Higher-order functions in Modern C++

Existing techniques and `function_ref`

Vittorio Romeo

vittorioromeo.info
vittorio.romeo@outlook.com
vromeo5@bloomberg.net
@supahvee1234

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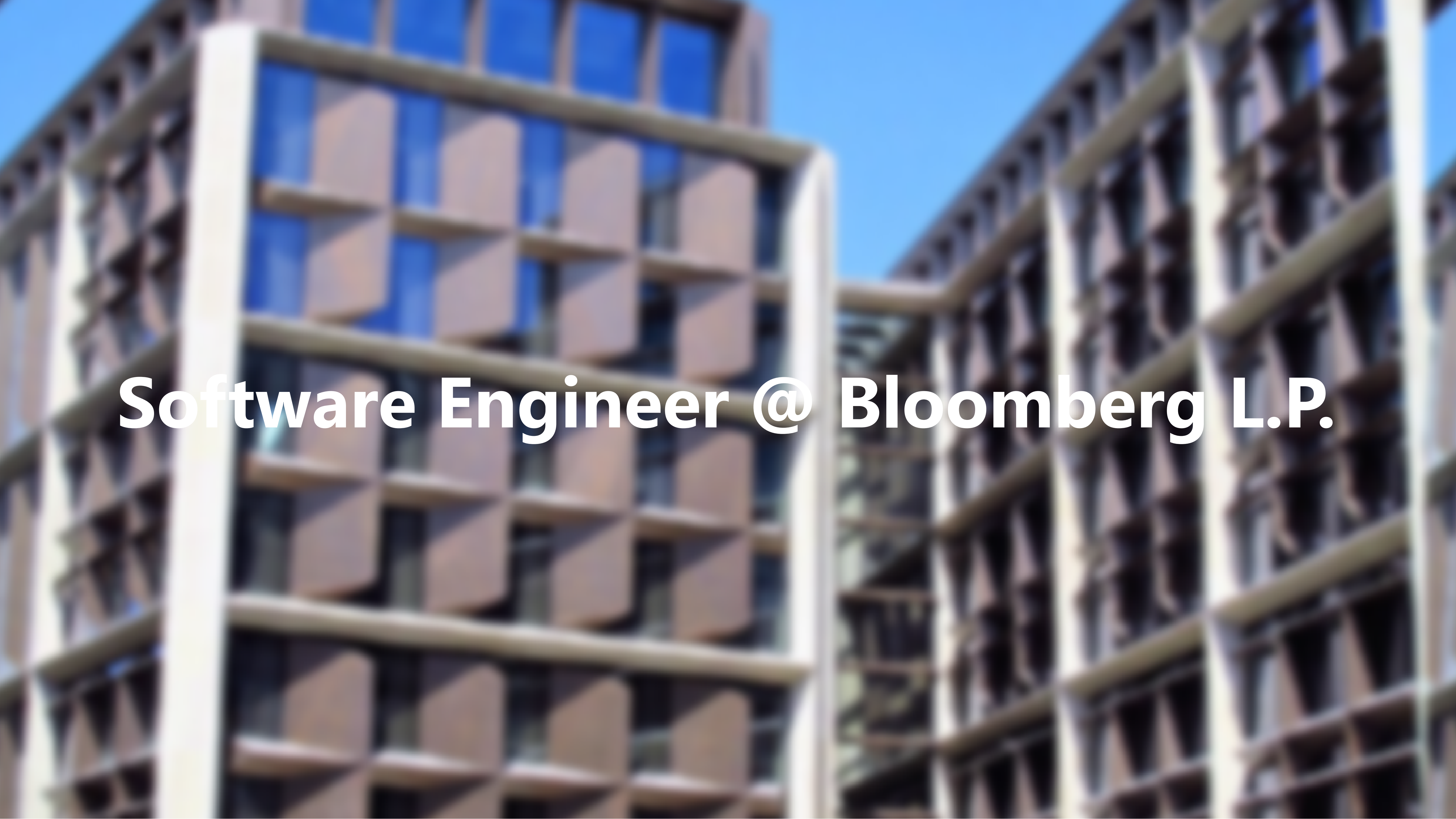

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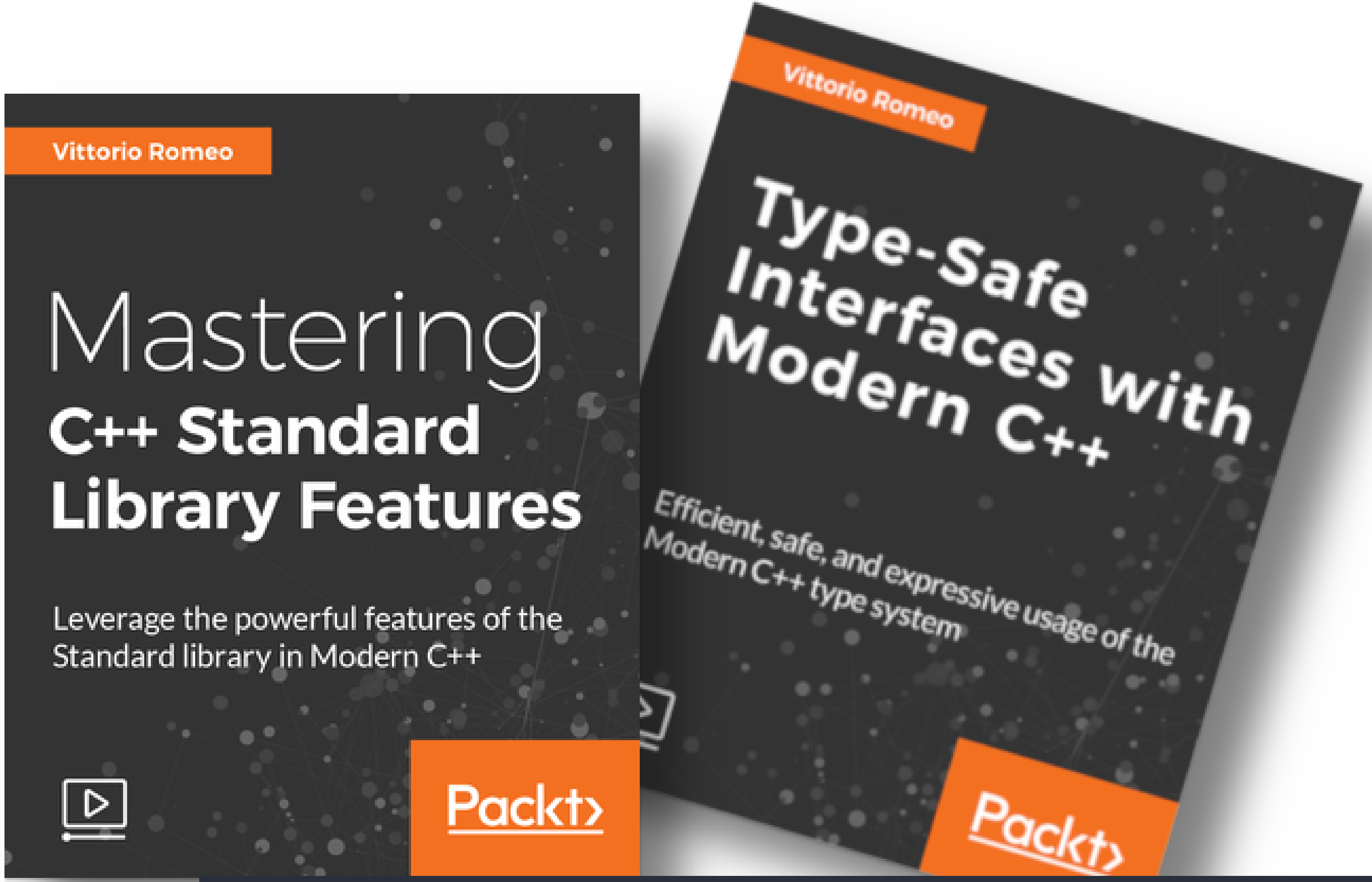

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about me

Hello! My name is Vittorio.
I'm a modern C++ enthusiast who loves to share his knowledge by creating video tutorials and participating to conferences.
I have a BS in Computer Sci... from the University ...aries,
... free ... my ... my

home page

Welcome to my blog.

---

compile-time iteration with C++20 lambdas

16 april 2018

c++ c++20 lambda tutorial

In one of my previous articles, "compile-time `repeat` & `noexcept`-correctness", I have covered the design and implementation of a simple `repeat<n>(f)` function that, when invoked, expands to `n` calls to `f` during compilation. E.g.

```
repeat<4>([]{ std...hello\n"; });
```

```
...);
...);
...);
...);
```

...rm of *compile-time iteration*. When writing generic code, ...n order to express the following actions:

... read more

Document number	P0792R3
Date	2018-10-07
Reply-to	Vittorio Romeo <vittorio.romeo@outlook.com>
Audience	Library Working Group (LWG)
Project	ISO JTC1/SC22/WG21: Programming Language C++

`function_ref`: a non-owning reference to a `Callable`

Abstract

This paper proposes the addition of `function_ref<R...` ... owning references to `Callable` objects.

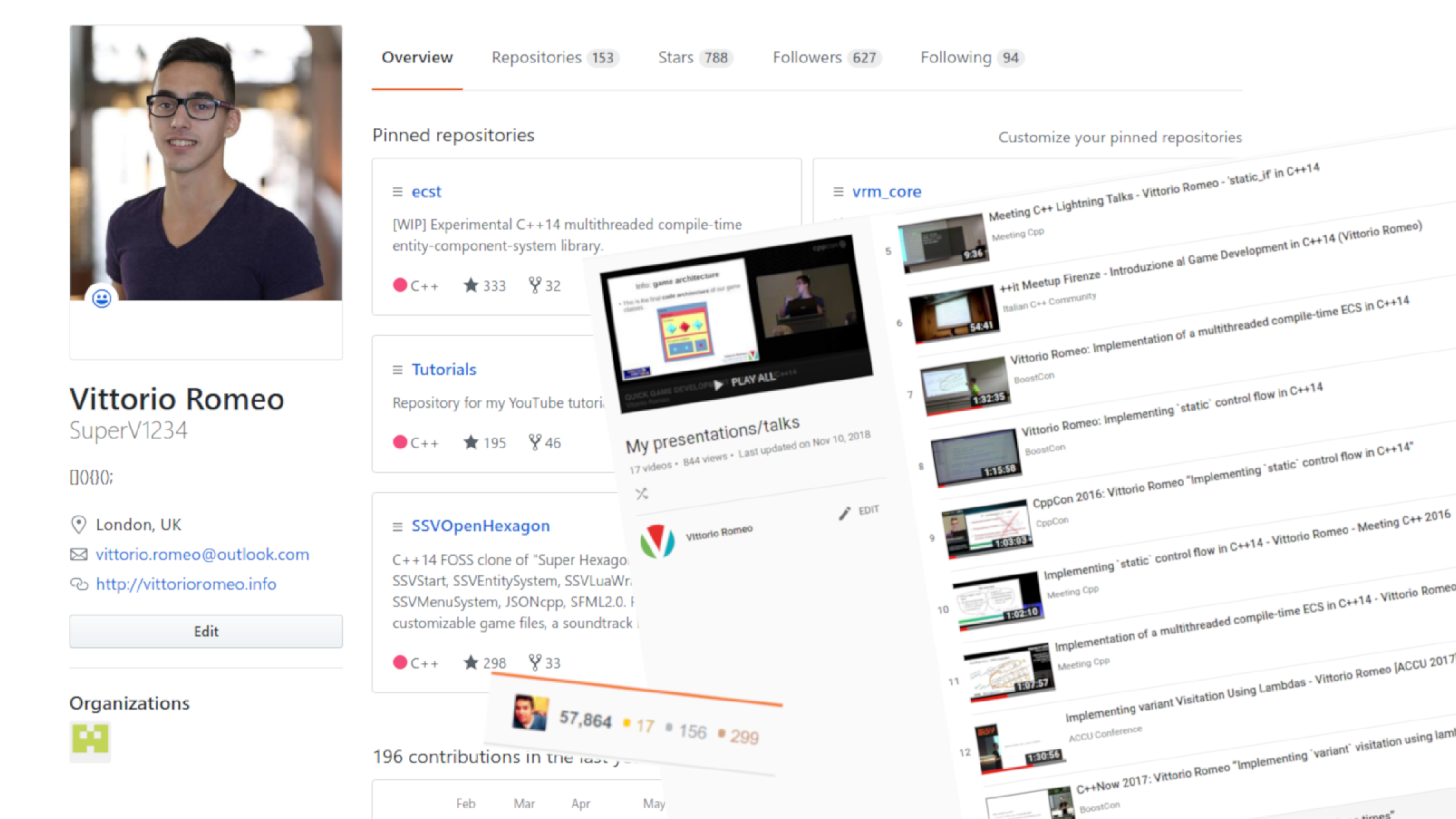
Changelog and polls

Document no.	P0915R0
Date	2018-02-08
Reply-to	Vittorio Romeo <vittorio.romeo@outlook.com>, John Lakos <jlakos@bloomberg.net>
Audience	Evolution Working Group
Project	ISO JTC1/SC22/WG21: Programming Language C++

Concept-constrained `auto`

Abstract

...holder type for variables. The primary goal is to



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Implementing variant Visitation Using Lambdas - Vittorio Romeo [ACCU 2017]
ACCU Conference
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Introduction

- Higher-order functions
  - What they are
  - Use cases and implementation techniques
- `function_ref`
  - Motivation
  - Specification and usage examples
  - Implementation
  - Benchmarks
  - Design decisions and controversies

- This is *not* a talk on functional programming
- We are going to look at:
  - *Pratical* every day uses of higher-order functions
  - Existing "functional" facilities in the language
  - Design and implementation of a ISO C++20 proposal

- You are somewhat familiar with:
    - Lambda expressions
    - Templates
    - Modern C++ features
- Do not hesitate to ask questions

Higher order functions

> In mathematics and computer science, a higher-order function is a function that does at least one of the following:
>
> - **takes one or more functions as arguments** (i.e. procedural parameters),
> - **returns a function as its result**.

\- Wikipedia

```
template <typename F>
void call_twice(F&& f)
{
    f();
    f();
}

call_twice([]{ std::cout << "hello"; });
```

- Takes a `FunctionObject` as an argument
- Implementation technique: `template` *parameter*

```cpp
auto greater_than(int threshold)
{
    return [threshold](int x)
    {
        return x > threshold;
    };
}

std::vector<int> v{0, 4, 1, 11, 5, 9};
assert(std::count_if(v.begin(), v.end(), greater_than(5)) == 2);
```

(on *wandbox.org*)

- Returns a `FunctionObject` invocable with an `int`
- Implementation technique: *closure* + `auto` return type

Do we have any higher-order function in the C++ Standard?

Do we have any higher-order function in the **C** Standard?

- `std::qsort`, `std::bsearch`
- `std::atexit`, `std::at_quick_exit`
- `std::signal`

std::signal

Defined in header <csignal>

```
/*signal-handler*/* signal(int sig, /*signal-handler*/* handler);   (1)
extern "C" using /*signal-handler*/ = void(int); // exposition-only (2)
```

Sets the handler for signal `sig`. The signal handler can be set so that default handling will occur, signal is ignored, or a user-defined function is called.

Parameters

sig - the signal to set the signal handler to. It can be an implementation-defined value or one of the following values:

SIGABRT SIGFPE SIGILL SIGINT SIGSEGV SIGTERM	defines signal types (macro constant)

handler - the signal handler. This must be one of the following:

- SIG_DFL macro. The signal handler is set to default signal handler.
- SIG_IGN macro. The signal is ignored.
- pointer to a function. The signature of the function must be equivalent to the following:

```
extern "C" void fun(int sig);
```



```
#include <csignal>

int main()
{
    std::signal(SIGINT, [](int signal_num)
    {
        std::cout << "signal: " << signal_num << '\n';
    });
}
```

(on *godbolt.org*)

- *Lambda expressions* work great with higher-order functions
- Stateless *closures* are implicitly convertible to *function pointers*

- `std::set_terminate`
- `std::visit`, `std::apply`, `std::invoke`
- `std::bind`, `std::bind_front` (C++20)
- `<numeric>` and `<algorithm>`
- ...


```cpp
std::vector<entity> entities;

entities.erase(
    std::remove_if(entities.begin(),
                   entities.end(),
                   [](const entity& e){ return !e._active; }),
    entities.end()
);
```

(on *godbolt.org*)

- "Erase-remove idiom":
    - Moves elements to keep towards the beginning of the range
    - Relative order of elements is preserved


```cpp
using event = std::variant<connect, disconnect, heartbeat>;

void process(event&& e)
{
    std::visit(
        overload([](connect)   { std::cout << "process connect\n";    },
                 [](disconnect){ std::cout << "process disconnect\n"; },
                 [](heartbeat) { std::cout << "process heartbeat\n";  }),
        e);
}

process(event{connect{}});
process(event{heartbeat{}});
process(event{disconnect{}});
```

(on *wandbox.org*)

- "*Implementing variant visitation using lambdas*" @ ACCU 2017, C++Now 2017

- Avoiding repetition
- Inversion of control flow
- Asynchronicity
- Compile-time metaprogramming
- ...

- Code repetition leads to bugs and maintenance overhead
- Sometimes, it is trivial to avoid

```cpp
void test_routing(context& ctx)
{
    const auto machine0 = ctx.reserve_port("127.0.0.1");
    const auto machine1 = ctx.reserve_port("127.0.0.1");
    const auto machine2 = ctx.reserve_port("127.0.0.1");
}
```

↓

```cpp
void test_routing(context& ctx)
{
    const auto get_port = [&]{ return ctx.reserve_port("127.0.0.1"); };
    const auto machine0 = get_port();
    const auto machine1 = get_port();
    const auto machine2 = get_port();
}
```

- Other times it can be more complicated

```
void widget::update()
{
    for (auto& c : this->_children)
        if (c->visible())
            c->recalculate_focus();

    for (auto& c : this->_children)
        if (c->visible())
            c->recalculate_bounds();

    for (auto& c : this->_children)
        if (c->visible())
            c->update();
}
```

```cpp
void widget::update()
{
    const auto for_visible_children = [this](auto f)
    {
        for (auto& c : this->_children)
            if(c->visible())
                std::invoke(f, *c);
    };

    for_visible_children(&widget::recalculate_focus);
    for_visible_children(&widget::recalculate_bounds);
    for_visible_children(&widget::update);
}
```

(on *wandbox.org*)

- Pass an *action/predicate* to a function which deals with the control flow
- Separate *what happens* from *how it happens*
- *Example:* C++17 parallel algorithms

```cpp
struct physics_component
{
    vec2f _pos, _vel, _acc;
};

std::vector<physics_component> components{/* ... */};

std::for_each(std::execution::par_unseq,
              components.begin(),
              components.end(),
              [](auto& c)
              {
                  c._vel += c._acc;
                  c._pos += c._vel;
              });
```

- Decoupling *control flow* from the desired *action*
    - Can be reused & tested separately
- *Example:* printing a comma-separated list of elements

- Initial version

```cpp
template <typename T>
void print(const std::vector<T>& v)
{
    if(std::empty(v)) { return; }
    std::cout << *v.begin();

    for(auto it = std::next(v.begin()); it != v.end(); ++it)
    {
        std::cout << ", ";
        std::cout << *it;
    }
}
```

(on *wandbox.org*)

- Identify the structure

```cpp
template <typename T>
void print(const std::vector<T>& v)
{
    if(std::empty(v)) { return; }
    /* action */

    for(auto it = std::next(v.begin()); it != v.end(); ++it)
    {
        /* separation */
        /* action     */
    }
}
```

- Create an abstraction

```
template <typename Range, typename F, typename FSep>
void for_separated(Range&& range, F&& f_action, FSep&& f_separation)
{
    if(std::empty(range)) { return; }
    f_action(*range.begin());

    for(auto it = std::next(range.begin()); it != range.end(); ++it)
    {
        f_separation();
        f_action(*it);
    }
}
```

- Redefine `print`

```
template <typename T>
void print(const std::vector<T>& v)
{
    for_separated(v,
                  [](const auto& x){ std::cout << x; },
                  []{ std::cout << ", "; });
}
```

(on *wandbox.org*)

- `for_separated` is reusable
  - It provides the *control flow*
  - The user provides the *actions*


```cpp
const auto wide_print = [](const auto& sentence)
{
    for_separated(sentence,
        [](const auto& x){ std::cout << x; },
        []{ std::cout << ' '; });
};

wide_print("helloworld"s);
```

(on *wandbox.org*)

> h e l l o w o r l d


```cpp
template <typename Range, typename Pred, typename F>
void consume_if(Range&& range, Pred&& pred, F&& f)
{
    for(auto it = std::begin(range); it != std::end(range);)
    {
        if(pred(*it))
        {
            f(*it);
            it = range.erase(it);
        }
        else { ++it; }
    }
}
```

```cpp
consume_if(_systems,
           [](auto& system){ return system.is_initialized(); },
           change_state_to(state::ready_to_sync));
```

- Currently the easiest way to express asynchronous callbacks
  - `std::future`, `std::thread`, ...
- Many use cases might be superseded by *coroutines*


```
auto graph = all
{
   []{ return http_get_request("animals.com/cat/0.png"); },
   []{ return http_get_request("animals.com/dog/0.png"); }
}
.then([](std::tuple<data, data> payload)
{
    std::apply(stitch, payload);
});
```

- "*Zero-allocation & no type erasure futures*" @ ACCU 2018, C++Now 2018

- *"zero-overhead C++17 currying & partial application"*
- *"compile-time iteration with C++20 lambdas"*

```
enumerate_types<int, float, char>([]<typename T, auto I>()
{
    std::cout << I << ": " << typeid(T).name() << '\n';
});
```

> 0: i
>
> 1: f
>
> 2: c

- Sometimes other abstractions can be used to achieve the same goals
    - RAII guards
    - Iterators
    - ...

- *Example:* thread-safe access to an object via `synchronized<T>`

```
class foo { /* ... */ };
synchronized<foo> s_foo;

// some way to access contents of `s_foo` in a thread-safe manner
```

- What interface should `synchronized` expose?

  i. RAII guards

  ii. Higher-order functions

higher order functions

vs RAII guards

```
synchronized<foo> s_foo;

{
    auto f = s_foo.access();
    f->some_foo_method();
}
```

- (+) Friendly to control flow

```
synchronized<foo> s_foo;

s_foo.access([](foo& f)
{
    f.some_foo_method();
});
```

- (+) Simpler implementation
- (−) Might require captures
- (−) Unfriendly to control flow

higher order functions

vs RAII guards

```
template <typename T>
class synchronized
{
    T _obj;
    std::mutex _mtx;

public:
    auto access()
    {
        struct access_guard
        {
            std::lock_guard<std::mutex> _guard;
            T* operator->();
            // ... constructors, etc ...
        };

        return access_guard{*this};
    }
};
```

```cpp
template <typename T>
class synchronized
{
    T _obj;
    std::mutex _mtx;

public:
    template <typename F>
    auto access(F&& f)
    {
        std::lock_guard guard{_mtx};
        return std::forward<F>(f)(_obj);
    }
};
```

(on *wandbox.org*)

- *Example:* benchmarking a function

```
template <typename F>
auto benchmark(F&& f)
{
    const auto t = std::chrono::high_resolution_clock::now();
    f();
    return std::chrono::high_resolution_clock::now() - t;
}
```


- *Example:* iterating over filtered range

```
std::vector<int> ints{/* ... */};

for(int x : filtered(ints, even))
{
    /* ... */
}
```

- (+) Friendly to control flow
- (+) More composable with `std`
- (−) Complicated implementation

```
std::vector<int> ints{/* ... */};

for_filtered(ints, is_even,
    [](int x){ /* ... */ });
```

- (+) Simpler implementation
- (−) Might require captures
- (−) Unfriendly to control flow

- From `Boost.Iterator`

filter_iterator synopsis

```
template <class Predicate, class Iterator>
class filter_iterator
{
 public:
    typedef iterator_traits<Iterator>::value_type value_type;
    typedef iterator_traits<Iterator>::reference reference;
    typedef iterator_traits<Iterator>::pointer pointer;
    typedef iterator_traits<Iterator>::difference_type difference_type;
    typedef /* see below */ iterator_category;

    filter_iterator();
    filter_iterator(Predicate f, Iterator x, Iterator end = Iterator());
    filter_iterator(Iterator x, Iterator end = Iterator());
    template<class OtherIterator>
    filter_iterator(
        filter_iterator<Predicate, OtherIterator> const& t
        , typename enable_if_convertible<OtherIterator, Iterator>::type* = 0 // exposition
        );
    Predicate predicate() const;
    Iterator end() const;
    Iterator const& base() const;
    reference operator*() const;
    filter_iterator& operator++();
private:
    Predicate m_pred; // exposition only
    Iterator m_iter;  // exposition only
    Iterator m_end;   // exposition only
};
```



```
for_filtered(ints, is_even, [](int x){ /* ... */ });
```

↓

```
template <typename Range, typename Pred, typename F>
void for_filtered(Range&& range, Pred&& pred, F&& f)
{
    for(auto&& x : range)
        if(pred(x))
            f(x);
}
```

- HOF iteration can have performance benefits compared to ranges
- *Example:* iterating over interleaved (or concatenated) ranges

```
for (std::variant<text, separator> x : interleave(names, separators))
{
    // ...
}

// vs

for_interleaved(overload([](text)      { /* ... */ },
                         [](separator){ /* ... */ }), names, separators);
```

- The latter does not require run-time dispatch

- Very powerful: many different use cases
- Easier to write than existing alternatives
  - When you need a quick testable/reusable abstraction that doesn't have to be composable, they're great
  - Language alternatives might come: *coroutines*, *ranges*, ...
- Do not play nicely with *control flow* on the caller side
  - Consider `return` / `break` / `continue` in a lambda body
- Even more powerful in C++17 and C++20
- Some proposals might have helped... - e.g. P0573

`function_ref`

What options do we have to implement *higher-order functions*?

Pointers to functions

```
int operation(int(*f)(int, int))
{
    return f(1, 2);
}
```

- Works with *non-member functions* and *stateless closures*
- Doesn't work with *stateful* `Callable` *objects*
- Small run-time overhead (easily inlined in the same TU)
- Constrained, with obvious signature

Template parameters

```
template <typename F>
auto operation(F&& f) -> decltype(std::forward<F>(f)(1, 2))
{
    return std::forward<F>(f)(1, 2);
}
```

- Works with any `FunctionObject` (or `Callable`, using `std::invoke`)
- Zero-cost abstraction
- Hard to constrain (less true in C++20)
- Might degrade compilation time

`std::function`

```
int operation(const std::function<int(int, int)>& f)
{
    return f(1, 2);
}
```

- Works with any `FunctionObject` or `Callable`
- Significant run-time overhead (hard to inline/optimize)
- Constrained, with obvious signature
- Unclear semantics: can be both *owning* or *non-owning*

`function_ref`

```
int operation(function_ref<int(int, int)> f)
{
    return f(1, 2);
}
```

- Works with any `FunctionObject` or `Callable`
- Small run-time overhead (easily inlined in the same TU)
- Constrained, with obvious signature
- Clear *non-owning* semantics
- Lightweight - think of "*`string_view`* *for* *`Callable`* *objects*"

- `function_ref<R(Args...)>` is a *non-owning reference* to a `Callable`
- Parallel:
  - `std::string` → `std::string_view`
  - `std::function` → `std::function_ref`
- Doesn't *own* or *extend the lifetime* of the referenced `Callable`
- Lightweight, friendly to `noexcept` and optimizations, `TriviallyCopyable`
- Proposed by me in P0792 - currently in LWG
  - Many thanks to: *Agustín Bergé*, *Dietmar Kühl*, *Eric Niebler*, *Tim van Deurzen*, and *Alisdair Meredith*

- Why use `function_ref` instead of `std::function`?
    - Performance
    - "Clear" reference semantics
- Why use `function_ref` instead of *template parameters*?
    - Easier to write/read/teach
    - Usable in *polymorphic hierarchies*
    - Better compilation times

```
template <typename Signature>
class function_ref
{
    void* object;                    // exposition only
    R(*erased_function)(Args...); // exposition only

public:
    function_ref(const function_ref&) noexcept = default;

    template <typename F>
    function_ref(F&&);

    function_ref& operator=(const function_ref&) noexcept = default;

    template <typename F>
    function_ref& operator=(F&&);

    void swap(function_ref&) noexcept;

    R operator()(Args...) const noexcept(*see below*);
};
```


`function_ref`

use case examples


```cpp
class replay_map
{
    std::unordered_map<command_id, ref_counted<command>> _items;
    std::unordered_map<queue_id, std::deque<command_id>> _queues;

    void iterate(const queue_id&                             id,
                 const function_ref<void(const command&)> f) const
    {
        const auto queue_it = _queues.find(id);
        if(queue_it == std::end(_queues)) { return; }

        const auto& q = queue_it->second;
        for(auto it = q.rbegin(); it != q.rend(); ++it)
        {
            f(_items.at(*it).get());
        }
    }
};
```

```
struct packet_cache
{
    using replay_cb = function_ref<void(const packet&)>;
    using consume_cb = function_ref<void(packet&&)>;

    virtual void replay(replay_cb cb) const = 0;
    virtual void consume(consume_cb cb) = 0;

    virtual ~packet_cache() { }
};
```

- ...


```cpp
struct contiguous_packet_cache : packet_cache
{
    // ...

    void replay(replay_cb cb) const override
    {
        for (const auto& p : _packets)
            cb(p);
    }

    void consume(consume_cb cb) override
    {
        for (auto& p : _packets)
            cb(std::move(p));

        clear();
    }
};
```

```cpp
using state_change_cb =
    function_ref<void(const node_id&, const state_transition&)>;

void node_monitor::sweep(const state_change_cb cb,
                         const timestamp&      ts)
{
    for(auto it = std::begin(_data); it != std::end(_data);)
    {
        if (    (it->second._state != node_state::down)
            && (ts - it->second._last_heartbeat >= 10s))
        {
            cb(it->first, change_state_to(node_state::down));
            it = _data.erase(it);
        }
        else { ++it; }
    }
}
```

```
using state_change_cb =
    function_ref<void(const node_id&, const state_transition&)>;

void node_monitor::sweep(const state_change_cb cb,
                         const timestamp&      ts)
{
    consume_if(_data,
               [](const auto& p)
               {
                   return (p.second._state == node_state::down)
                       || (ts - p.second._last_heartbeat < 10s);
               },
               [](const auto& p)
               {
                   cb(p.first, change_state_to(node_state::down));
               });
}
```

- "Match" a signature though template specialization:

```
template <typename Signature>
class function_ref;

template <typename Return, typename... Args>
class function_ref<Return(Args...)>
{
    // ...
};
```


- Store *pointer to* `Callable` *object* and *pointer to erased function*:

```
template <typename Return, typename... Args>
class function_ref<Return(Args...)>
{
private:
    void* _ptr;
    Return (*_erased_fn)(void*, Args...);

public:
    // ...
};
```

```
private:
    void* _ptr;
    Return (*_erased_fn)(void*, Args...);
```

- On construction, set the pointers:

```
template <typename F, /* ...constraints... */>
function_ref(F&& f) noexcept : _ptr{(void*) &f}
{
    _erased_fn = [](void* ptr, Args... xs) -> Return
    {
        return (*static_cast<F*>(ptr))(std::forward<Args>(xs)...);
    };
}
```

```
private:
    void* _ptr;
    Return (*_erased_fn)(void*, Args...);
```

- On invocation, go through `_erased_fn`:

```
Return operator()(Args... xs) const noexcept(/* ... */)
{
    return _erased_fn(_ptr, std::forward<Args>(xs)...);
}
```



```
template <typename Return, typename... Args>
class function_ref<Return(Args...)>
{
    void* _ptr;
    Return (*_erased_fn)(void*, Args...);

public:
    template <typename F, /* ...constraints... */>
    function_ref(F&& f) noexcept : _ptr{(void*) &f}
    {
        _erased_fn = [](void* ptr, Args... xs) -> Return {
            return (*static_cast<F*>(ptr))(std::forward<Args>(xs)...);
        };
    }

    Return operator()(Args... xs) const noexcept(/* ... */)
    {
        return _erased_fn(_ptr, std::forward<Args>(xs)...);
    }
};
```

```
template <typename F>
constexpr function_ref(F&& f);
```

> - *Constraints:* `is_same_v<remove_cvref_t<F>, function_ref>` is `false` and
>   - If **`Signature`** has a **`noexcept`** specifier:
>   **`is_nothrow_invocable_r_v<R, cv-qualifiers F&, Args ... >`** is **`true`**;
>   - Otherwise:
>   **`is_invocable_r_v<R, cv-qualifiers F&, Args ... >`** is **`true`**.
>
> [...]


```
void might_throw();
void well_behaved() noexcept;

void f(function_ref<void() noexcept>);

f(&might_throw);  // Compile-time error
f(&well_behaved); // OK
```

(on *godbolt.org*)

- Behavior described in **P0045**: "*Qualified `std::function` signatures*" (D. Krauss)

```
const function_ref<int()> get_number = []{ return 42; };
std::cout << get_number() << '\n'; // Undefined behavior (!)
```

- `function_ref` has the same lifetime concerns as `std::string_view`
  - When used as a function parameter, everything is usually fine
  - In other cases, care is needed to avoid *dangling references*

- `constexpr` was removed in the latest revision (R4), as it's not implementable
    - A `reinterpret_cast` (or cast from `void*`) is required
- Unfortunately this forces users to either use templates or write code twice
- Can we do anything about this?
    - `constexpr`-friendly cast from `void*` to `T*`?
    - Compiler magic for `function_ref`?

`function_ref`

Benchmarks

- Used quick-bench.com with Simon Brand's `function_ref` implementation
  - Internally uses Google Benchmark
- Scenario: invoke simple higher-order function in a loop
- Test with:
  - *template parameter*
  - `function_ref`
  - `std::function`
- Also with and without inlining

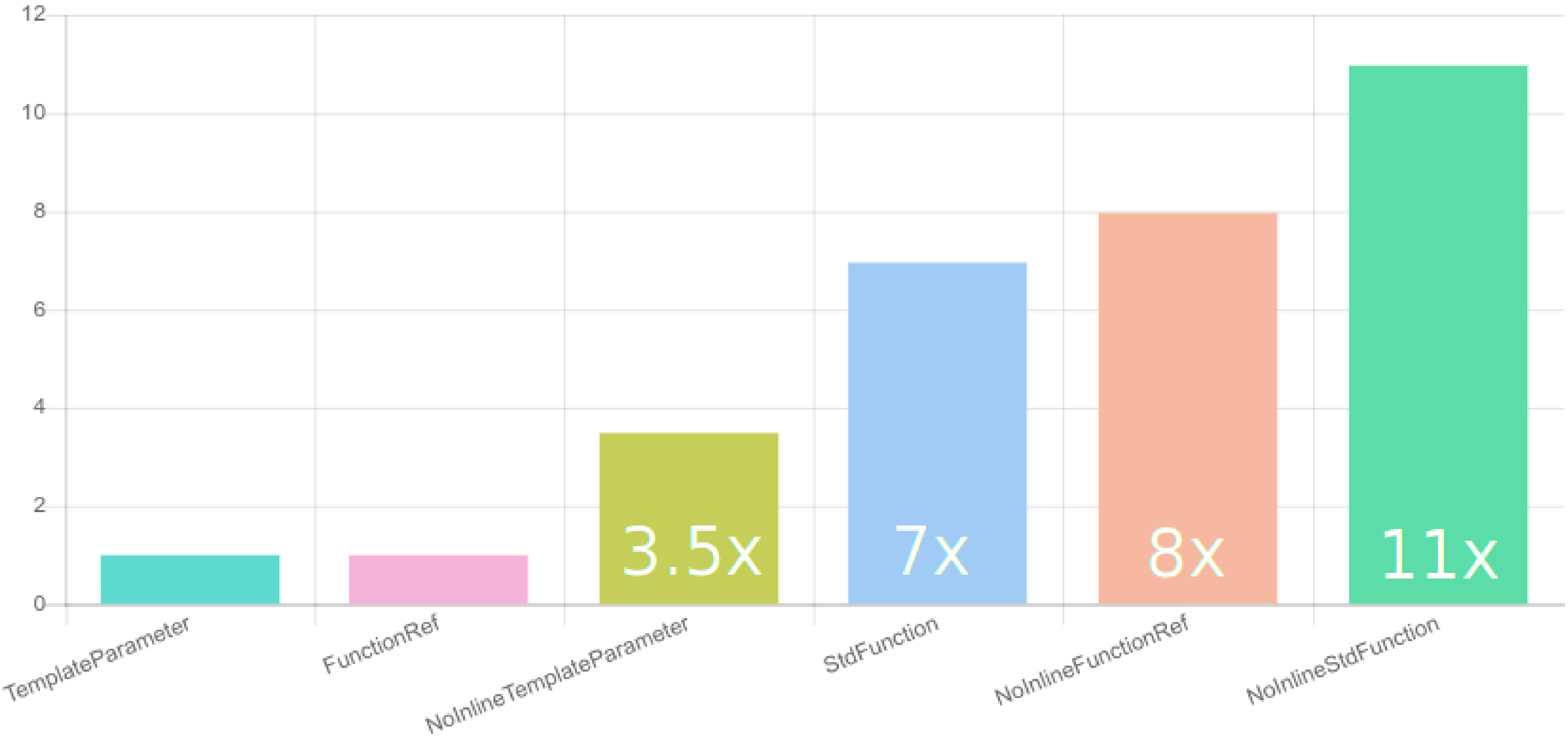

```cpp
template <typename F>
void templateParameter(F&& f)
{
    benchmark::DoNotOptimize(f());
}

void stdFunction(const std::function<int()>& f)
{
    benchmark::DoNotOptimize(f());
}

void functionRef(const tl::function_ref<int()>& f)
{
    benchmark::DoNotOptimize(f());
}
```

```
template <typename F>
void __attribute__((noinline)) noInlineTemplateParameter(F&& f)
{
    benchmark::DoNotOptimize(f());
}

void __attribute__((noinline)) noInlineStdFunction(const std::function<int()>& f)
{
    benchmark::DoNotOptimize(f());
}

void __attribute__((noinline)) noInlineFunctionRef(const tl::function_ref<int()>& f)
{
    benchmark::DoNotOptimize(f());
}
```

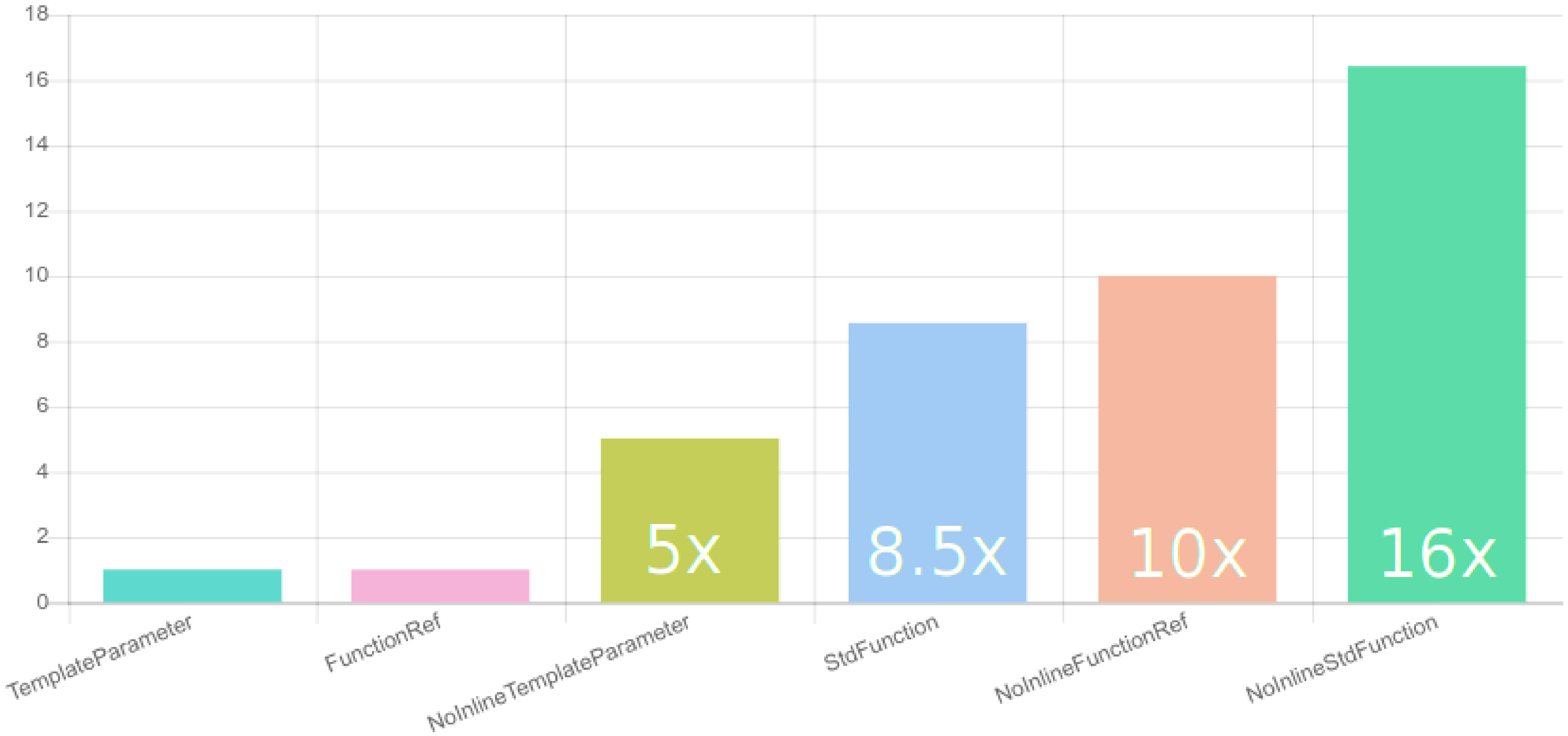


```
static void TemplateParameter(benchmark::State& state) {
  for (auto _ : state) {
    templateParameter([]{ return 1; });
  }
}

BENCHMARK(TemplateParameter);

static void FunctionRef(benchmark::State& state) {
  for (auto _ : state) {
    functionRef([]{ return 1; });
  }
}

BENCHMARK(FunctionRef);

// ... and so on...
```

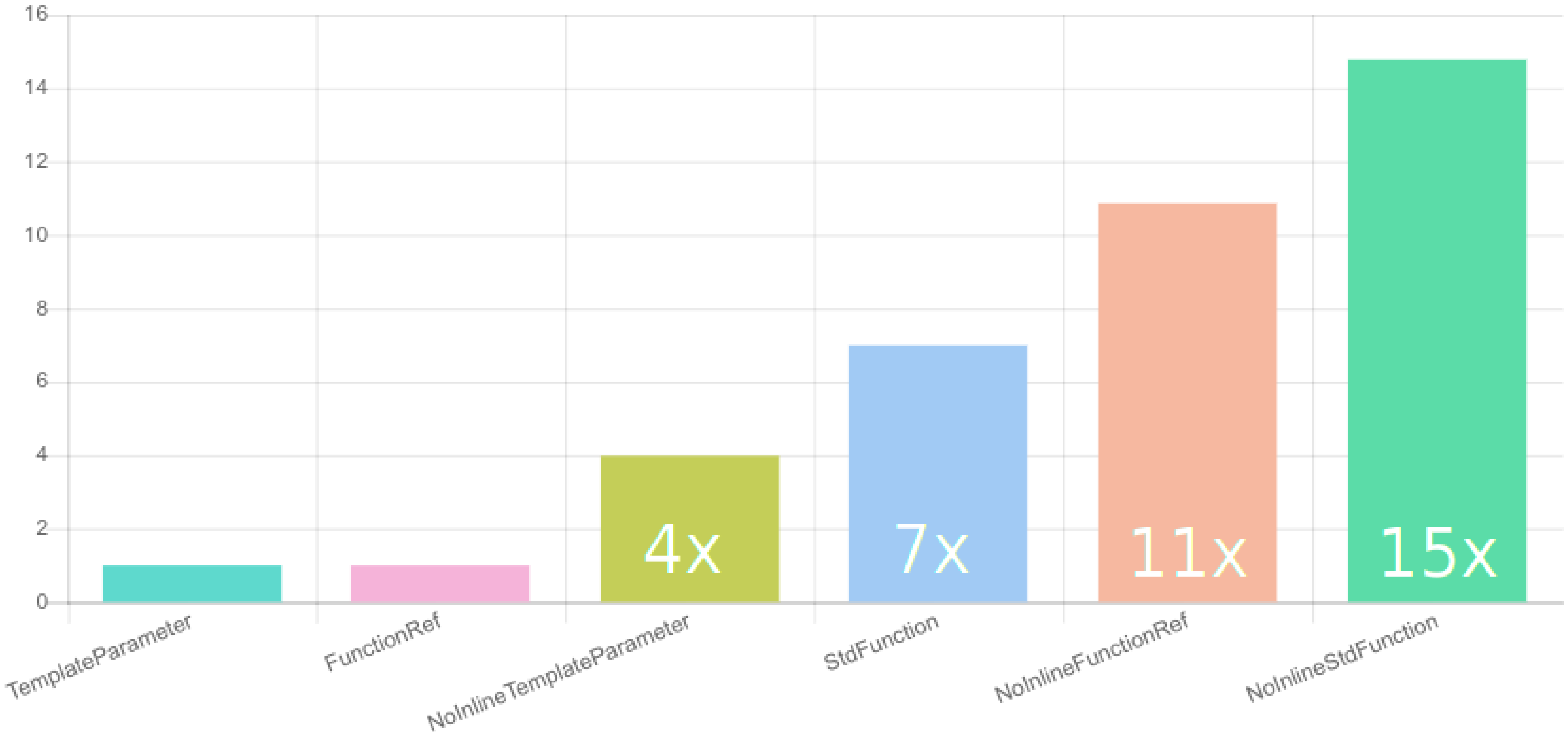
- `g++ 8.x`, `-O3`, `libstdc++` - *(link)*



- `clang++ 7.x`, `-O3`, `libstdc++` - *(link)*



- `clang++ 7.x`, `-O3`, `libc++` - *(link)*



- When inlining happens:
  - `function_ref` is as fast as a *template parameter*
  - `std::function` is at least **7x slower** than `function_ref`
- When inlining doesn't happen:
  - `function_ref` is around **2x slower** than a *template parameter*
  - `std::function` is around **1.5x slower** than `function_ref`
- `function_ref` is optimizer-friendly and thrives with inlining
- `function_ref` is always faster than `std::function`

`function_ref`

Design decisions and controversies

- `sizeof(function_ref)` is required to be `sizeof(void*) * 2`
  - This makes `function_ref` lightweight and likely to be passed in registers
  - Vocal opposition to bigger sizes
- Consequence: PMFs must outlive a `function_ref` instance

```
function_ref<void(const Service&)> fr = &Service::connect;
    // Points to the temporary `&Service::connect` instance.

fr();
    // UB, as the temporary `&Foo::f` is dead.
```

- The previous case could techincally be well-defined for a *pointer-to-function*
    - For consistency, it is not

```
void connect(const Service&);

function_ref<void(const Service&)> fr = &connect;
    // Points to the temporary `&connect` instance.

fr();
    // UB, as the temporary `&connect` is dead.
```

- LEWG approved this design

- The main use case for `function_ref` is to be used as a function paremeter
  - Yet, it exposes an *assignment operator*
- This could be misleading

```
void choice0(context& ctx);
void choice1(context& ctx);

void menu(context& ctx, int choice)
{
    auto default_choice = &choice0;
    function_ref<void(context&)> choice{default_choice};

         if (choice == 1) { choice = choice1; } // UB!
    else if (choice == 2) { choice = choice2; } // UB!

    choice(ctx);
}
```

- `function_ref` does not automatically unwrap a `std::reference_wrapper`
    - This leads to double indirection and affects the semantics

```
auto l0 = []{ std::cout << "l0\n"; };
auto l1 = []{ std::cout << "l1\n"; };

std::reference_wrapper rw{std::ref(l0)};
function_ref<void()> fr(rw); // Points to `rw` itself.

fr(); // Prints out `l0`.

rw = l1;

fr(); // Prints out `l1`.
```

- Discussed in LEWG, unanimous dissent to automatically unwrap

- Idea suggested by Adam N. (Yakk)
  - Allow multiple signatures at the same time

```
function_ref<void(int), double()> fr;
fr = overload([](int){ },
              []() → double { });
```

- Can be implemented more efficiently compared to `overload` of `function_ref`
- Thoughts?
  - Backwards-compatible future addition?
  - `multi_function_ref`?
  - Complexity not justifiable?

Conclusion

- Any function accepting or returning another is an "*higher-order function*"
    - Many examples in both the C and C++ Standards
- Varied use cases: *avoiding repetition*, *inverting control flow*, ...
- Highly usable thanks to *lambda expressions*
- Easier to implement compared to some alternatives
    - At the cost of introducing an extra function scope
- **You don't have to go *fully functional* to benefit from them!**

- Non-owning reference to any `Callable` with a given signature
- On the way to standardization, hopefully C++20
- Lightweight, trivial for the compiler to optimize
- Clearer semantics and higher performance compared to `std::function`
- **You can start using `function_ref` today!**
    - P0792
    - github:TartanLlama/function_ref

Thanks!

https://vittorioromeo.info

https://github.com/SuperV1234/cppcon2019

vittorio.romeo@outlook.com

vromeo5@bloomberg.net

@supahvee1234

Bloomberg