

C++ Club Meeting Notes

Gleb Dolgich

2019-03-14

Making C++ Exception Handling Smaller On x64

<https://devblogs.microsoft.com/cppblog/making-cpp-exception-handling-smaller-x64/>

*Visual Studio 2019 Preview 3 introduces a new feature to reduce the binary size of C++ exception handling (try/catch and automatic destructors) on x64. Dubbed **FH4** (for `_CxxFrameHandler4`, see below), I developed new formatting and processing for data used for C++ exception handling that is ~60% smaller than the existing implementation, resulting in overall binary reduction of up to 20% for programs with heavy usage of C++ exception handling.*

https://www.reddit.com/r/cpp/comments/ayeg0b/making_c_exception_handling_smaller_on_x64/

C++, it's not you. It's me.

Blog post:

<https://c0de517e.blogspot.com/2019/02/c-its-not-you-its-me.html>

The crux of the issue <...> is the growing disconnect between people working on big, complex, performance-sensitive and often monolithic and legacy-ridden codebases that we find in game development, and the ideas of "modernity" of the C++ standard community.

Reddit

I'm just going to throw it out there: I'm tired of reading this kind of stuff from game devs.

Acting like they are the only ones with performance issues. The only ones with complex codebases. The only ones who actually ship code. The ones who are just solving more unique and difficult problems than anyone else, for which C++ falls short by more.

C++ On Sea 2019 - Walter E. Brown - C++ Function Templates: How Do They Really Work?

<https://youtu.be/nfIX8yWIByY>

The image shows a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide contains an "Instructive example" section with code snippets and questions. To the right, a man in a suit and glasses is speaking, gesturing with his hands. A logo for "C++ On Sea 2019" is visible in the bottom right corner.

Instructive example

- First, let's overload the name `g` (braced def'n bodies omitted):
 - template< class T > void g(T const&) //function template
 - template < > void g(int const&) // explicit specialization
 - void g(double) // ordinary function
- Q1: How many *declarations* are in the above?
- Q2: How many names do they *introduce* (declare)?
- Answers:
 - There are **3** declarations (numbered above), but ...
 - Only **2** (mangled) names are being introduced.
 - An explicit specialization does not introduce a new name; it re-uses the (existing) name of its primary template!

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<https://youtu.be/nfIX8yWIByY>

The image shows a video frame. On the left is a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide features a "SPOILER ALERT!" section with a horizontal line. Below it, a bulleted list discusses template declarations. To the right of the slide, a man with glasses and a beard, wearing a dark suit and tie, is gesturing while speaking. In the bottom right corner of the slide area, there is a logo for "C++ On Sea 2019" featuring stylized waves and the year.

SPOILER ALERT!

- From those same 3 declarations ...
✗ template< class T > void g(T const&) //function template
✗ template < > void g(int const&) // explicit specialization
✓ void g(double) // ordinary function
... at most 2 candidate declarations will be considered!
- What are those 2 candidate declarations?
 - The ordinary function declaration void g(double); , and ...
 - A synthesized function declaration void g<>(D const&);
 - Type D is often inferred (e.g., from the arg's type in the call).
 - Then the primary template's declaration is copied, with each instance of template param T replaced by the inferred type D.
 - Can ensure this substitution by calling as g<D>(-); .

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<https://youtu.be/nfIX8yWIByY>

The image shows a video frame. On the left is a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide contains a bulleted list and some code snippets. On the right is a photograph of a man with glasses and a beard, wearing a dark suit, standing and gesturing while speaking. In the bottom right corner of the slide area, there is a logo for "C++ On Sea 2019" featuring a stylized yellow and blue geometric pattern over wavy lines.

Wait, what?

- Why is the (primary) function template not a candidate?
✗ template< class T > void g(T const&) //function template
✗ template < > void g(int const&) // explicit specialization
✓ void g(double) // ordinary function
- Recall that the goal is to select a function (to be called), but:
 - A primary template can't be called.
 - Why not? Because a template isn't a function!
 - Nor is a template any other kind of callable entity.
- ∴ Templates are never candidates for overload resolution.

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Another way to think about it

A cookie cutter :: a function template.

Instantiation

Different dough?
Different cookie!

Cookie dough :: template arg's. A cookie :: a function.

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C++ On Sea 2019 - Walter E. Brown - C++ Function Templates: How Do They Really Work?

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The image shows a video frame. On the left, a presentation slide has a dark blue header with white text reading "C++ Function Templates: How Do They Really Work? - Walter E. Brown". Below the header, a section titled "So why can't we call a function template?" is shown in yellow. A bulleted list follows, with some items in green. On the right, a man with a beard and glasses, wearing a dark suit and tie, stands in a room, holding a small device. In the bottom right corner of the slide area, there is a logo for "C++ On Sea 2019" featuring stylized waves and the year.

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So why can't we call a function template?

- Well, would you try to eat a cookie cutter?
 - A cookie cutter isn't edible; it's not a cookie.
 - A function template isn't callable; it's not a function.
- So, a template can never be a candidate to be called:
 - But just as we use cookie cutters + dough to make cookies, ...
 - A compiler uses templates + arguments to make functions!
- I.e., the compiler will make/create/**synthesize** a function declaration from a (primary) function template declaration:
 - But first inspects the call, **deduces** argument type(s), then ...
 - Substitutes** those argument types for template parameters ...
 - Resulting in a **synthesized** candidate for overload resolution.

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The image shows a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide content includes a question, several bullet points, and some code snippets. To the right of the slide, a man with glasses and a beard, wearing a dark suit and blue tie, is seated and looking towards the screen. In the bottom right corner of the slide, there is a logo for "C++ On Sea 2019" featuring a stylized sun and waves.

Well, okay, but then ...

- Why is the explicit specialization not a candidate?
~~template< class T > void g(T const&) //function template~~
~~template < > void g(int const&) // explicit specialization~~
✓ void g(double) // ordinary function
- Yes, it's a declaration, but:
 - Some declarations introduce no new names!
 - E.g., `static_assert` (see [dcl.dcl]/6).
 - E.g., a redeclaration (repeats a name previously introduced).
 - Of more interest, “[an] explicit specialization of a template does not introduce a name” (see [namespace.memdef]/1).
 - Hence “specializations don’t participate in overloading”
— Herb Sutter, 2001

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We still need a function def'n to compile/call — where is it?

- Suppose *overload resolution* selects a candidate declaration synthesized from `template< class T > void g(T const&);`:
 - E.g., for a call `g(42)`, makes/selects `void g<>(int const&);`.
 - E.g., for a call `g('4')`, makes/selects `void g<>(char const&);`.
- ① If there's a pre-existing specialization of that template ...
 - Whose template arg's match those of the chosen candidate, ...
 - That specialization is our function to compile (once)/(later) call.
- ② Otherwise, the compiler must/will (only now) *instantiate* a specialization matching the chosen candidate declaration:
 - By duplicating the primary template's definition and ...
 - Substituting template arguments for template parameters ...

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The image shows a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide content is about controlling instantiation, listing points such as demanding instantiation and syntax. To the right, a man in a suit and glasses is speaking, holding a blue pen. A logo for "C++ On Sea 2019" is visible in the bottom right corner.

C++ Function Templates: How Do They Really Work? - Walter E. Brown

Controlling instantiation ①

- It's possible to demand a template's instantiation:
 - Even if there's no corresponding call or other use.
 - Will guarantee which compilation unit contains the function.
 - Useful when creating a library, for example.
- Syntax:
 - After the primary template:
`template< class T > go(T const &) { ... }`
 - Declare an explicit instantiation:
`template< int > go(int const &);`.
 - Can omit the template argument if it's otherwise obtainable.
- Explicit instantiation is rarely useful in a header.

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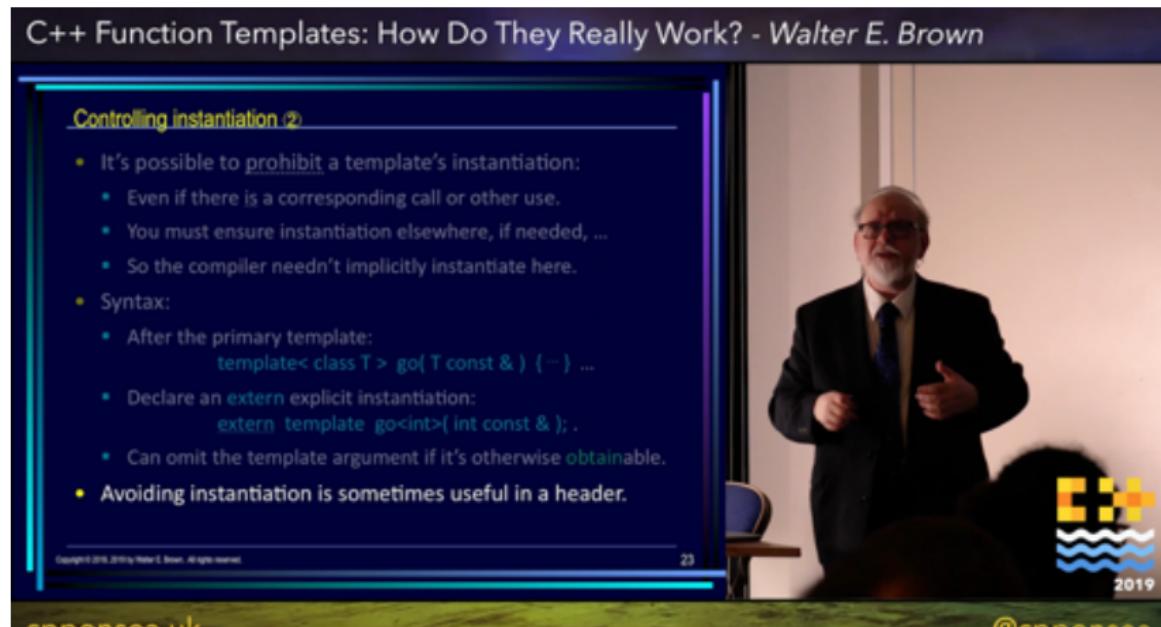
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Controlling instantiation ②

- It's possible to prohibit a template's instantiation:
 - Even if there is a corresponding call or other use.
 - You must ensure instantiation elsewhere, if needed, ...
 - So the compiler needn't implicitly instantiate here.
- Syntax:
 - After the primary template:

```
template< class T > go( T const & ) { ... }
```
 - Declare an extern explicit instantiation:

```
extern template go<int>( int const & );
```
 - Can omit the template argument if it's otherwise obtainable.
- Avoiding instantiation is sometimes useful in a header.

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Compiler-generated function templates (since C++14)

- Recall that evaluating a *lambda-expression* produces a *closure* object that “behaves like a function object”:
 - auto *lambda1* = [] (int *x*) { return *x* < 0; };
 - struct { // *lambda1*'s type; such a type's name can't be uttered auto *operator()* (int *x*) { return *x* < 0; } ;};
- Evaluating a *generic lambda-expression* produces a closure object whose *operator()* is a function template:
 - auto *lambda2* = [] (auto *x*) { return *x* < 0; };
 - struct { // *lambda2*'s type; such a type's name can't be uttered template< class _T > auto *operator()* (_T *x*) { return *x* < 0; } ;};

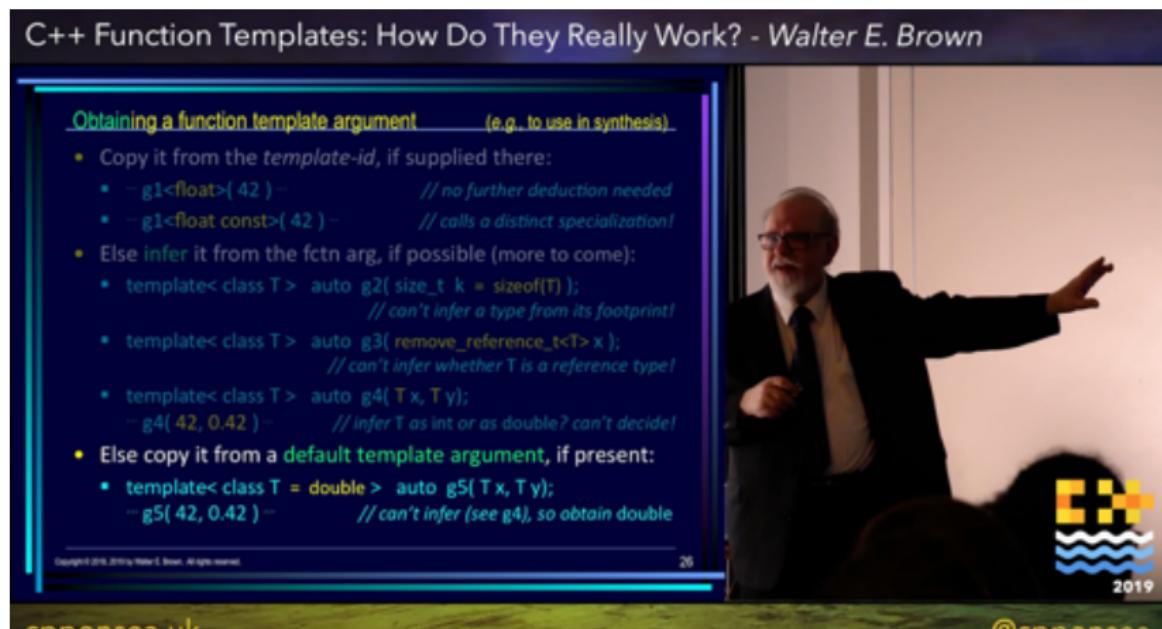
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Obtaining a function template argument (e.g., to use in synthesis).

- Copy it from the *template-id*, if supplied there:
 - `- g1<float>(42) -` *// no further deduction needed*
 - `- g1<float const>(42) -` *// calls a distinct specialization!*
- Else infer it from the fctn arg, if possible (more to come):
 - `template< class T > auto g2(size_t k = sizeof(T));` *// can't infer a type from its footprint!*
 - `template< class T > auto g3(remove_reference_t<T> x);` *// can't infer whether T is a reference type!*
 - `template< class T > auto g4(T x, T y);`
`- g4(42, 0.42) -` *// infer T as int or as double? can't decide!*
- Else copy it from a default template argument, if present:
 - `template< class T = double > auto g5(T x, T y);`
`- g5(42, 0.42) -` *// can't infer (see g4), so obtain double*

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The image shows a video frame. On the left, a presentation slide has a dark blue header with white text that reads "C++ Function Templates: How Do They Really Work? - Walter E. Brown". Below the header, there is a question in green text: "What does type inference consider?". A bulleted list in white text follows: "The success and result of type inference considers:" with four sub-points: "The function parameter's type (ref-qual? cv-qual?), vis-à-vis the function argument's type, ...", "So that that argument can initialize that parameter.", and "Conversions? Never considered when inferring a type!". At the bottom of the slide, there is a copyright notice: "Copyright 2019, 2019 by Walter E. Brown. All rights reserved." and the number "27". On the right side of the frame, a man with a beard and glasses, wearing a dark suit and tie, is standing and gesturing with his hands while speaking. In the bottom right corner of the video frame, there is a logo for "C++ On Sea 2019" featuring a stylized yellow and blue wave design.

What does type inference consider?

- The success and result of type inference considers:
 - The function parameter's type (ref-qual? cv-qual?), vis-à-vis the function argument's type, ...
 - So that that argument can initialize that parameter.
 - Conversions? Never considered when inferring a type!

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Inferring template arg `T` from fcn param/arg combinations

<code>g(?)</code>	<code>T</code>	<code>T &</code>	<code>T const&</code>	<code>T const &&</code>	<code>T &&</code>
42	<code>int</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int</code>
<code>k</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int &</code>
<code>kl</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int &</code>
<code>kr</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int</code>	<code>int &</code>
<code>kc</code>	<code>int</code>	<code>int const</code>	<code>int</code>	<code>int</code>	<code>int const &</code>
<code>kcl</code>	<code>int</code>	<code>int const</code>	<code>int</code>	<code>int</code>	<code>int const &</code>
<code>kcr</code>	<code>int</code>	<code>int const</code>	<code>int</code>	<code>int</code>	<code>int const &</code>

forwarding reference

- Type inference happens in other C++ contexts, too, and follows analogous rules. E.g., `auto x = 42;`.
- Recall that parameter passage is initialization; thus, a call's argument is just an initializer for the fcn param.

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The video frame shows a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide content is as follows:

The role of partial ordering (adapted from <https://docs.microsoft.com/>)

- Sometimes, candidates can be synthesized from each of several function templates that match a call's arguments:
 - C++ performs **partial ordering** of such templates/candidates to determine which function is preferred.
 - (The ordering is **partial** because some templates/candidates can be considered equally specialized.)
- The compiler seeks the **most specialized** of the possible (**viable**) candidates:
 - E.g., suppose one fctn template has a fctn param of type **T**, while a second fctn template has a fctn param of type **T***.
 - Given a call with a fctn arg of pointer type, the **T*** param is deemed **more specialized**, hence preferred over the **T** param (although both would be viable matches).

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Test your understanding. (the "Dimov/Abrahams example")

- First, let's overload the name `h` (no tricks; this is valid code):
 - `template< class T > void h(T) { ... } // (a)`
 - `template< > void h(int *) { ... } // (b)`
 - `template< class T > void h(T *) { ... } // (c)`
- Now, let's call `h` — but which `h`? (This matters; bodies may differ.)
 - `int * p = nullptr;`
`h(p); // will call an implicit specialization of (c)`
- What templates/candidates will be considered?
 - ✗ Synthesized from (a): `void h<int *>(int *);`
 - ✓ Synthesized from (c): `void h<int >(int *); // more specialized`
 - Note that (b) is an explicit specialization of (a), not of (c).
Why? Where (b) is declared, only (a) is in scope; haven't yet seen (c).

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Test your understanding [②](#)

- Here are the same declarations, but in a different order:
 - `template< class T > void h(T) { ... } // (a)`
 - `template< class T * > void h(T *) { ... } // (c)`
 - `template< > void h(int *) { ... } // (b)`
- Let's call `h` the same way — same `h` as before?
 - `int * p = nullptr;`
`h(p); // will call (b), now an explicit specialization of (c)`
- What changed by moving (b) to follow both (a) and (c)?
 - Both (a) and (c) are now in scope when (b) is seen, so ...
 - Partial ordering of function templates picks (c) as the primary template corresponding to the explicit specialization (b).
Why pick (c) over (a)? Just as before, (c)'s parameter is already a pointer type, hence (c) is **more specialized**.

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Test your understanding (3)

- Finally, let's restore the original order, then append (d):
 - template< class T > void h(T) { ... } // (a)
 - template< > void h(int *) { ... } // (b)
 - template< class T > void h(T *) { ... } // (c)
 - template< > void h(int *) { ... } // (d) →
- Note the similarity of (b) and (d):
 - Is the above still legal code? If so, which **h** is called now?
 - int * p = nullptr;
h(p); // this time will call (d), an explicit specialization of (c)
- Note the substitutions in the explicit specializations:
 - template< > void h<int *>(int *) { ... } // (b)
 - template< > void h<int >(int *) { ... } // (d)

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The image shows a video frame. On the left, a presentation slide has a dark blue header with white text reading "C++ Function Templates: How Do They Really Work? - Walter E. Brown". Below the header, a section titled "Why write your own specialization?" is shown with a horizontal line. A bulleted list follows:

- Typically, to improve an algorithm's performance in a particular case, via instructions particular to that case.
- Example:
 - The generic `swap` algorithm takes 3 copy/move operations.
 - Sometimes can swap uints faster via 3 xor operations.
- Often termed **tuning, refining, special-casing, adapting, customizing, tailoring**, or simply **specializing** an algorithm:
 - Do take care to obtain an outcome equivalent to that yielded by the algorithm for the general/generic case.
 - (Not enforced by C++, but Bad Things will otherwise ensue.)

At the bottom of the slide, there is a copyright notice: "Copyright © 2019, 2019 by Walter E. Brown. All rights reserved." and the number "35". To the right of the slide, a man with a beard and glasses, wearing a dark suit, is standing and gesturing with his hands. In the bottom right corner of the video frame, there is a logo consisting of a stylized yellow and orange cross-like shape above three wavy blue lines, with the text "C++ On Sea 2019" below it. At the very bottom of the slide, there is a URL "cpponsea.uk" and a handle "@cpponsea".

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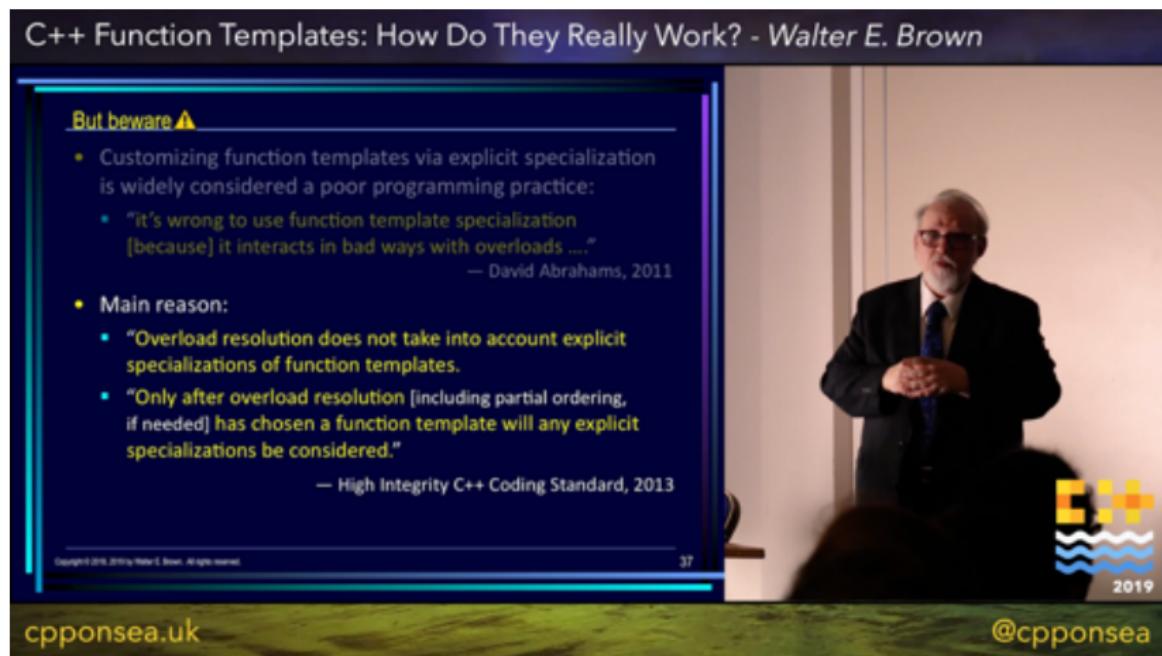
The image shows a video frame. On the left is a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide has a blue header and a white body. In the top right corner of the slide, there is a small logo consisting of a stylized orange and yellow cross-like shape above three wavy lines, with the text "C++ On Sea" and "2019" below it. The main content of the slide is titled "Placement of specializations" and contains two bullet points:

- As of C++17, "an explicit specialization may be declared in any scope in which the corresponding primary template may be defined" [temp.expl.spec]/2.
- Examples:
 - template< >
void A :: g<int>() { ... }
// specializes g, a member function template of class A
 - template< class T >
template< >
void B<T> :: h<int>() { ... }
// specializes h, a member function template
// of class template B

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But beware ▲

- Customizing function templates via explicit specialization is widely considered a poor programming practice:
 - “it’s wrong to use function template specialization [because] it interacts in bad ways with overloads ...”
— David Abrahams, 2011
- Main reason:
 - “Overload resolution does not take into account explicit specializations of function templates.”
 - “Only after overload resolution [including partial ordering, if needed] has chosen a function template will any explicit specializations be considered.”
— High Integrity C++ Coding Standard, 2013

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Advice

- ① Avoid explicit specialization of function templates as a customization technique.
- ② If you need to customize function template `f` for type `M`:
 - Prefer to overload it ...
 - Via an ordinary function `f` taking parameter(s) of type `M`.
- ③ If you must specialize to customize:
 - Recall: class template specializations can't affect overload resolution — names of class templates can't be overloaded!
 - So, invent a helper `class` template `H` with an `operator()`, ...
 - Customize `operator()` in an explicit specialization `H<M>`, ...
 - Then have `f<T> forward` (instantiate & call) to a `function object` of type `H<T>`: e.g., `H<T>{ }(-)`.

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Expo 2019

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The image shows a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide content discusses the use of `constexpr-if` instead of specialization, mentioning that it is evaluated at compile-time, becomes a discarded statement if not taken, and each branch must be parseable. It provides an example of calculating x^N using fewest multiplies without explicit specializations. The slide also includes a copyright notice and a page number (39). To the right of the slide, a man with glasses and a beard, wearing a dark suit, is standing and gesturing with his hands. In the bottom right corner of the slide area, there is a logo for "C++ On Sea 2019".

Consider `constexpr-if` in lieu of specialization (C++17)

- An ordinary `if`, but evaluated at compile-time:
 - Branch not taken becomes a **discarded statement**,
 - Even if discarded, each branch must be parseable.
- E.g., x^N using fewest mult's w/out explicit specializations:

```
template< unsigned N, class T > // N is a non-type parameter
T power( T x ) {
    if constexpr( N == 0 ) return T(1);
    else if constexpr( N % 2 == 0 )
        return power<N/2>( x * x ); // O(log N) multiplications
    else // N is odd
        return x * power<N-1>( x );
}
```

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<https://youtu.be/nfIX8yWIByY>

The image shows a video frame. On the left, a presentation slide has a dark blue header with white text reading "C++ Function Templates: How Do They Really Work? - Walter E. Brown". Below the header, a section titled "Review" is visible. Under "Review", there are two main bullet points: "Recall that a `friend` declaration injects (introduces) the friend's name into the nearest enclosing namespace:" and "Examples:". The "Examples:" section contains three code snippets. The first snippet shows a class A with a friend function go() that is not visible in its own scope due to unqualified name lookup. The second snippet shows the same class A with a friend function go() that is now visible in its own scope because it is qualified by the class name. The third snippet shows a class B with a friend function go() that is visible in its own scope. At the bottom of the slide, there is a copyright notice: "Copyright 2019, JotW Ltd. All rights reserved." and the number "42". On the right side of the frame, a man with glasses and a beard, wearing a dark suit, is standing and gesturing with his hands, likely speaking to an audience. In the bottom right corner of the slide area, there is a small logo consisting of a yellow cross-like shape above three wavy lines, with the year "2019" written below it. The bottom of the image shows a dark green surface, possibly a table or stage, with the text "cpponsea.uk" and "@cpponsea" repeated twice.

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The image shows a video frame. On the left is a presentation slide titled "C++ Function Templates: How Do They Really Work? - Walter E. Brown". The slide has a blue header and a white body. It contains a section titled "Function templates & friendship" with a horizontal line. Below it is a bulleted list of points about function template friendship, followed by examples of code. At the bottom of the slide, there is a copyright notice and the number "43". On the right side of the frame, a man with glasses and a beard, wearing a dark suit and tie, is standing and gesturing with his hands as if speaking. In the bottom right corner of the slide area, there is a small logo consisting of a yellow cross-like shape above three wavy lines, with the text "C++ On Sea 2019" underneath.

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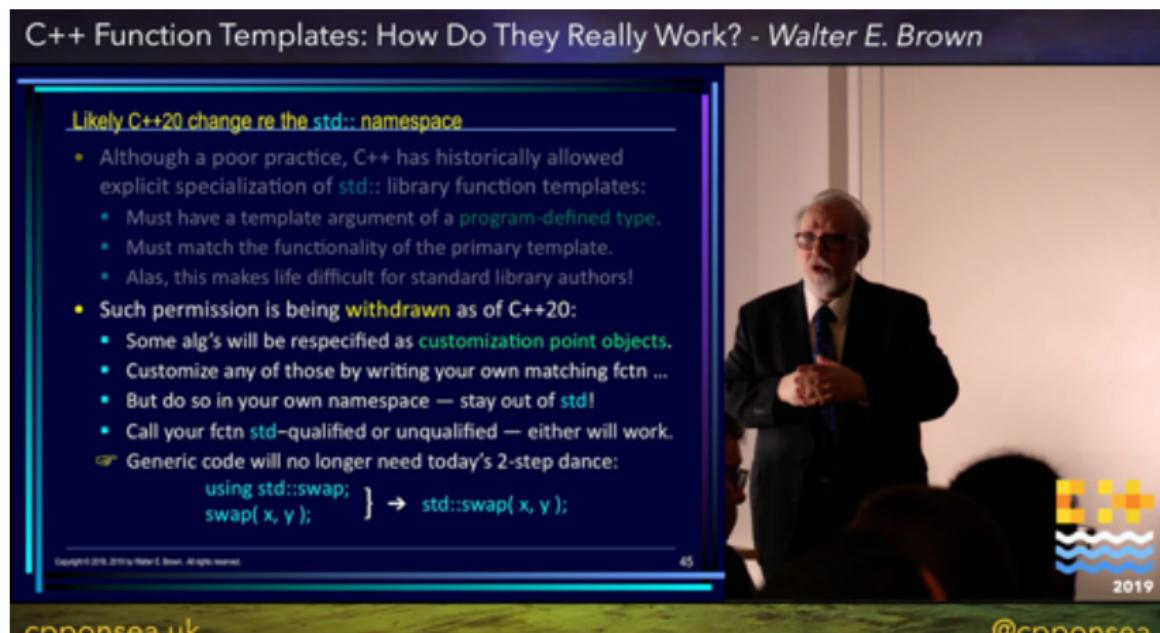
Function templates & friendship

- A class (or class template) can grant `friendship`:
 - To any particular specialization of a function template, or ...
 - To all specializations of a function template.
- Same name visibility rules hold.
- Examples; assume `template< class T > void go() { ... };`
 - `class A { friend void go<int>(); }; // just go<int>`
 - `class B { template< class T > friend void go(); }; // all gos`
 - `template< class T >`
`class C { friend void go<T>(); }; // just the corresponding go`

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Likely C++20 change re the `std::` namespace

- Although a poor practice, C++ has historically allowed explicit specialization of `std::` library function templates:
 - Must have a template argument of a `program-defined type`.
 - Must match the functionality of the primary template.
 - Alas, this makes life difficult for standard library authors!
- Such permission is being withdrawn as of C++20:
 - Some alg's will be respecified as `customization point objects`.
 - Customize any of those by writing your own matching fctn ...
 - But do so in your own namespace — stay out of `std`!
 - Call your fctn `std`-qualified or unqualified — either will work.

Generic code will no longer need today's 2-step dance:

```
using std::swap; } → std::swap( x, y );
```

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Likely C++20 simpler template declaration syntax

- An `auto`-based syntax is en route for C++20:
 - `template< class T >`
`auto f(T& x);` // C++17 return type deduction
 - `auto f(auto& x);` // C++20 abbrev. function template
- Intended to work with constrained declarations, too ("*Constraint auto goes wherever auto goes*"):
 - `template< class T >`
`requires Sortable<T>;` // Concepts TS → C++20
`auto f(T& x);`
 - `template< Sortable T >` // Stepanov → TS → C++20
`auto f(T& x);`
 - `auto f(Sortable auto& x);` // recent adjective syntax → C++20

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There's always more to learn in C++

- `class`, `alias` (C++11), and `variable` (C++14) templates.
- Templates with several template parameters.
- Templates involving `parameter packs`, `non-type template parameters`, and/or `template template parameters`.
- Class template argument deduction and its guides (C++17).
- Template metaprogramming (see my CppCon 2014 videos).
- Constrained templates (concepts TS/C++20).
- Recommended reading:
 - Vandevoorde, Josuttis, & Gregor:
C++ Templates: The Complete Guide, 2nd Ed.
© 2017. ISBN 978-0321714121.

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Online resources

- David Abrahams: Comment on "How to overload std::swap()."
 - stackoverflow.com/questions/11562/how-to-overload-stdswap#comment-5729583
- Herb Sutter: "Why Not Specialize Function Templates?"
 - www.gotw.ca/publications/mill17.htm
- Programming Research Ltd.: "Do not explicitly specialize a function template that is overloaded with other templates."
 - www.codingstandard.com/rule/14-2-2-do-not-explicitly-specialize-a-function-template-that-is-overloaded-with-other-templates

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WG21 papers

- Walter E. Brown: "Thou Shalt Not Specialize std Function Templates!"
 - wg21.link/p0551
- Eric Niebler: "Suggested Design for Customization Points."
 - wg21.link/N4381
- Davis Herring & Roger Orr: "Differences Between Functions and Function Templates"
 - wg21.link/p1392

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RxCpp and Executors with Kirk Shoop

<http://cppcast.com/2019/03/kirk-shoop/>

- ▶ Ranges deal with objects distributed in space, Rx deals with objects distributed in time
- ▶ Executors need to be compatible with tasks and observables
- ▶ Works at Facebook with Eric Niebler and Lewis Baker on making ranges work with coroutines and executors
- ▶ Rx was developed for a garbage-collected object lifetime, but with C++ it's more complicated

Stackless vs. Stackful Coroutines

Article by Varun Ramesh, 18 August 2017

Announcing the Open Sourcing of Windows Calculator

- ▶ Blog post
- ▶ <https://github.com/Microsoft/calculator>
- ▶ https://www.reddit.com/r/programming/comments/ay2aq6/announcing_the_open_sourcing_of_windows/
- ▶ Counting Bugs in Windows Calculator

Everything You Never Wanted to Know About CMake

<https://izzys.casa/2019/02/everything-you-never-wanted-to-know-about-cmake/>

Quote

Unknown:

Weeks of coding can save you hours of planning.