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A polymorphic wrapper for all Callable objects (rev. 3)

A new template `unique_function` is proposed. It is just like `std::function`, minus the copy constructor and copy assignment operator. This allows it to wrap function objects containing non-copyable resources, per LEWG issue 34. It also helps to express the idea of an operation that can only be performed once.

1. Motivation

In the beginning, `boost::function` was designed as a generalization of function pointers — as opposed to a radically broad notion of function values. Function objects were small and stateless. Users with a penchant for adventure and compiler diagnostics could use `boost::bind`, and given a few arguments, it would push `function` into the heap allocation regime. More prudent engineering would call for a manually-defined local class, filtered through `boost::ref` to squash the inefficient value semantics.

Times have changed. Lambda-capture syntax like `[u = std::move(u)](io_response r) {r.send_next(u);}` is not only trendy, but safe and convenient. Functional programming patterns are actually gaining traction, which means that real-world function objects are expected to do whatever other objects do, and to encapsulate whatever might be found in a local scope. Non-copyable objects are not uncommon, and non-copyability is viral.

Separately, since `function` is useful as an interface type, it can delegate resource ownership to a library. Before a library frees a resource, it may still be safely referenced locally. Such cases require a guarantee that the target object used by the library is the original one and not a copy.

Finally, when performance analysis finds that a copying a particular class causes a bottleneck, one may wish to delete its copy constructor, to prevent the problem from returning. Likewise, copy constructors of target objects that are never copied are template bloat.

1.1. Difficulty of workarounds

An event dispatching system, for example, might wish to manage ownership of event handler objects via `std::function`. This would require that the user provide copyable objects even though each will remain unique.

Current workarounds include using `reference_wrapper` as the function target type, trying to pass a unique `std::function` object always by reference or `reference_wrapper`, or defining an always-throwing copy constructor. These sacrifice overhead or user-friendly ownership semantics for artificial copyability.

With `unique_function`

An event-handler map is trivial to implement if the library is willing to demand that the handlers be copyable. The end result is optimal, but inflexible.

```
std::map< std::string, std::function< void() > > commands;
    // ^ Want unique_function here.

template< typename ftor >
void install_command( std::string name, ftor && handler ) {
    commands.insert({ std::move( name ),
        std::forward< ftor >( handler ) });
}
```

Without `unique_function`

Improving the external interface quality by allowing non-copyable types is fairly difficult. Efficiency is also reduced. In particular, we need two parallel type erasures.

```
struct owned_function {
    // Order of these members is significant, and this must remain an aggregate.
    std::function< void() > wrapper;
    std::unique_ptr< void, void (*)( void * ) > alloc;
};
std::map< std::string, owned_function > commands;

template< typename ftor, typename ... a >
void install_command( std::string name, a && ... arg ) {
    auto ptr = std::make_unique<ftor>( std::forward< a >( arg ) ... );
    commands.insert( std::make_pair(
        std::move( name ), owned_function {
            std::ref( * ptr.get() ),
            { // unique_ptr constructor arguments
                ptr.release(), // Must call get() before release().
                [] (void *p) { delete static_cast< ftor * >( p ); }
            },
        }
    ) );
}

template< typename ftor >
void install_command( std::string name, ftor && handler ) {
    install_command< std::decay_t< ftor >, ftor && >
        ( std::move( name ), std::forward< ftor >( handler ) );
}
```

Plenty of other solutions exist, perhaps some simpler than this. Arriving at a simple solution is hard, though! The above has non-obvious aspects in overload resolution, order of evaluation, and `unique_ptr` deleter customization. It works around some [unimplemented DRs](#) and exposes some [other bugs](#). Many solutions are less flexible or incorporate extraneous functionality such as data structures. None are easy or efficient enough, and certainly none are idiomatic.

2. Proposal

A new template `unique_function` is introduced. Its members and their behavior are identical to `std::function`, except:

- Its copy constructor and copy assignment operator are defined as deleted.
- It does not use (nor require the existence of) copy constructors of target objects.
- Zero-overhead converting constructors and assignment operators from the corresponding `std::function` specialization are provided.

There are no changes to `std::function` whatsoever. The new template can be placed in namespace `std` or within `std::experimental`. Let its feature test macro be called `__cpp_lib_[experimental_]unique_function`.

The Fundamentals TS already specifies a class `experimental::function` with polymorphic allocation policies. Its changes are orthogonal to this proposal, but to this author's knowledge no current public implementation exists. This proposal's prototype also implements P0043 *Function wrappers with allocators and noexcept*, which generalizes the allocation features of `experimental::function` and thus could be used as the basis for a shipping implementation of it. Bearing `std::function` interoperability in mind, though, direct adoption into the standard is preferable.

2.1. Rationale

This is a minimalistic proposal. Other problems exist in `std::function`, but they are better solved separately.

Introducing a new template

A new primary template is introduced, as opposed to a specialization of `std::function`. Good generic code is written against an interface (e.g. Callable or availability of `target`), without naming an implementation (e.g. `function`). Existing templates which do hard-code `function` support may not be compatible with `unique_function` anyway.

Naming

The name `unique_function` is chosen because it only permits one instance of the target value. Like `unique_ptr`, it does not generate duplicate copies. While it is possible for two function objects to have identical invocation behavior, this does not necessarily contradict uniqueness: Behavioral equivalence is an impossible problem. On the other hand, it is intuitive to think of *resources* managed by e.g. `unique_ptr` as unique. When a reader sees `unique_function`, it may be assumed that it holds, and is, such a resource.

Another possible name is `move_only_function`. This would confusingly refer to the behavior of the wrapper itself as opposed to qualities of the wrapped object. The target may be copyable, or (given in-place construction) non-movable.

When such a utility has been implemented (see §6 *Implementations* below), `unique_function` has been the more popular name.

Interoperability

When `std::function` is converted to `unique_function`, the target is transferred just as if it were a copy- or move-construction. No wrapping overhead will be added when an interface migrates `std::function` parameters to `unique_function`.

No in-place construction

In-place construction has been removed from this proposal since N4543. It may be added as a uniform interface with `variant`, `any`, and other type-erasure facilities.

const safety

One known defect of `std::function` is that it offers a const-qualified call operator which invokes the target by a non-const access path. This problem is not addressed by this proposal. It is addressed by P0045R1 §2.1 like so:

1. Introduce a wrapper which performs const access: `function<void() const>`.
2. Add a const-unqualified `operator()` overload to wrappers like `function<void()>`.
3. Deprecate the legacy, const-qualified call operator in unqualified wrappers.

Ignoring the first step, the second two steps are already a conforming extension, and do not require any proposal.

Rather than introduce `unique_function` with a soon-to-be deprecated call operator signature, we could simply never provide it in the first place. However, this would render `const unique_function` uncallable, with no user recourse except to switch back to `function` or to use `const_cast`. (For example, a `unique_function` nonstatic member would not be callable from a `const&` reference to a class.) This would be an unacceptable defect.

The idea of introducing `unique_function` with the `const` qualification defect has proven controversial, so P0045R1 recommends to omit the deprecated call operator from `unique_function`.

3. Usage

`unique_function` is available as a solution when `std::function` balks at a non-copyable target. In the broad middle ground of usage where wrappers may be copied but aren't, the choice between `unique_function` and `std::function` comes down to aesthetics.

Interfaces

Non-template interfaces taking function objects are encouraged to accept `unique_function` instead of `std::function`. Like `function`, it should canonically be passed by value. Moving should incur minimal overhead, and there is no potentially expensive copy or heap allocation.

When returning polymorphic function objects to the user, it is still better to use `std::function` if possible, for the sake of flexibility.

Passing by value

`std::ref` is used to non-destructively pass `unique_function` using the by-value convention, for example to the standard Algorithms library, when it will not be retained. This is also a good practice for `std::function`, as it achieves equivalent behavior without incurring a potentially expensive copy.

4. Method of description

Differences are given relative to P0045R1 *Qualified `std::function` signatures* applied to the working draft N4618. That proposal is considered a prerequisite to this one because it is undesirable to introduce the new class with a `const-unsafe` call operator.

The text, including the `unique_function` synopsis, should reflect any adopted changes to `function` from other proposals or defect resolutions, for example, if `noexcept` is restored to the move constructor.

`function` continues to evolve according to defect reports, and several further proposals are foreseeable. Therefore, much work will be saved by avoiding text duplication. It is proposed to use a method of description where `function` and `unique_function` share most of their specification.

5. Proposed wording

First, adjust [func.wrap] §20.9.12 to broader scope.

¶1 This subclause describes a polymorphic wrapper class templates that ~~encapsulates~~ encapsulate arbitrary callable objects.

Remove a specific mention of `function` from [func.wrap.badcall].

¶1 An exception of type `bad_function_call` is thrown by ~~`function::operator()` (20.9.12.2.4)~~ when the `function` call operator [func.wrap.func.inv] of a polymorphic wrapper object that has no target.

Change the title of the [func.wrap.func] clause.

20.9.12.2 ~~Class template function~~ Call wrapper class templates [func.wrap.func]

Add a `unique_function` synopsis after that of `function`.

```
template<Sig> class unique_function {
public:
    // construct/copy/destroy:
    unique_function() noexcept;
    unique_function(nullptr_t) noexcept;
    unique_function(const unique_function&) = delete;
    unique_function(unique_function&&);
```

```

template<class F> unique_function(F);

unique_function& operator=(const unique_function&) = delete;
unique_function& operator=(unique_function&&);
unique_function& operator=(nullptr_t) noexcept;
template<class F> unique_function& operator=(F&&);
template<class F> unique_function& operator=(reference_wrapper<F>)
    noexcept;

~unique_function();

// Polymorphic call wrapper modifiers:
void swap(unique_function&) noexcept;

// Polymorphic call wrapper capacity:
explicit operator bool() const noexcept;

// Polymorphic call wrapper invocation:
R operator()(ArgTypes...) qualifiers;
    // R, ArgTypes..., and qualifiers are the return type, the parameter-type-list,
    // and the sequence “cv-qualifier-seqopt ref-qualifieropt noexcept-specifieropt”
    // of the function type Sig, respectively.

// Polymorphic call wrapper target access:
const type_info& target_type() const noexcept;
template<class T> T* target() noexcept;
template<class T> const T* target() const noexcept;
};

// Null pointer comparisons:
template <typename Sig>
    bool operator==(const unique_function<Sig>&, nullptr_t) noexcept;

template <typename Sig>
    bool operator==(nullptr_t, const unique_function<Sig>&) noexcept;

template <typename Sig>
    bool operator!=(const unique_function<Sig>&, nullptr_t) noexcept;

template <typename Sig>
    bool operator!=(nullptr_t, const unique_function<Sig>&) noexcept;

// specialized algorithms:
template <typename Sig>
    void swap(unique_function<Sig>&, unique_function<Sig>&) noexcept;

```

Duplicate some of the forgoing synopsis into the `<functional>` synopsis at [function.objects].

```
template<typename Sig> class unique_function;

template<typename Sig>
    void swap(unique_function<Sig>&, unique_function<Sig>&) noexcept;

template<typename Sig>
    bool operator==(const unique_function<Sig>&, nullptr_t) noexcept;
template<typename Sig>
    bool operator==(nullptr_t, const unique_function<Sig>&) noexcept;
template<typename Sig>
    bool operator!=(const unique_function<Sig>&, nullptr_t) noexcept;
template<typename Sig>
    bool operator!=(nullptr_t, const unique_function<Sig>&) noexcept;
```

Back to [func.wrap.func], adjust the high-level description following the synopsis.

¶1 The function `class template provides` and `unique function class templates provide` polymorphic wrappers that generalize the notion of a function pointer. Wrappers can store, copy, and call arbitrary callable objects (20.9.1), given a call signature (20.9.1), allowing functions to be first-class objects.

¶2 [...]

¶3 A specialization `function<Sig>` or `unique function<Sig>` is a call wrapper ([func.def]) whose call signature is `Sig`.

Add a paragraph to clarify the present method of description. The intent is to follow the stylistic precedent of the unnamed class `resource_adaptor_imp` in LFTS v1 (N4480) §8.7.1. The meta-name `polymorphic_call_wrapper` appears twice in the declaration of non-member `swap`; though the synopsis is already clear, this paragraph should avert any suggestion that a `unique_function` can be swapped with a function.

¶ The following clauses describe the templates `function` and `unique function`. In each clause, the name `polymorphic_call_wrapper` denotes either `function` or `unique function`. In descriptions of class members, `polymorphic_call_wrapper` refers to the enclosing class.

Adjust the constructor specifications in [func.wrap.func.con] §20.9.12.2.1.

function `Polymorphic call wrapper` construct/copy/destroy [func.wrap.func.con]

`function` `polymorphic call wrapper`() noexcept;

¶1 *Postconditions*: !*this.

`function` `polymorphic call wrapper`(nullptr_t) noexcept;

¶- *Postconditions*: !*this.

The copy constructor is not affected because it is defined as deleted for `unique_function`, per the synopsis.

```
function(const function& f);
¶4 Postconditions: [...]
¶5 Throws: [...]
function(function
polymorphic call wrapper(polymorphic call wrapper && f);
¶6 Effects: [...]
template<class F> function polymorphic call wrapper(F f);
¶7 Requires: For function constructors, F shall be CopyConstructible. For
unique_function constructors, F shall be MoveConstructible.
¶8 Remarks: [...]
```

Modify a bullet in ¶9 and add a subsequent new paragraph, to handle conversions between specializations of `function` and `unique_function`.

```
¶9 Postconditions: ...
¶9.3 — F is an instance of the function a polymorphic call wrapper class template, and !f.
¶? Otherwise, if F is a specialization of the function a polymorphic call wrapper class
template, and the return and parameter types of its call signature are respectively identical to
those of Sig, then the target of *this is the target of f or a move-constructed object of the same
type.
¶10 Otherwise, *this targets a copy of f initialized ...
¶11 Throws: [...]
¶12 Effects: [...]
¶13 Returns: [...]
function polymorphic call wrapper& operator=
    (function polymorphic call wrapper&& f);
¶14 Effects: [...]
¶15 Returns: [...]
function polymorphic call wrapper& operator=(nullptr_t) noexcept;
¶16 Effects: [...]
¶17 Postconditions: [...]
¶18 Returns: [...]
template<class F> function polymorphic call wrapper& operator=(F&& f);
¶19 Effects:
```



```
function polymorphic call wrapper(std::forward<F>(f)).swap(*this);
```

§20 Returns: [...]

§21 Remarks: [...]

```
template<class F> function polymorphic call wrapper&operator=  
    (reference_wrapper<F> f) noexcept;
```

§22 Effects: **function** polymorphic call wrapper(f).swap(*this);

§23 Returns: [...]

```
~function ~polymorphic call wrapper();
```

§24 Effects: [...]

Likewise adjust swap in [func.wrap.func.mod].

function Polymorphic call wrapper modifiers [func.wrap.func.mod]

```
void swap(function polymorphic call wrapper& other) noexcept;
```

§1 Effects: [...]

Adjust the next several titles.

function Polymorphic call wrapper capacity [func.wrap.func.cap]

function Polymorphic call wrapper invocation [func.wrap.func.inv]

function Polymorphic call wrapper target access [func.wrap.func.targ]

Likewise adjust the comparison operators in [func.wrap.func.nullptr].

```
template <typename Sig>  
bool operator==(const function polymorphic call wrapper  
                <Sig>& f, nullptr_t) noexcept;
```

```
template <typename Sig>  
bool operator==(nullptr_t, const function polymorphic call wrapper  
                <Sig>& f) noexcept;
```

§1 Returns: !f.

```
template <typename Sig>  
bool operator!=(const function polymorphic call wrapper  
                <Sig>& f, nullptr_t) noexcept;
```

```
template <typename Sig>  
bool operator!=(nullptr_t, const function polymorphic call wrapper  
                <Sig>& f) noexcept;
```

§2 Returns: (bool) f.

And `swap` again in `[func.wrap.func.alg]`.

```
template<typename Sig>
void swap(function polymorphic call wrapper<Sig>& f1,
          function polymorphic call wrapper<Sig>& f2) noexcept;
¶1 Effects: f1.swap(f2);
```

Finally, add a feature test macro, `__cpp_lib_unique_function`.

6. Future directions

Given `in_place_type` construction, `unique_function` would support non-movable target objects. This feature was removed since the previous revision, N4543, and it will be proposed again separately.

It may typically be easier to implement SFINAE, not a hard error, when a `std::function` constructor encounters a non-copyable target type. If `function` and `unique_function` obtain their constructors from a common template, `unique_function` cannot evaluate `is_copy_constructible` if that metafunction may instantiate a copy constructor. Let's keep an eye on this issue, but it's not a defect yet.

It is possible, without added overhead, to convert a `unique_function` value to `function`, provided it was initialized by conversion from `function`. This could be implemented as an explicit conversion, with an exception thrown upon failure.

7. Implementations

Matt Calabrese implemented a `unique_function` together with further extensions. He worked to combat bloat and developed the principle of minimizing constructor ODR-use.

In mid 2014, Agustín “K-ballo” Bergé [implemented](#) a `unique_function` within the HPX library.

In early 2015, StackOverflow user “Yakk” implemented a `move_only_function` to answer a question.¹ S/he included support of value categories and `const`-qualification as well.

In mid 2015, I attempted to implement this proposal within the `libc++` `function` implementation. Due to difficulties in achieving interoperability of target objects, I gave up and started from scratch.

My `cxx_function` library² implements this proposal together with P0042R0 `std::recover_undoing_type erasure`, P0043R0 `Function wrappers with allocators and noexcept`, P0045R0 `Overloaded and qualified std::function`, and in-place construction. It adds little compile-time overhead and it outperforms `libc++` and `libstdc++` at runtime.

¹ <http://stackoverflow.com/questions/28179817/how-can-i-store-generic-packaged-tasks-in-a-container>

² https://github.com/potswa/cxx_function

In early 2016, the *function2* library³ by Denis Blank (Naios) likewise implements a `unique_function` together with other enhancements including rvalues and cv-qualifiers. It is likely that other implementations exist. This idea is ripe for standardization.

8. Kudos

Kudos to Geoffrey Romer for initiating the direction in N4159.

Thanks to Daniel Krügler for kind direction and in-depth review.

Revision history

N4543 — Initial revision.

P0288R0 — Removed in-place construction.

Added full proposed text.

Updated with implementation experience and feedback from Kona discussion.

P0288R1 — Expand rationale regarding method of description.

Mention P0045R1 regarding const-correctness issue.

Minor changes to standardese content and formatting.

Update standardese to latest working draft standard.

³ <http://naios.github.io/function2/>