Or can use a requires-expression within a requires-clause:
  - E.g., -- requires requires { e<sub>1</sub>; e<sub>2</sub>; --; } -- .
  - The associated constraint is satisfied iff each expression e<sub>i</sub> is well-formed.

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4. A Case Study: Implementing std::swap

Every man lives by exchanging.
— ADAM SMITH

### Overview of the experiment

- Implemented std::swap's specification twice:
  - Once with only enable\_if technology, and then ...
  - Separately with only requires technology.
  - Identical function bodies; different function introductions.
- Validated each, identically, to ensure conformance:
  - Used established test cases from well-respected public and private sources.
  - Unexpectedly, testing showed a somewhat subtle difference in the two implementations' behavior!

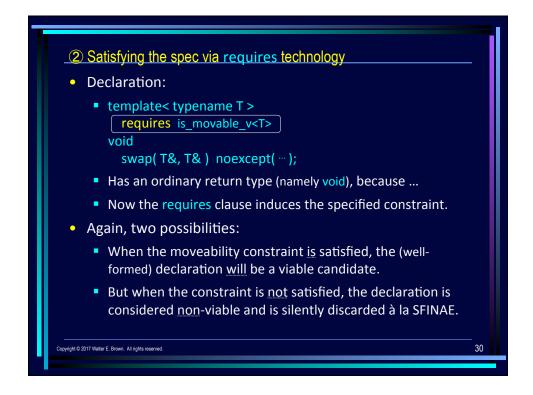
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### std::swap's specification

- Salient excerpts (from [utility.swap]):
  - template < class T > void swap( T&, T& ) noexcept( ··· );
  - This function "shall not participate in overload resolution unless [T is a movable type]."
- The highlighted formulaic words specify a constraint:
  - Namely, they require SFINAE-like behavior.
  - In this case, conforming implementers must tell the compiler to instantiate std::swap<T> only when T is a movable type.

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# Then came validation Consisted of several public and private test program suites. All went well, until ... When tested against is\_swappable.pass.cpp (from libc++): The enable\_if-based implementation passed, but ... The requires-based implementation failed! So what went wrong?

```
The failing test probes the is_swappable trait

Relevant excerpt (names shortened):

namespace ns {
    struct A { };
    template< class T > void swap(T&, T&) { }
}

Consider ns::A a, b; using std::swap; swap(a, b);:

Ordinary (unqualified) name lookup finds std::swap, and ...

Argument-dependent lookup (ADL) finds ns::swap.

Which is better to call? Classic partial ordering says neither!

static_assert(! std::is_swappable_v< ns::A > );

The test passes if A is not swappable — which it isn't, here, due to the expected ambiguity re which function to call.

This works fine for enable_if, but not for requires!
```

### So what's different about a requires-clause?

- It comes with a new rule (a tie-breaker of sorts):
  - When partial ordering considers two viable candidates, ...
  - The more constrained (by a *requires-clause*) candidate wins.
- In the second implementation:
  - std::swap was constrained by a requires-clause, so ...
  - The new rule applies (even though ns::swap was unconstrained).
- Result? The test code is no longer ambiguous:
  - std::swap is now the more constrained overload, and wins.
  - And the test's assertion, expecting ambiguity, now fails!

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### A caveat

- This talk uses the requires syntax and semantics as formulated in the *Concepts [Lite] TS*:
  - And as implemented by gcc -fconcepts for several years now.
- Much of that wording has been recently absorbed into the C++20 Working Draft, but:
  - That wording has already been considerably tweaked, and ...
  - WG21 discussions will continue, and so ...
  - Further technical adjustments seem likely.
- Therefore, what we actually get in C++20 may be slightly (or not-so-slightly ) different from today's exposition.
- But the thrust of today's talk will hold up, namely the ...

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# About language constraints C++ constraints via requires-clauses are more than just a language solution for the ugliness of enable\_if. If present, a constraint comes into play: Whenever instantiating a template, or even when just using a template name. As part of overload resolution, when compared during partial ordering. E.g., given void g() requires false { } // not overloaded g(); // no; can't call g void (\*p)() = g; // no; can't take g's address decltype(g)\* p = nullptr; // no; decltype(g) is an invalid type

### The big picture

- Core language constraints (*requires-clauses*, *etc.*) become an integral part of a declaration.
- Traditional declarations, not constrained in this way, just aren't quite the same!
- With requires-clauses come an additional set of rules for overload resolution.
- We programmers must be cognizant of those new rules in our coding.
  - Most of these details seem not yet widely well-understood.
  - Sample misleading advice: "If an implementation turns
     [enable\_if] constraints into concepts, you won't be able to
     tell the difference, programmatically." NAME WITHHELD

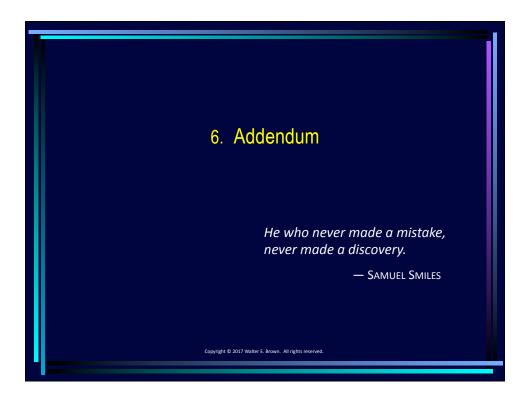
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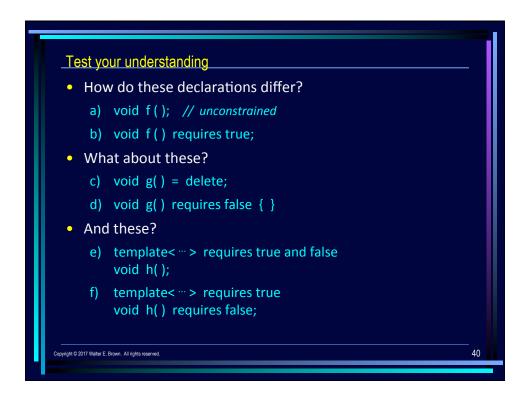
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### Consequences

- "You potentially change overload resolutions every time you add constrained overloads [to] a set containing [only] unconstrained templates with equivalent types."
  - Andrew Sutton
- "enable\_if cannot be directly replaced with requires without a semantic difference."
  - David Sankel
- Vendors are already free to meet today's standard library specifications via this new technology:
  - Doing so can (greatly!) simplify some implementations, ...
  - But, as shown, this (a) is detectable, (b) can affect user code in edge cases, and (c) affects the ABI (due to name mangling).

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### When you train/consult/discuss I respectfully suggest that only experienced programmers (journeymen and masters) should learn these details in the order I've presented them, namely bottom-up. Novices and apprentices should likely best approach this material from first principles, namely top-down. As you pass on this information, please keep in mind your various listeners' level of experience.

