Higher-order functions and `function_ref`

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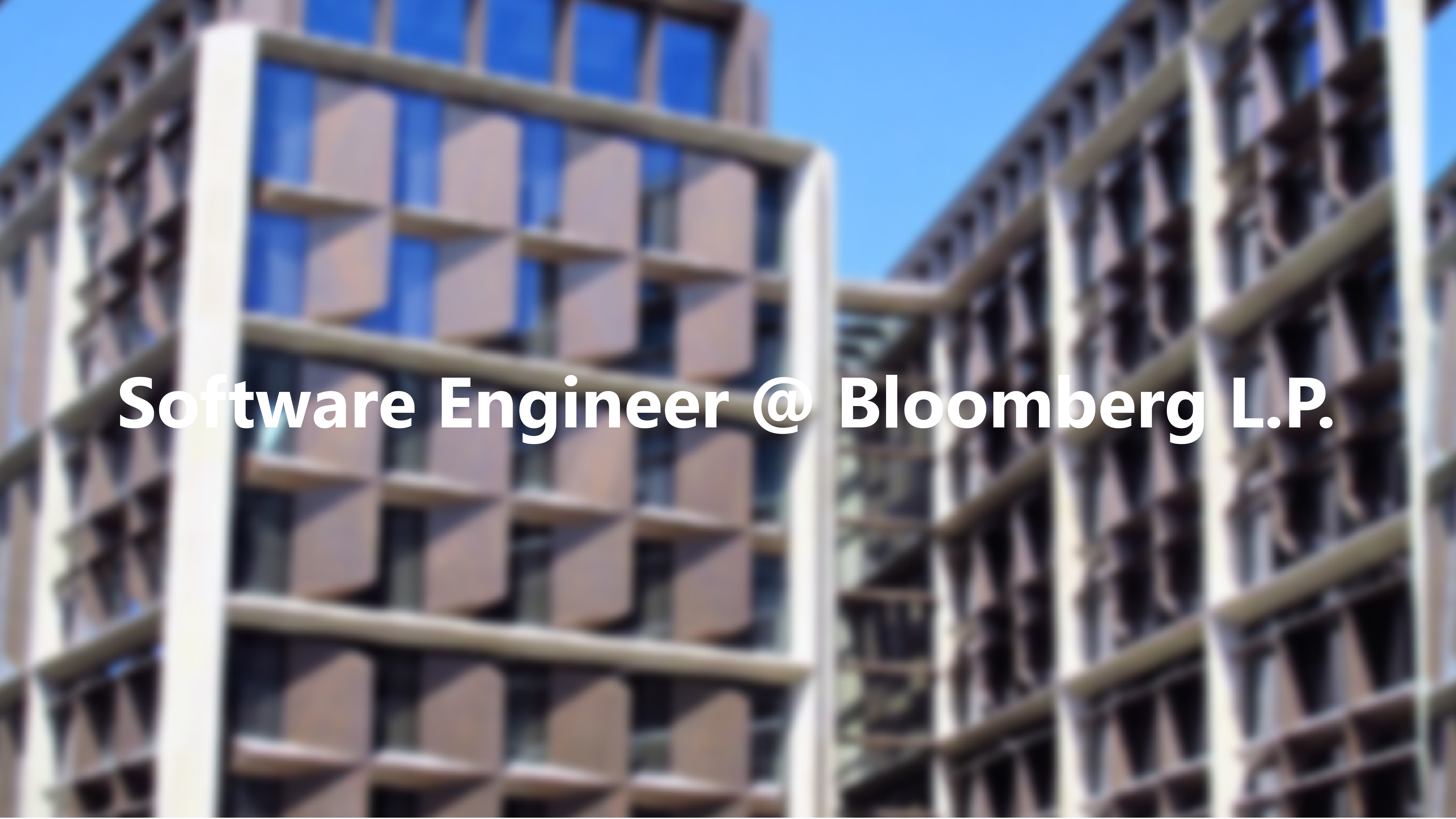
About me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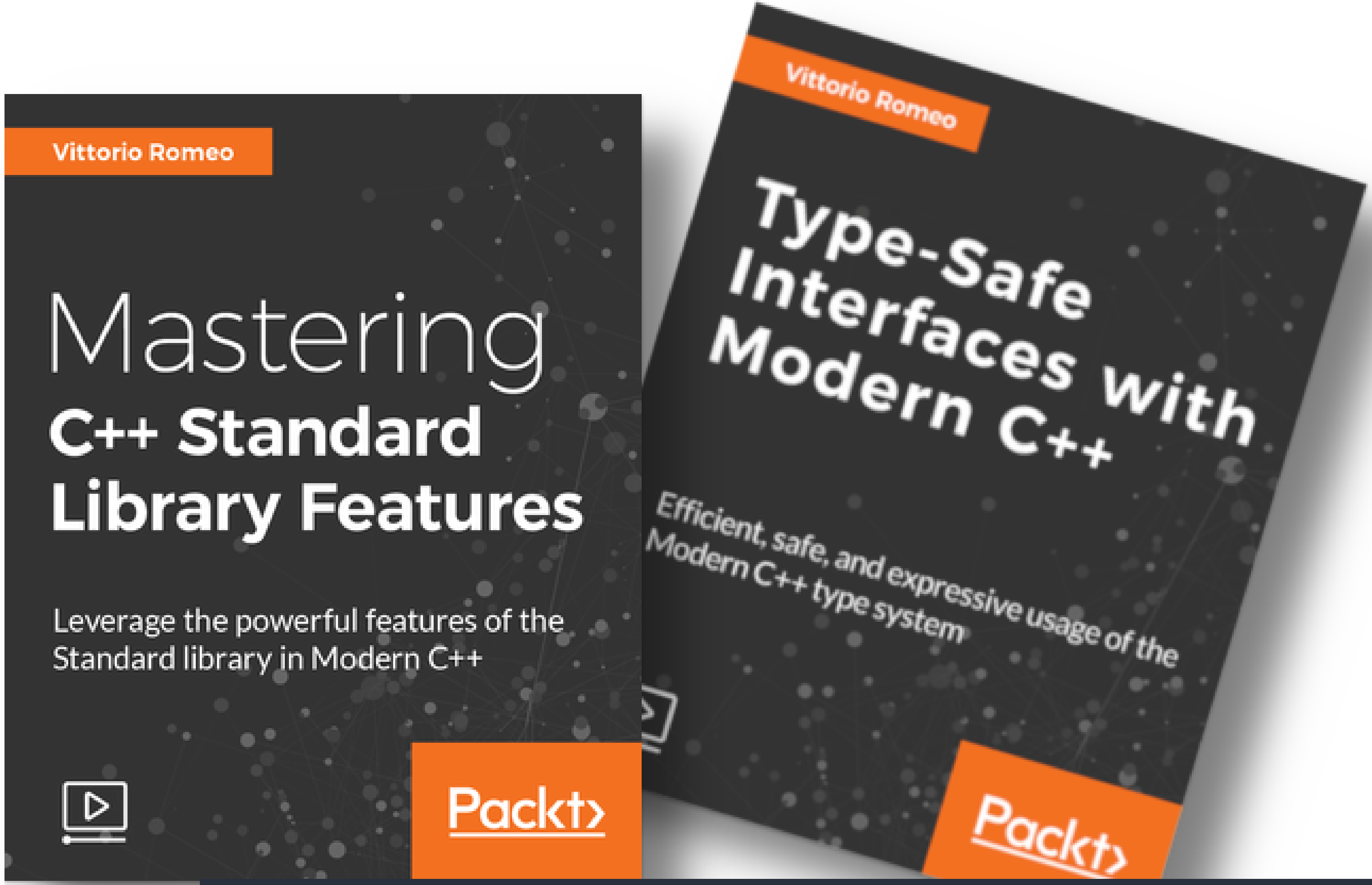

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vittorio romeo
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about me
Hello! My name is Vittorio.
I'm a modern C++ enthusiast who loves to share his knowledge by creating video tutorials and participating to conferences.
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Welcome to my blog.
compile-time iteration with C++20 lambdas
16 april 2018
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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.
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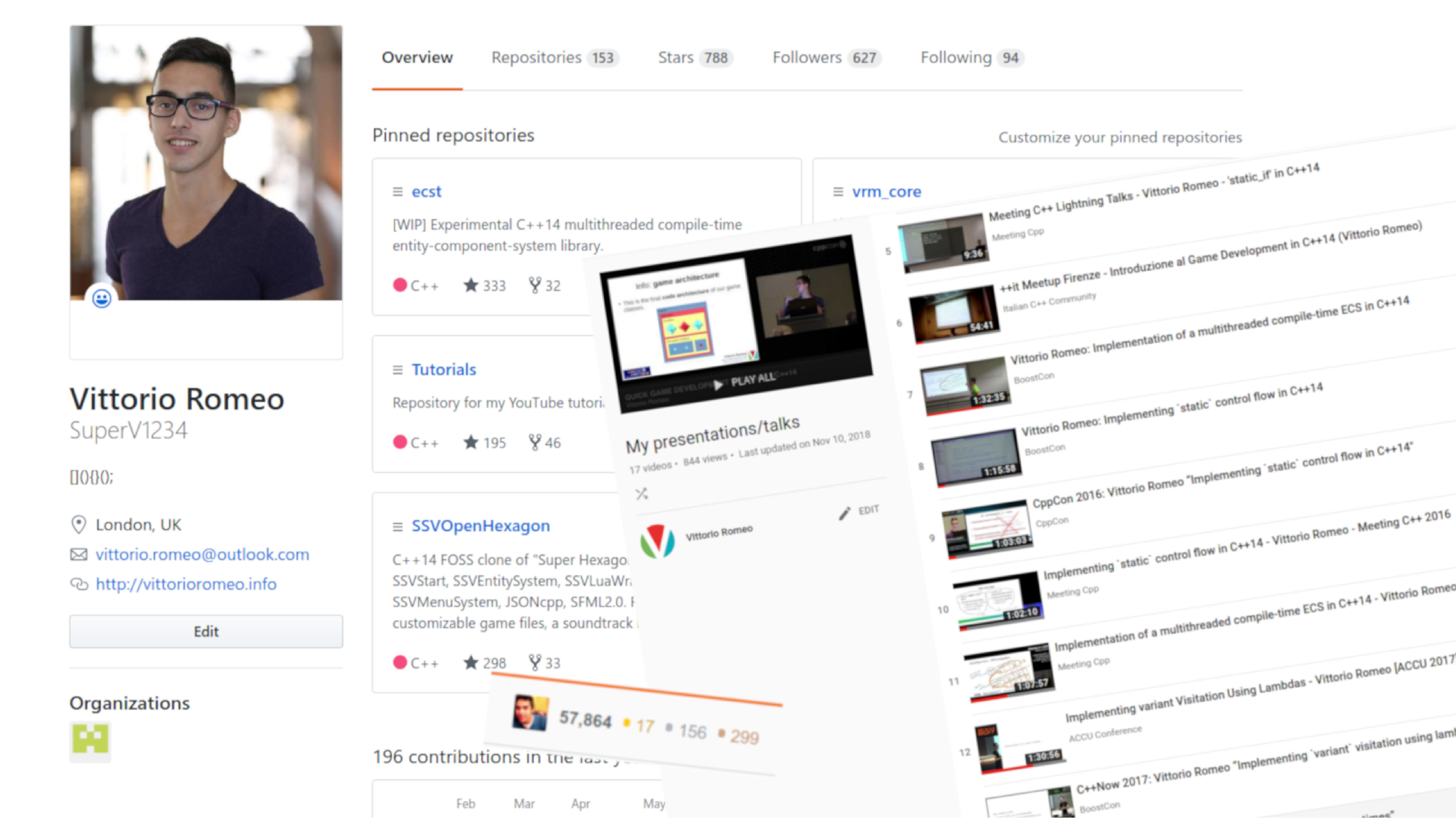
Document number
P0792R3
Date
2018-10-07
Reply-to
Vittorio Romeo <vittorio.romeo@outlook.com>
Audience
Library Working Group (LWG)
Project
ISO JTC1/SC22/WG21: Programming Language C++
function_ref: a non-owning reference to a Callable
Abstract
This paper proposes the addition of function_ref<R
owning 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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Meeting Cpp
Implementing variant Visitation Using Lambdas - Vittorio Romeo [ACCU 2017]
ACCU Conference
C++Now 2017: Vittorio Romeo "Implementing `variant` visitation using lam
BoostCon

Introduction

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

- 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?

higher order functions
in the 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);
```



```cpp
#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 kept elements to 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())
                f(*c);
    };

    for_visible_children([](auto& c){ c.recalculate_focus(); });
    for_visible_children([](auto& c){ c.recalculate_bounds(); });
    for_visible_children([](auto& c){ c.update(); });
}
```


- 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

```
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

```
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, FSep&& f_sep)
{
    if(std::empty(range)) { return; }
    f(*range.begin());

    for(auto it = std::next(range.begin()); it != range.end(); ++it)
    {
        f_sep();
        f(*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*


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

corrupt_print("helloworld"s);
```

(on *wandbox.org*)

> h%e$ltl3o□w/o�r□l_d
>
> h�eyl□l�oPwCo□r�l�d

```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

```
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; }
    }
}

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


```
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};
    }
};
```

```
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*)


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

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

(on *wandbox.org*)

- Way simpler to implement and review

- *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

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

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

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

```cpp
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);
}
```

- 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
- 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...) qualifiers;   // exposition only

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

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

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

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

    constexpr void swap(function_ref&) noexcept;

    R operator()(Args...) const noexcept-qualifier;
};
```



```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(qk);
        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());
        }
    }
};
```

```cpp
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() { }
};
```

- ...

```
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();
    }
};
```

```
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; }
    }
}
```

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

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


- What happens here?

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

- How about here?

```
int get_number() { return 42; }

const function_ref<int()> f = &get_number;
std::cout << f() << '\n';
```


- 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

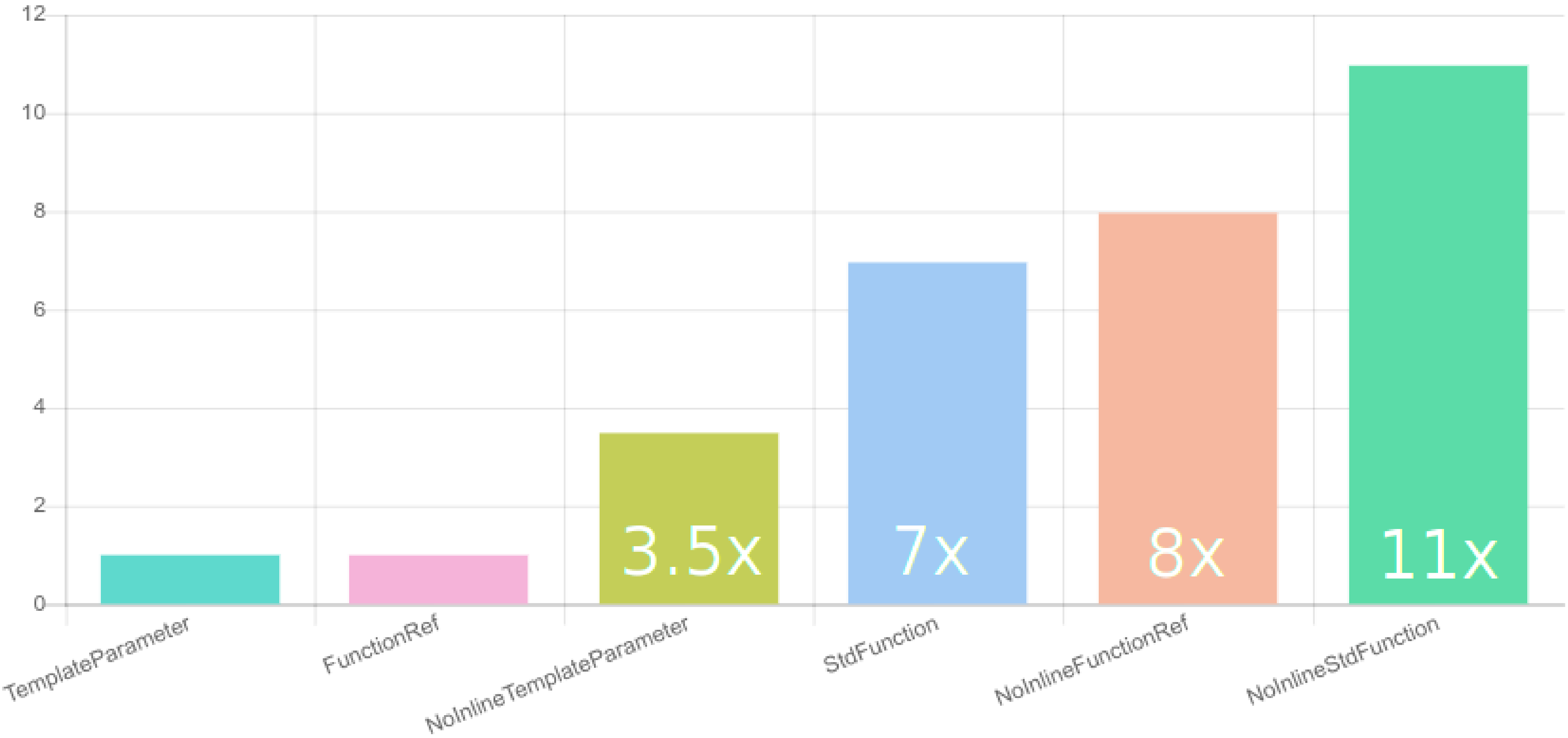

```cpp
template <typename F>
void templateParameter(F&& f)
{
    benchmark::DoNotOptimize(f());
}

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

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

```cpp
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());
}
```

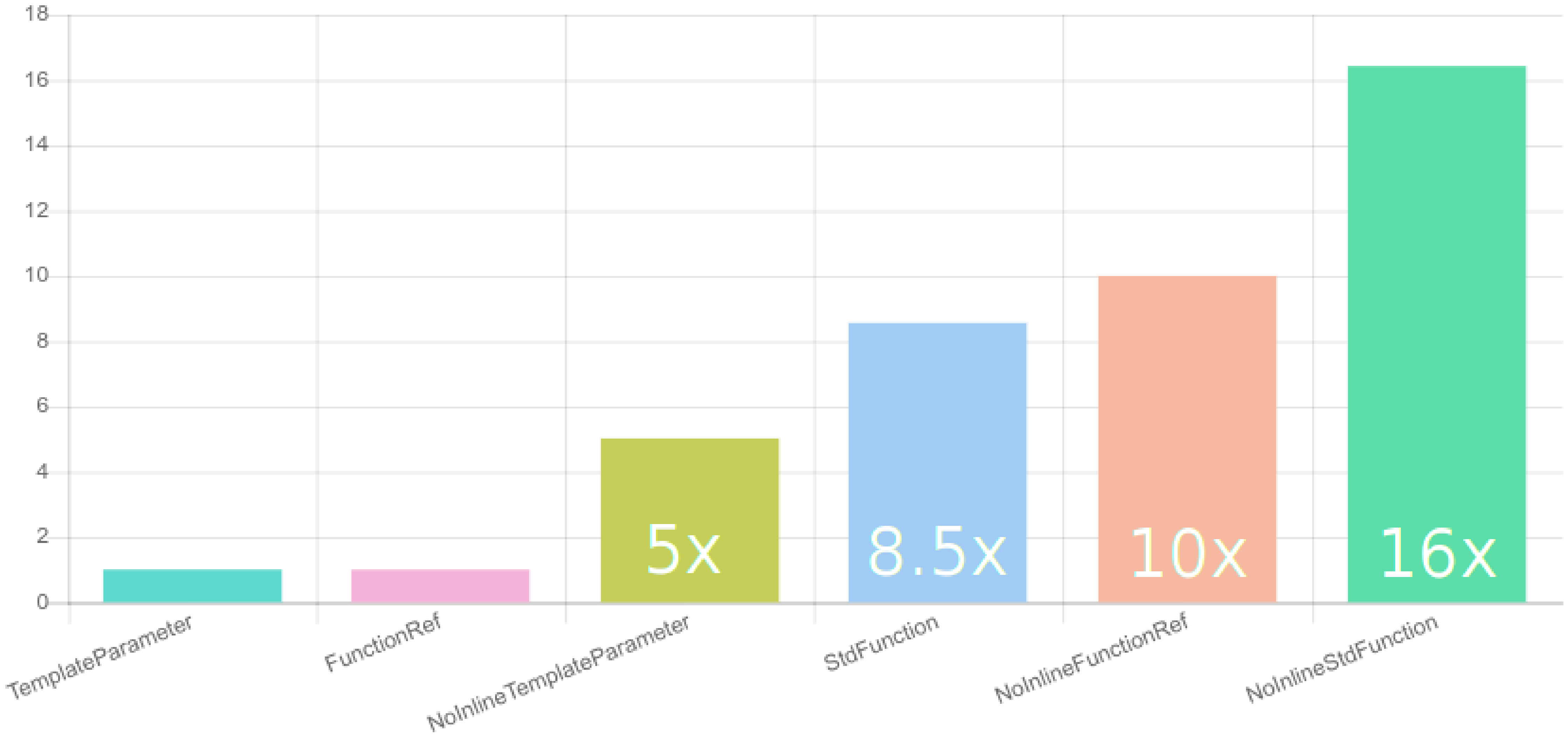


```cpp
static void TemplateParameter(benchmark::State& state) {
  for (auto _ : state) {
    templateParameter([]{ return 1; });
  }
}

BENCHMARK(TemplateParameter);

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

BENCHMARK(FunctionRef);

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

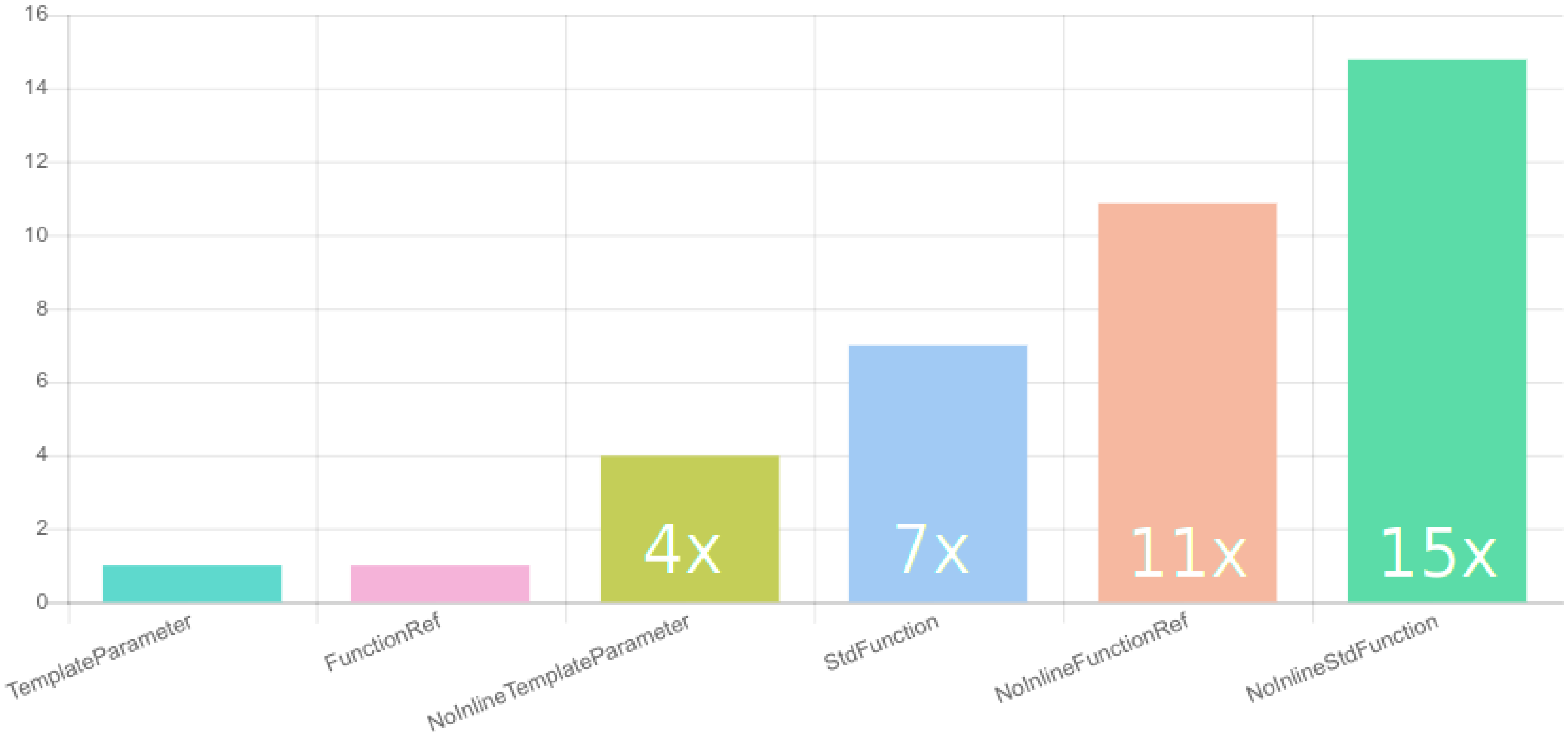
- `g++ 8.x`, `-O3`, `libstdc++` - *(link)*



- `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`

- 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/accu2019

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Extras

- *"compile-time iteration with C++20 lambdas"*
- *"P0573R2: Abbreviated Lambdas for Fun and Profit" (by Barry Revzin & Tomasz Kamiński)*

