Cross-compiling C++ to JavaScript

Challenges in porting the join.me common library to HTML5

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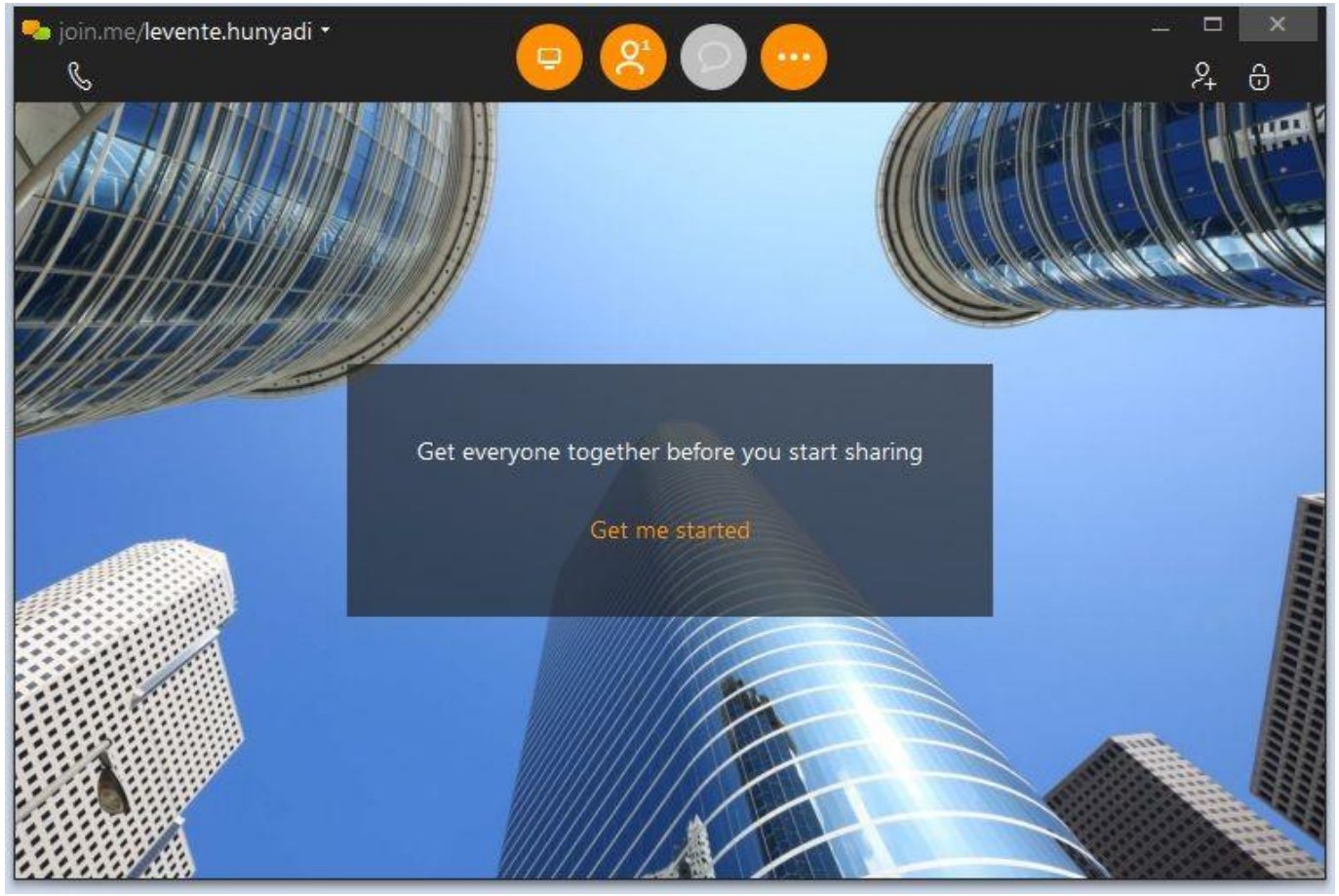
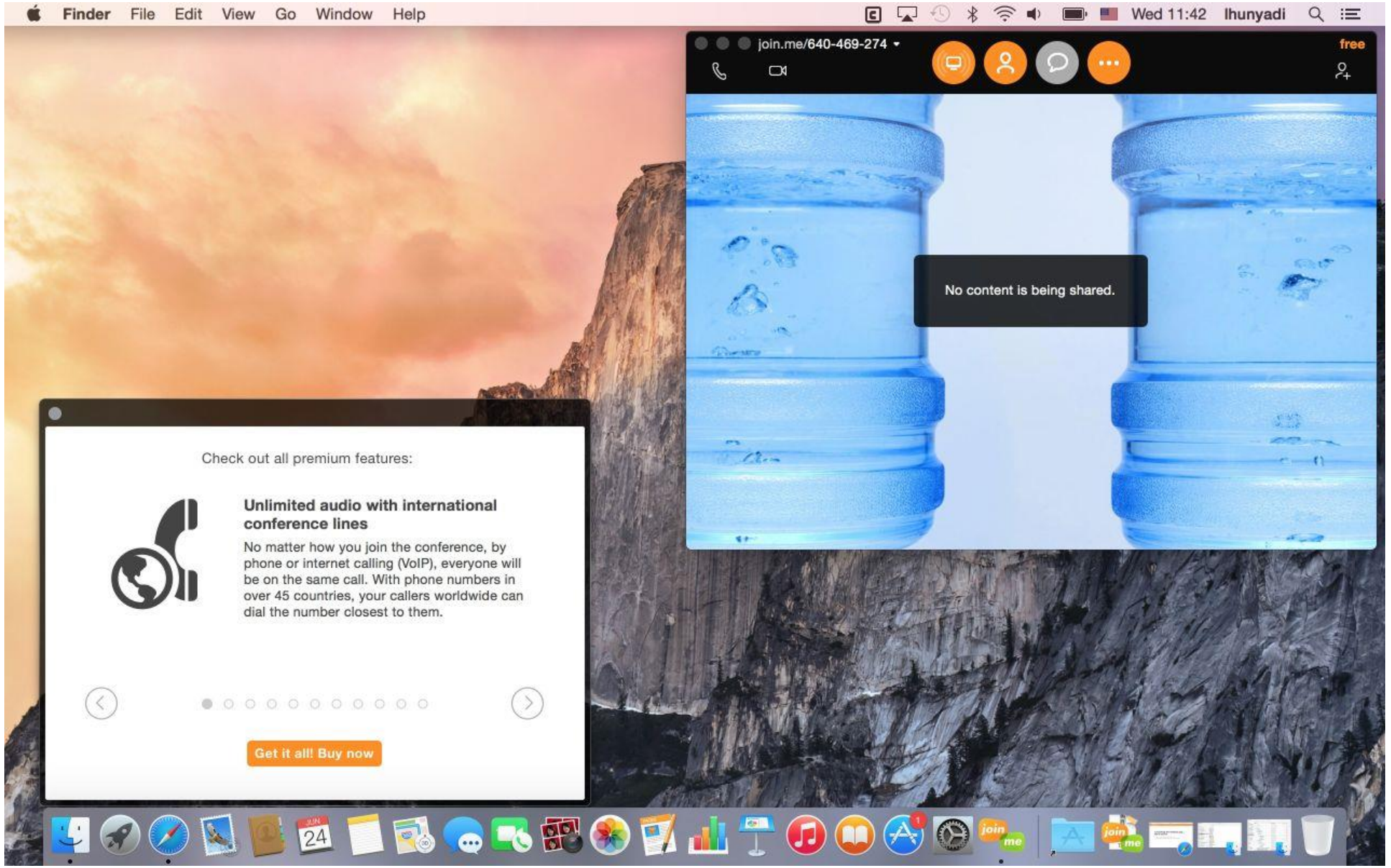
join.me at a glance





join.me characteristics

Application deployed to several platforms

- Windows, Mac, Android, iOS, etc.

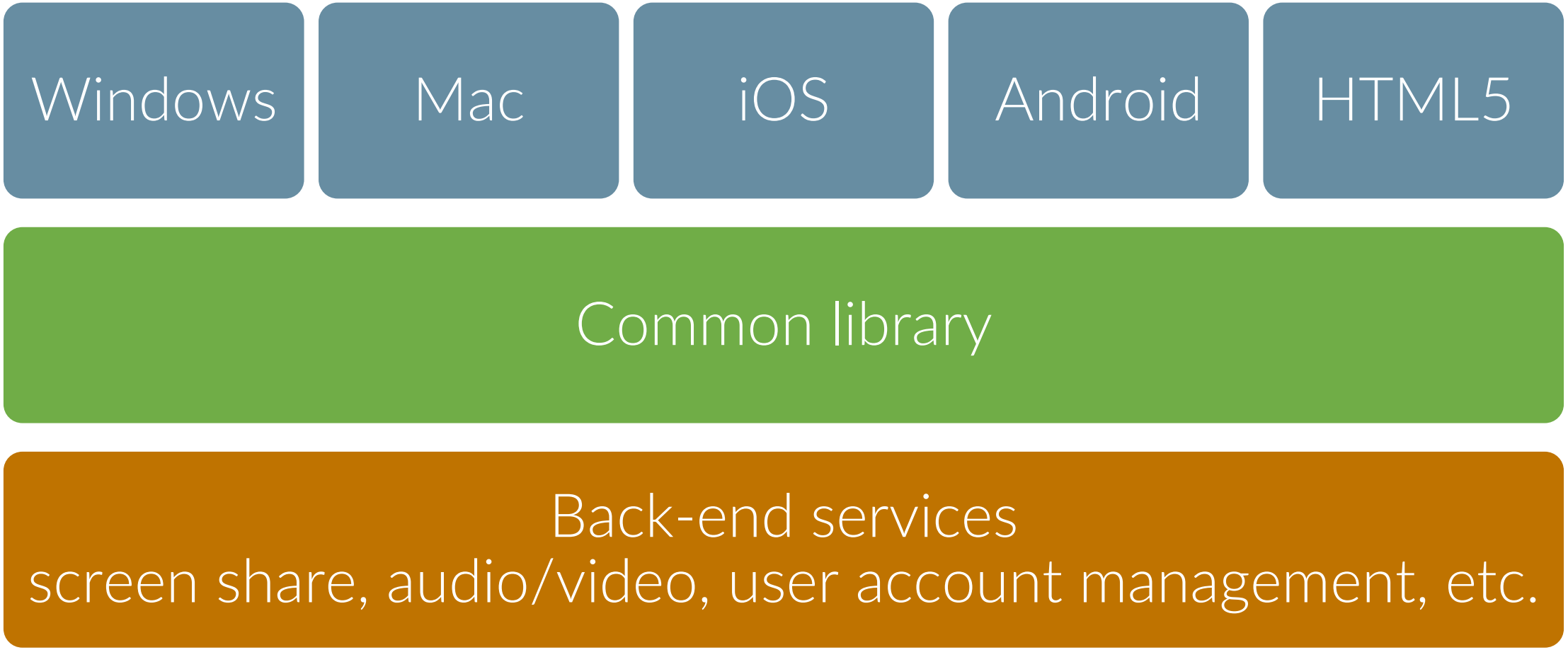
Native UI that looks natural

- Utilizes native functionality exposed by the platform

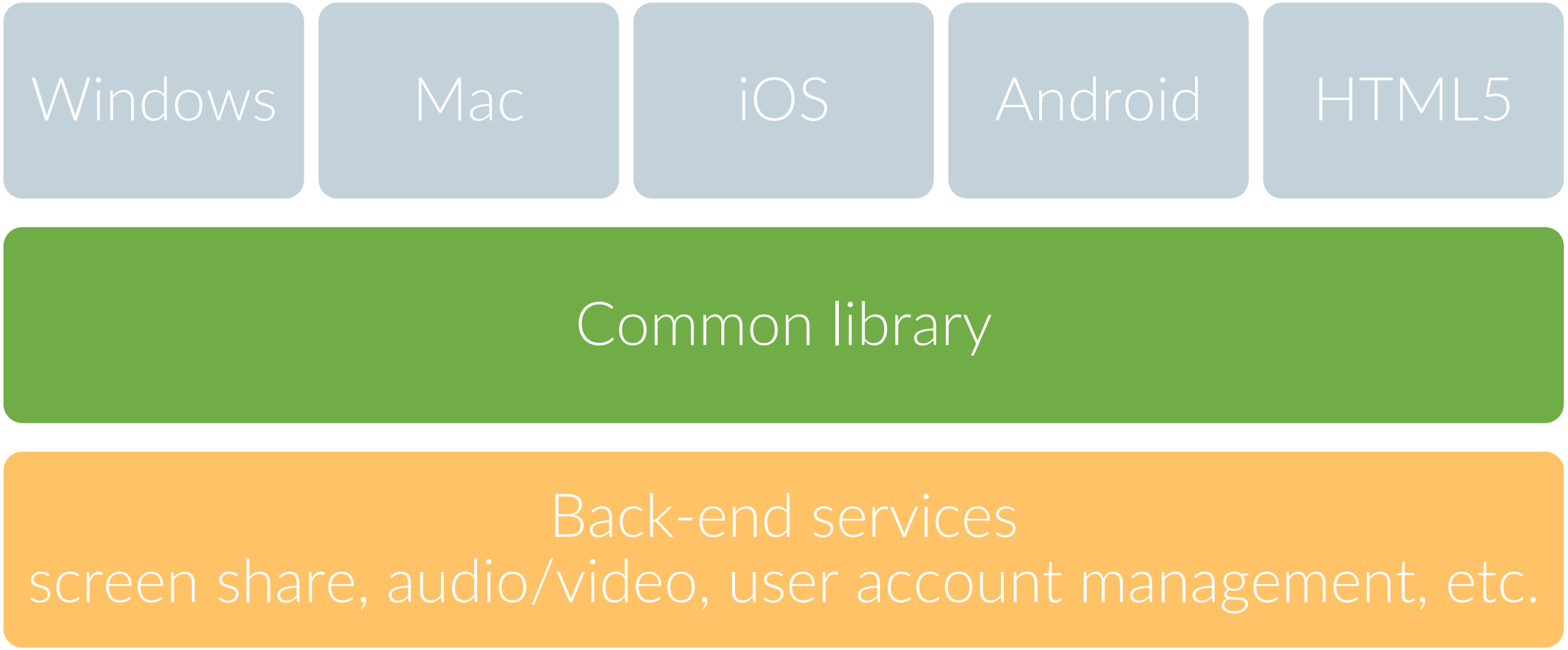
Common functionality in a single library shared across platforms

- Encapsulates application logic for sharing a screen or window, scheduling a meeting, using audio and video, etc.

Simplified architectural outline



Simplified architectural outline



C++ as the choice of language

Cross-platform

- Integrates into Windows, Mac, Android, iOS, etc. (with appropriate wrappers)

Speeds up development

- Develop and maintain a single code base, deploy to several platforms

Porting the join.me common library to HTML5

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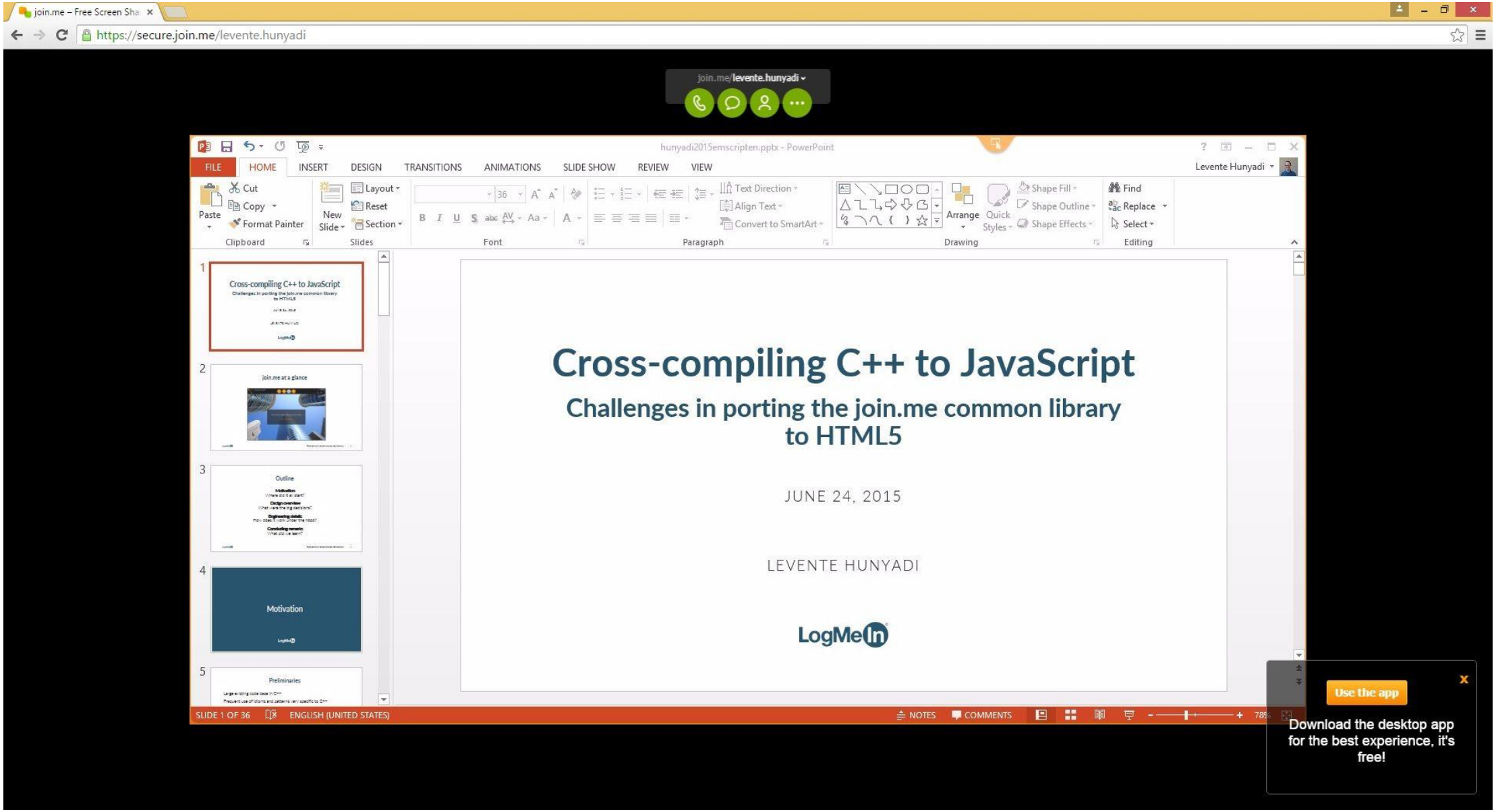
Motivation for HTML5

Join a meeting with a “single click” on the website

- Zero deployment

Universal browser support

- No special plug-ins needed for things to work out of the box



Preliminaries regarding common library

Large existing code base in C++

Frequent use of idioms and patterns very specific to C++

Code meant to be deployed to several platforms

Our principal problem:

Browsers run JavaScript, not C++

Some consequences

Large existing code base in C++

- Use a fully (or at least mostly) automated procedure

Frequent use of idioms and patterns very specific to C++

- Migrate code in a way that “eats everything”
  - truly multi-paradigm: our library code covers several fields including scheduling, low-level data manipulation, managing application state, notifications, etc.
  - modern C++ features like lambdas, *auto*, *decltype*, move semantics, etc.

Code meant to be deployed to several platforms

- Avoid introducing platform-specific behavior
  - if possible, no *#if defined(…)*

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Ingredients for our recipe

Compiles arbitrary C++ source code

- generates and operates on low-level primitives

Generates cross-browser compiled code

- no browser-specific dependencies

Does not sacrifice efficiency

- compiled code is fast, only cross-interface calls are relatively expensive

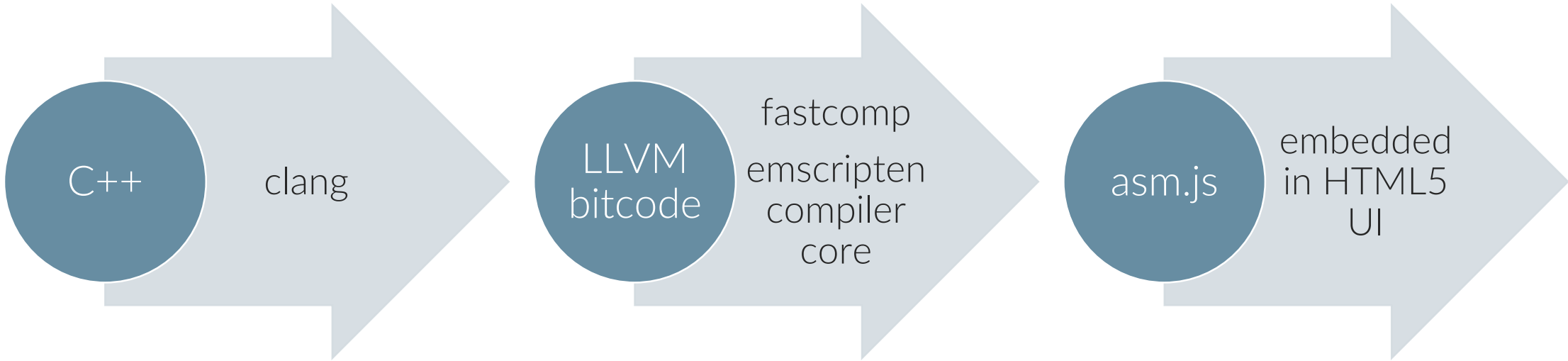
Our solution:

emscripten with embind

emscripten

Emscripten is an LLVM-based project that compiles C and C++ into highly-optimizable JavaScript in asm.js format. This lets you run C and C++ on the web at near-native speed, without plugins.

emscripten toolchain



Why emscripten?

Compiles arbitrary C++ code

- compiles advanced C++11 features our common library uses (emscripten is based on C++11 conforming clang compiler)
- compatible with any programming paradigm
- bidirectional interface with JavaScript (call JS in C++, call C++ in JS)

Why emscripten?

Generates portable code, no browser-specific dependencies

- compiled code runs in a (sandboxed) pseudo-virtual machine
  - fixed-size (16 MB) memory for stack, heap and static data allocated in JavaScript memory area
  - no special add-on binaries or browser plug-ins required (“no-download” common library)
- external context (e.g. window) wrapped in C++ functions
  - C++ standard library *libc* implemented in JavaScript (e.g. *printf* writes to browser console)
  - JavaScript environment is almost totally opaque to C++

Why emscripten?

Compiled code is fast, only cross-interface calls are expensive

- C++ optimization techniques apply
  - LLVM optimization for C++ source code
  - advanced C++ optimization carry over to JavaScript domain (for free)
- harness high-efficiency techniques in JavaScript
  - compiled code runs in asm.js mode
  - memory model implemented with fast JavaScript typed arrays (Uint8Array)
- relatively little data passes C++/JavaScript boundary

Interesting design challenges

or

the join.me common library under the hood illustrated with two case studies

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More (or less) common programming techniques applied in the join.me common library

Task-based parallelism

- cross-thread communication with execution queues
- asynchronous operation scheduling

Extensive use of callbacks in continuation passing style

- what to do next is wrapped in a callback in C++, passed to and called from external code but executed in C++
- error-handling with status codes and state change, not exceptions

Abstract classes with virtual functions act as interfaces

Typical code sample from join.me

```
auto self = shared_from_this();
UpdateEarlyAccess(reason, [self, sessionDesc, reason](
        bool didTriggerUpdate, ICommonToUI::ErrorCode errorCodeForLaunchpad) {

    if (didTriggerUpdate) {
        return;
    }

    LMI::ENQUEUE(self->GetQueue(), [self, sessionDesc, errorCodeForLaunchpad]() {
        SendOp(self->GetUI(), ICommonToUI::OpReset, ..., sessionDesc, ...);
        // ...
        self->m_State = STATE_ON_LAUNCHPAD;
    });
});
```

Continuation passing style

```
auto self = shared_from_this();
UpdateEarlyAccess(reason, [self, sessionDesc, reason](
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Cross-thread communication with queues

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```

Error handling with status codes and state

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Abstract classes with virtual functions

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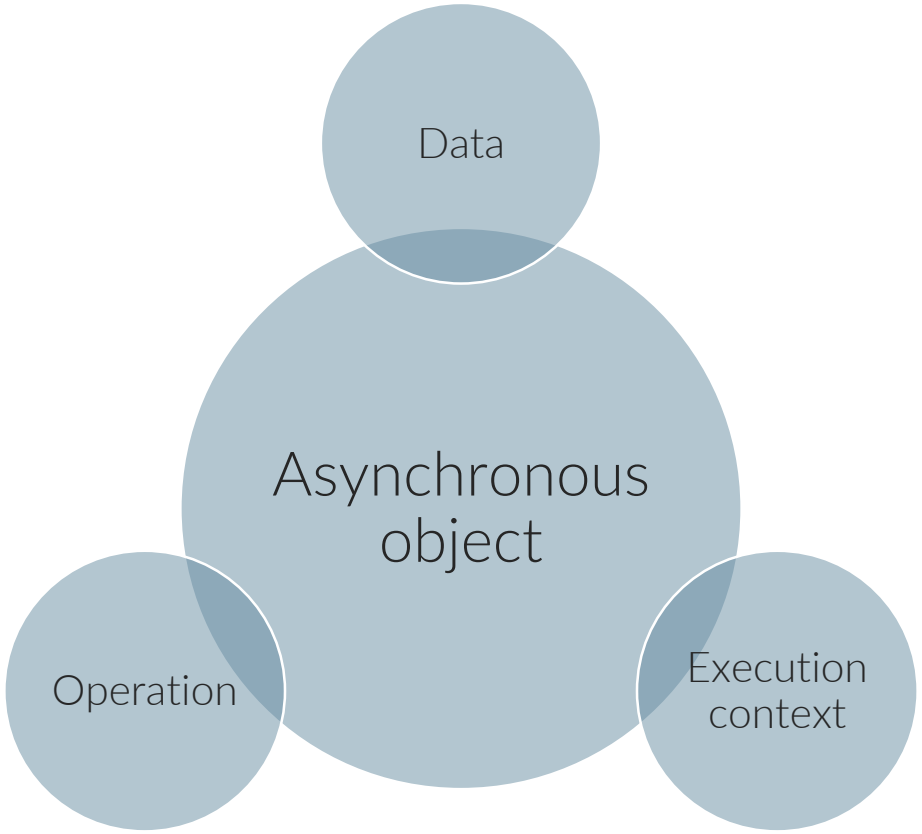
        self->m_State = STATE_ON_LAUNCHPAD;
    });
});
```

Case study 1

Task-based parallelism

Traditional OO

Task-based parallelism



Typical code sample from join.me

```
LMI::ENQUEUE(self->GetQueue(), [self, sessionDesc, errorCodeForLaunchpad]() {
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    // ...
    self->m_State = STATE_ON_LAUNCHPAD;
});
```

- statement does not block, returns immediately
- operation is posted on execution queue
- callback is invoked when operation is scheduled

Our C++ library vs. JavaScript

- asynchronous
- uses callbacks
- supports timed operations

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- uses callbacks
- supports timed operations

Our C++ library vs. JavaScript

- native hosts are multi-threaded (parallel execution)
- native implementations use lock-free queues
- synchronous operations are supported

- JavaScript is single-threaded (global execution order)
- browsers have their own scheduler (*setTimeout* and *setInterval*)
- synchronous operations are **not** supported

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Our C++ library vs. JavaScript

Implementation

- assign the same global thread to all execution contexts in JavaScript
- use a special-purpose queue for JavaScript exposed over our asynchronous object interface
  - *SendOp(…)* uses *window.setImmediate(fn)*
  - *SendDelayedOp(…)* uses *window.setTimeout(fn, delay)*
- re-write all synchronous operations in our common library as asynchronous operations to be compatible with JavaScript paradigm

End result: full transparency

- no need to be aware whether we target a native platform or HTML5
- uses most efficient task scheduling available on the target platform

Case study 2

Communicating over external interfaces

Traditional OO interface vs. JavaScript

- exposes interface with virtual functions
- mixes value types and (ownership-retaining) reference (pointer) types
  - int, enum, std::string
  - T&
  - std::shared_ptr<T>

- no true interfaces or virtual functions (uses prototyping instead)
- only value types and ownership-ignorant reference types
  - string
  - object

Interacting with OO interface from JS

1) Call a common library operation from JavaScript front-end

   a JavaScript function must be able to call a member function implemented in C++

2) Implement a library interface in JavaScript front-end

   a C++ member function must be able to call a JavaScript function bound to an object

   cross-language inheritance at work: JavaScript “derives” from C++ class (e.g. TCP socket interface in common library implemented with web sockets in browser)

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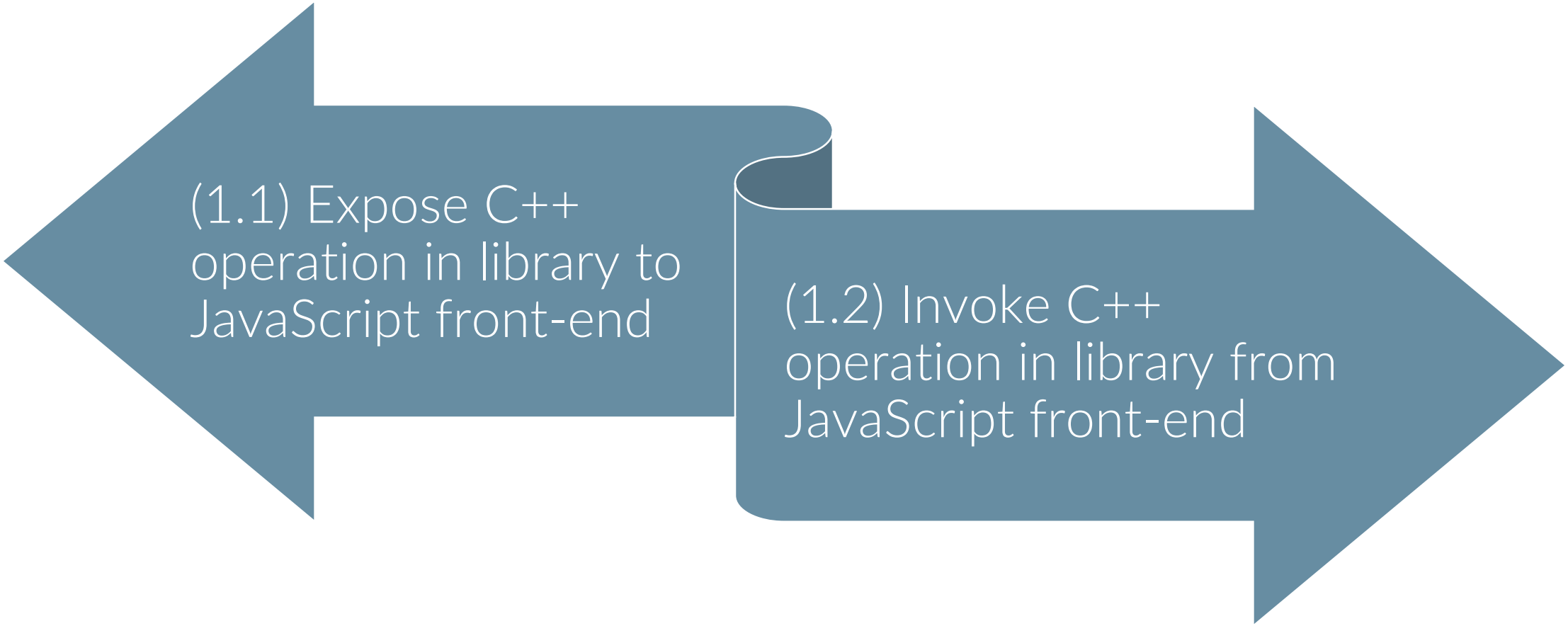
(1) Call a library operation in C++ from JavaScript front-end



(1.1) Expose library operation in C++ to JS

- expose class type by registering a unique name with *em::class_(…)*
- add binding using emscripten method *.function()* to register signature
- use embind utility functions in common to help with type mapping, e.g. UTF-8 strings

(1.1) Expose library operation in C++ to JS

```
em::class_<IUIToCommon>("IUIToCommon")
    .smart_ptr<std::shared_ptr<IUIToCommon>>("IUIToCommonSPtr")
    .function("OpPresenterSwitch_Initiate",
        EMBIND_METHOD(IUIToCommon::OpPresenterSwitch_Initiate))
    .function("OpPresenterSwitch_Cancel",
        EMBIND_METHOD(IUIToCommon::OpPresenterSwitch_Cancel))
;
```

(1.1) Expose library operation in C++ to JS "Dark magic" inside

```
template<typename MemberFunctionType, MemberFunctionType memberFunction, typename ReturnType,
    typename ClassType, typename... Args>
struct MethodInvoker {
    static ReturnType invoke(ClassType& obj, typename TypeTransformer<Args>::type... args) {
        return (obj.*memberFunction)(reverse_transform_argument<Args>(args)...);
    }
};

template<typename MemberFunctionType, MemberFunctionType memberFunction, typename ReturnType,
    typename ClassType, typename... Args>
constexpr auto wrap_method(ReturnType(ClassType::*)(Args...)) -> ReturnType(*)(ClassType&, typename
TypeTransformer<Args>::type...)
{
    return &MethodInvoker<MemberFunctionType, memberFunction, ReturnType, ClassType, Args...>::invoke;
}

#define EMBIND_METHOD(method) wrap_method<decltype(&method),&method>(&method)
```

(1.1) Expose parameter types and callbacks in C++ to JS

- add binding for function parameter types with *em::class_(...)*
- add binding for properties of newly registered types with *.property(...)*, *.field(...)*
- add binding for new callback function signatures (unique globally, no aliases)
- add binding for enumerations (both new- and old-style enums)

(1.1) Expose parameter types and callbacks in C++ to JS

```
em::value_object<Point>("Point")
    .field("x", &Point::x)
    .field("y", &Point::y)
;

typedef std::function<void(ErrorCode)> Callback;
em::class_<ITCPSocket::Callback>("TCPCallback")
    .constructor<const ITCPSocket::Callback&>()
    .function("Invoke", &ITCPSocket::Callback::operator())
;
```

(1.2) Invoke library operation in C++ from JS

- use global object *Module* to access C++ class as a prototype
- use keyword *new* to instantiate an object
- use the instance almost as a regular JavaScript object

(1.2) Invoke library operation in C++ from JS

```
AsyncConnect: function (address, port, bufferSize, callback) {
    var address = 'wss://' + address + ':' + port + '/endpoint';
    var connectCallback = new Module.TCPCallback(callback);
    var socket = new WebSocket(address);
    socket.binaryType = 'arraybuffer';
    socket.onopen = function () {
        connectCallback.Invoke(0);
        connectCallback.delete();
        connectCallback = null;
    };
}
```

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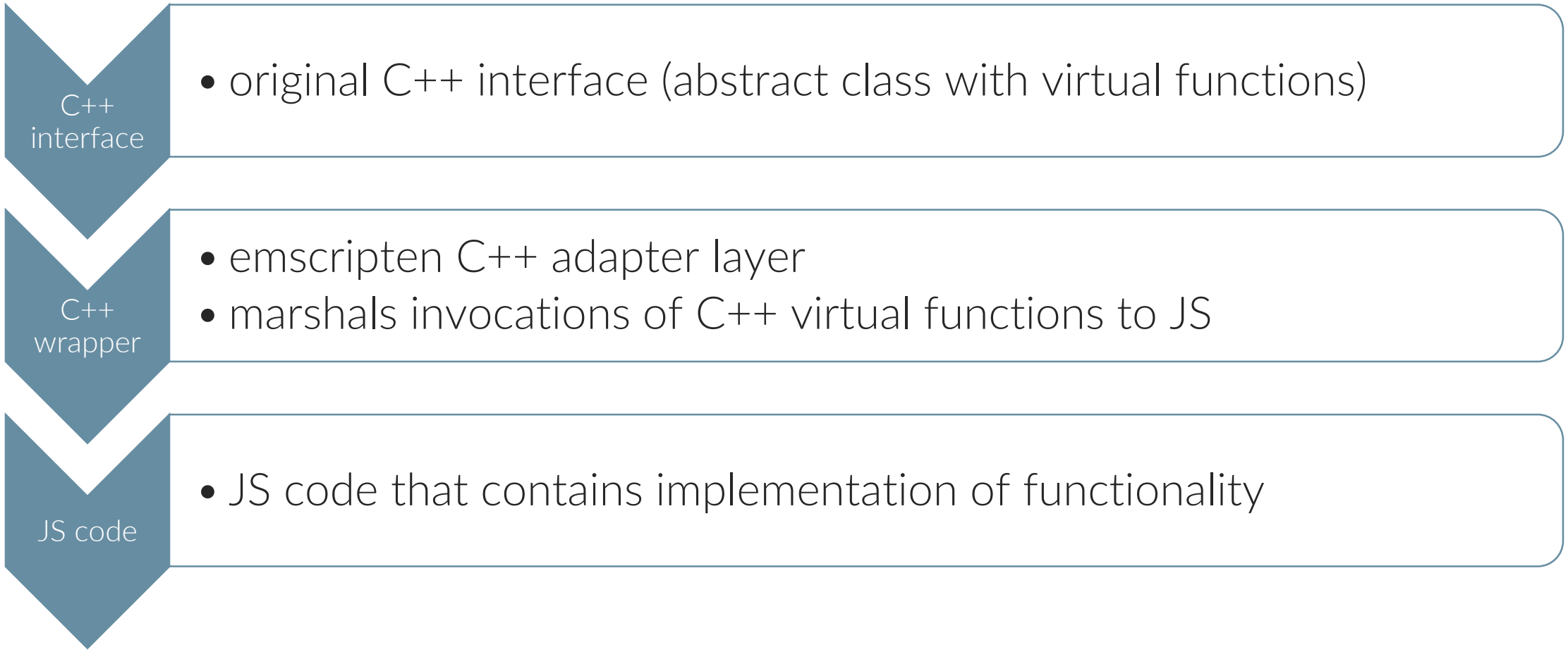
(2) Implement a library interface in JavaScript



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(2) Implement a library interface in JavaScript

(2.1) C++

- add a new wrapper class
- add special macro to generate emscripten constructor
- add member functions to map virtual function calls to JavaScript calls (no virtual methods in JavaScript)

(2.2) JavaScript

- use the function *.implement(…)* to bind to C++ interface

(2.1) Annotating an interface for external calls in C++

```
struct CommonToUI : public em::wrapper<ICommonToUI> {
    EMSCRIPTEN_WRAPPER(CommonToUI);

    void OpChatMessageDelivered(std::string msg) override {
        return call<void>("OpChatMessageDelivered", msg);
    }

    // ...
};
```

(2.1) Register an interface for external calls in C++

```
em::class_<ICommonToUI>("ICommonToUI")
    .allow_subclass<CommonToUI>("CommonToUI")
    .function("OpChatMessageDelivered",
        EMBIND_METHOD(ICommonToUI::OpChatMessageDelivered),
        em::pure_virtual()
    )

    // ...
;
```

(2.2) Pass an object implementing an interface in JS for external calls in C++

```
var iCommonToUI = {
    OpChatMessageDelivered: function (targetId, msgTime, msg) {
        console.log('OpChatMessageDelivered');
    }
}

var jsCommonToUI = Module.WrapCommonToUI(
    Module.ICommonToUI.implement(iCommonToUI)
);
var service = new Module.Facade(
    jsCommonToUI, jsPlatform, jsBasicDependencyProvider
);
```

Pitfalls in cross-compiled code

- no *long* type (only *Number*, which is equivalent to C++ *double*)
- passing long arrays is inefficient (involves data copies)
  - memory views to elide copies for reads/writes (*emscripten::memory_view<T>*)
- no garbage collection in JavaScript for objects originating from C++
  - must clean everything up in JavaScript (use *delete()* method)
- native JavaScript in C++ (*emscripten::val*)
  - conversion functions in common library to an interval JSON class type
- synchronous (blocking) operations are not supported

Parting thoughts

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Things we learned

Very effective code re-use is possible

- limited emscripten-specific code in common library
- limited rewrite required in common library to be compatible with HTML5

Tracking down errors originating from C++ is not easy

- no interactive debugger
- many nested lambdas leave little clue as to what could be going on

Inadequate compile-time verification of type binding correctness

- undefined or ill-defined types discovered only at run time when parameters are passed

Thank you!

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