typescripten

Type-safe web development with C++

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Live Coding

Live Coding

1. Download TypeScript interface definition

```
npm install @types/tableau
```

2. Call typescripten compiler

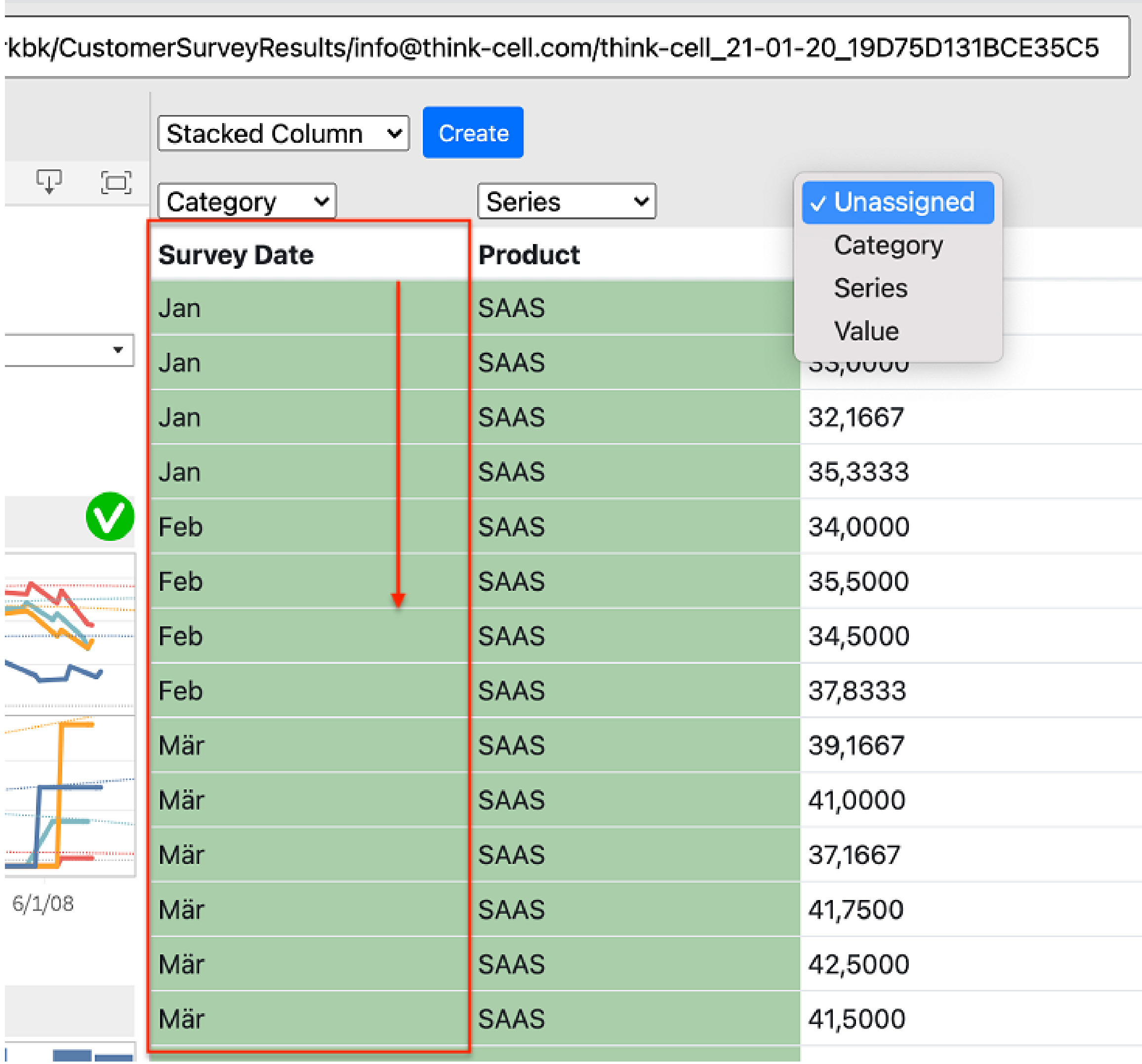
3. Use C++ header definitions to call JavaScript API

JavaScript for Beginners

One simple problem:

Transform data into tabular format

- data could be `number|string|date`
- sort, make unique, do binary search



JavaScript for Beginners

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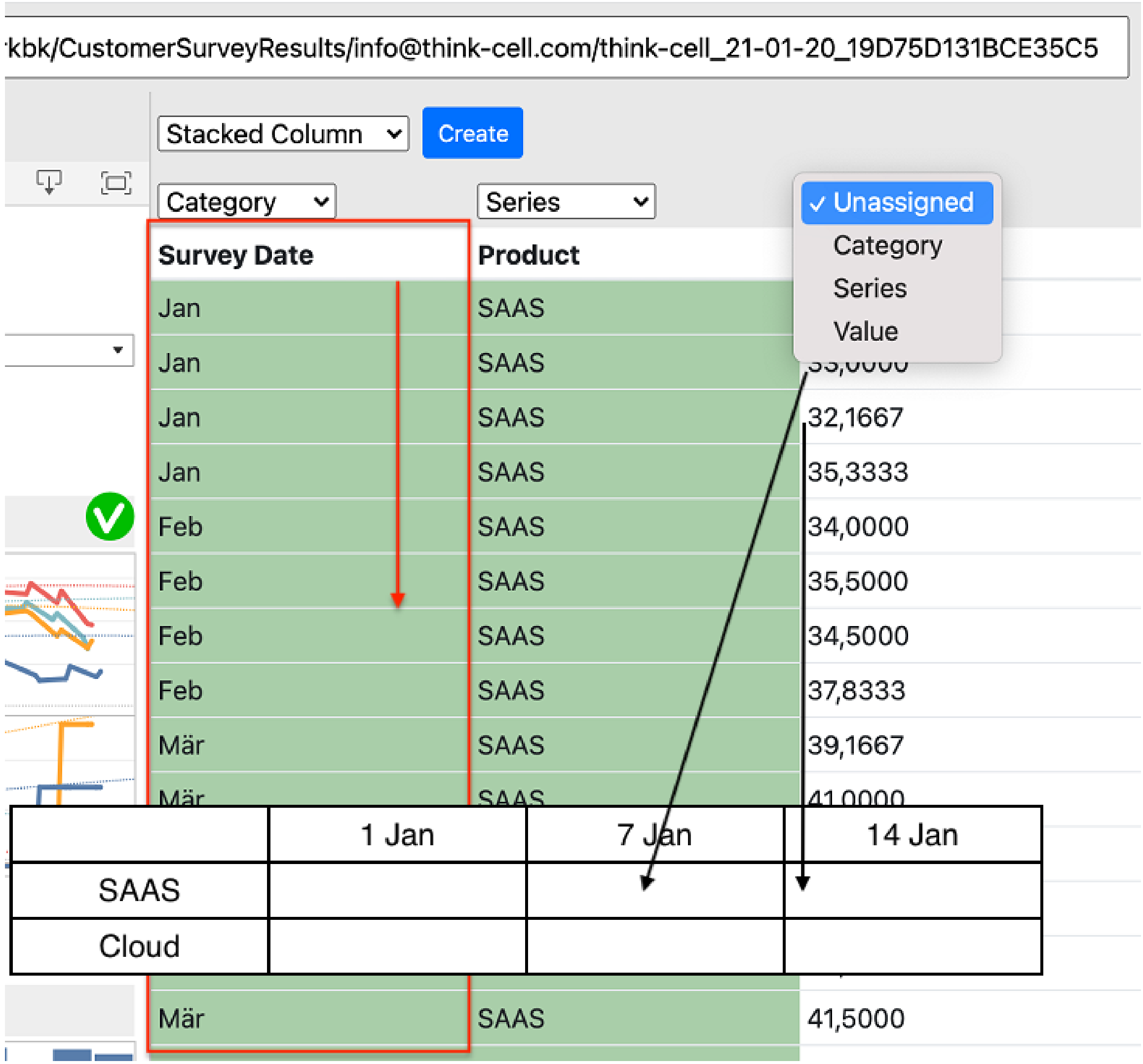


MDN Web Docs: Array.sort

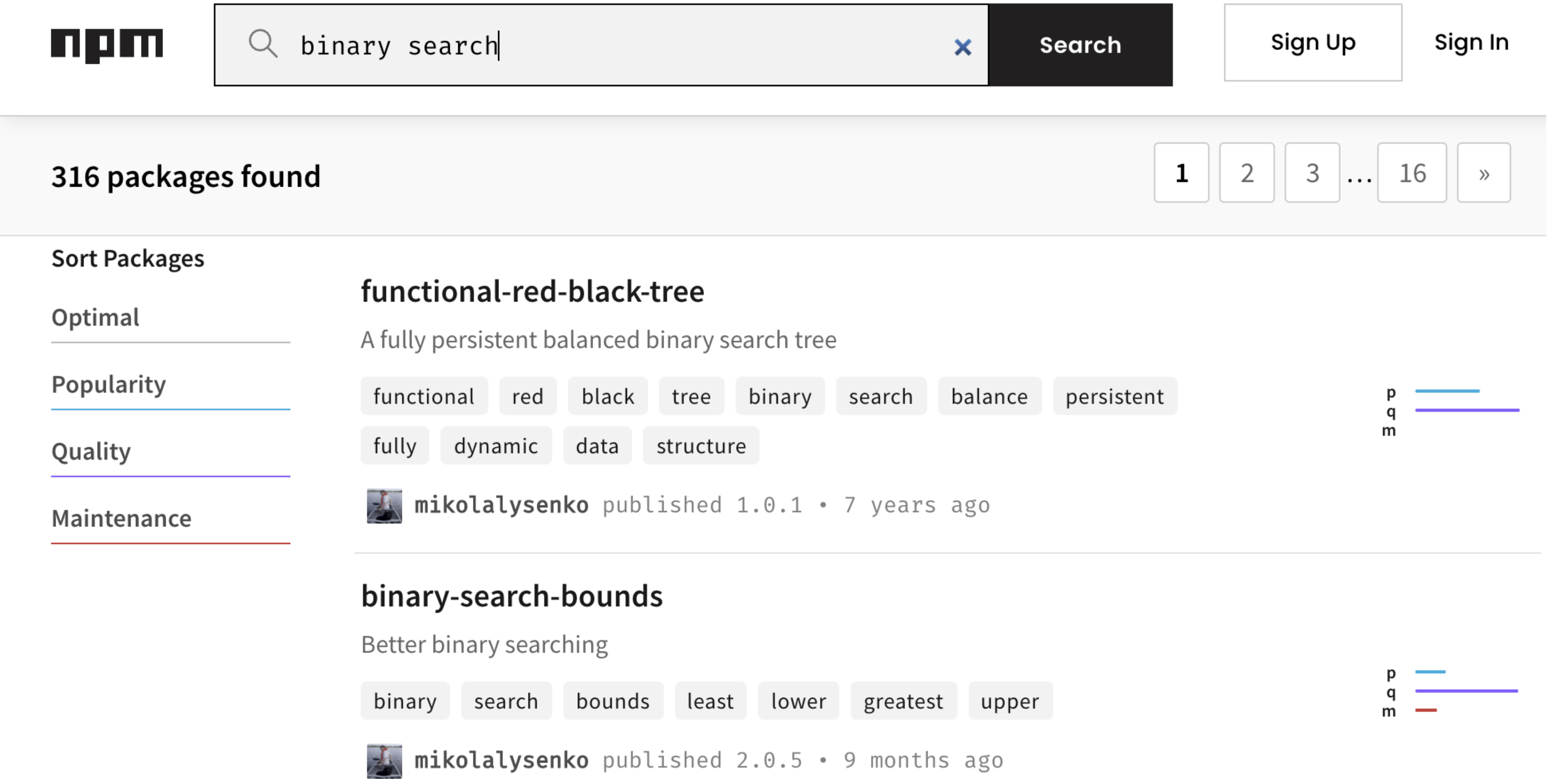
"The default sort order is ascending, built upon converting the elements into strings, then comparing their sequences of UTF-16 code units values.

***The time and space complexity of the sort cannot be guaranteed** as it depends on the implementation."*

🚫 No unique

🚫 No binary search

JavaScript for Beginners



Meanwhile, in C++ land

Everything could be so easy:

```
using datavalue = std::variant<double, std::string, std::chrono::time_point>

std::vector<datavalue> vecdata;
// Fill vecdata

auto const rng = std::ranges::unique(std::ranges::sort(vecdata));

std::ranges::binary_search(rng, x)
```

What Do I Need?

Compile C++ for the Web

Call JavaScript from C++

Type-safe calls to JS

Enter WebAssembly

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CppCon 2014: Alon Zakai "Emscripten and asm.js: C++'s role in the modern web"

CppCon 2014: Chad Austin "Embind and Emscripten: Blending C++11, JavaScript, and the Web Browser"

CppCon 2016: Dan Gohman "C++ on the Web: Let's have some serious fun."

CppCon 2017: Lukas Bergdoll "Web | C++"

CppCon 2018: Damien Buhl "C++ Everywhere with WebAssembly"

CppCon 2019: Ben Smith "Applied WebAssembly: Compiling and Running C++ in Your Web Browser"

CppCon 2019: Borislav Stanimirov "Embrace Modern Technology: Using HTML 5 for GUI in C++"

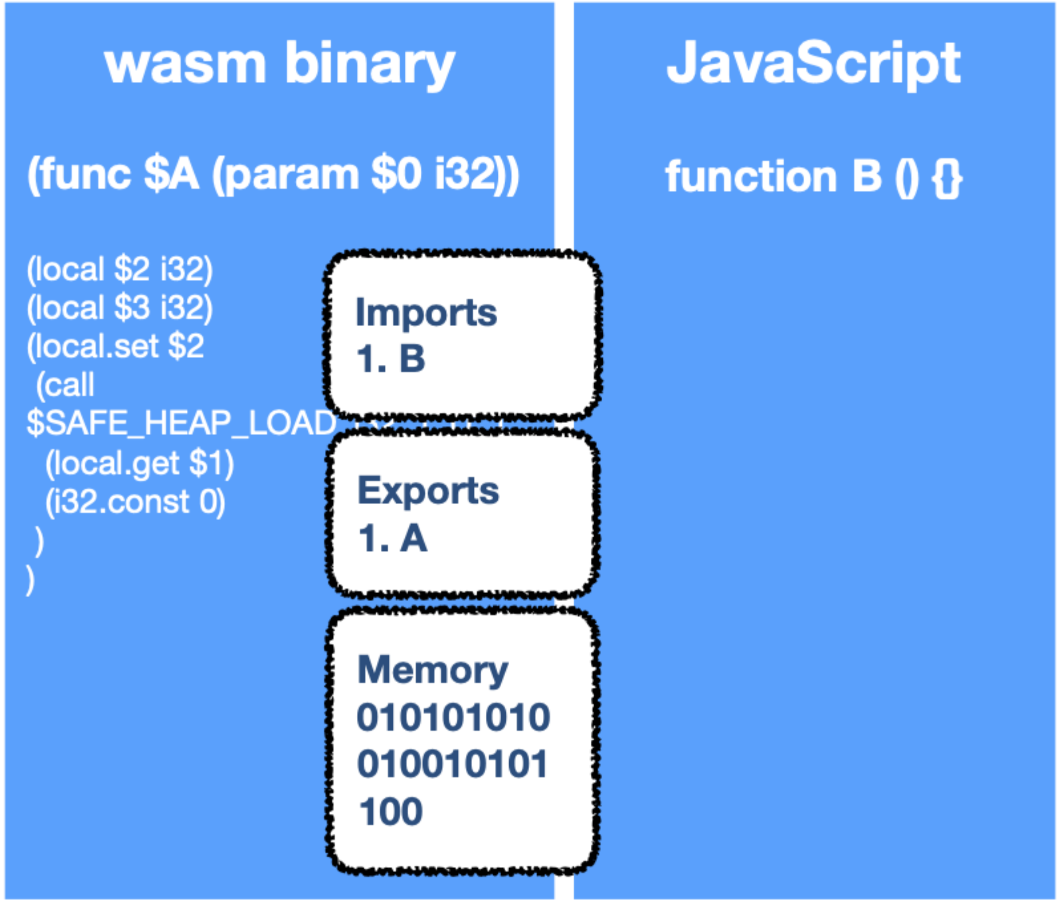
Enter WebAssembly

The shortest intro to WebAssembly

- compiled, binary format, standardised and supported by all major browser vendors
- fast and compact
- low level data types: integer and floating point numbers
- secure per-application sandbox, runs in browser VM

Enter WebAssembly

WebAssembly is instantiated from and interacts with JavaScript



Enter WebAssembly

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WebAssembly is instantiated from and interacts with JavaScript

```
function _abort() { abort(); }

function _handle_stack_overflow() { abort("stack overflow"); }

var imports = {
 "_handle_stack_overflow": _handle_stack_overflow,
 "abort": _abort
}

var instance = WebAssembly.instantiate(
    binary,
    {"env": imports}
).instance;

instance.exports["exported_func"]();
```

https://hacks.mozilla.org/2018/10/calls-between-javascript-and-webassembly-are-finally-fast-🎉/

Enter WebAssembly

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```
(func $strcmp (param $0 i32) (param $1 i32) (result i32)
(local $2 i32)
(local $3 i32)
(local.set $2
 (call $SAFE_HEAP_LOAD_i32_1_U_1
  (local.get $1)
  (i32.const 0)
 )
)
(block $label$1
 (br_if $label$1
  (i32.eqz
   (local.tee $3
    (call $SAFE_HEAP_LOAD_i32_1_U_1
     (local.get $0)
     (i32.const 0)
    )
   )
  )
 )
...
```

Compiling C++ for the Web

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- Toolchain based on clang/llvm with WebAssembly backend
- Simple DirectMedia Layer API (SDL) for input device access and graphics output
- Access to OpenGL API and HTML5 input events
- Virtualized file system

emscripten

emscripten

Easy to compile portable C or C++ to WebAssembly and run it in browser

What Do I Need?

✅ Compile C++ for the Web — **WebAssembly & emscripten**

Call JavaScript from C++

Type-safe calls to JS

emscripten

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How to call JavaScript?

1. Implement C functions in JS
    - WebAssembly imports or exports
    - `extern "C" int my_js_function() noexcept;`
    - limited to WebAssembly supported types, integers or floating point

1. Direct Embedding

```
int x = EM_ASM_INT({
    console.log('I received: ' + $0);
    return $0 + 1;
}, 100);
printf("%d\n", x);
```

- `int` or `double` return values

emscripten

`emscripten::val` "transliterates JavaScript" to C++

```
using namespace emscripten;

int main() {
  val AudioContext = val::global("AudioContext");
  val context = AudioContext.new_();
  val oscillator = context.call<val>("createOscillator");
  oscillator.set("type", val("triangle"));
  oscillator["frequency"].set("value", val(261.63)); // Middle C
}
```

emscripten

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}
```

Pro: Convenient interaction with JS objects

Con: Combines disadvantages of both languages:

1. Compiled
2. Not type-safe

emscripten

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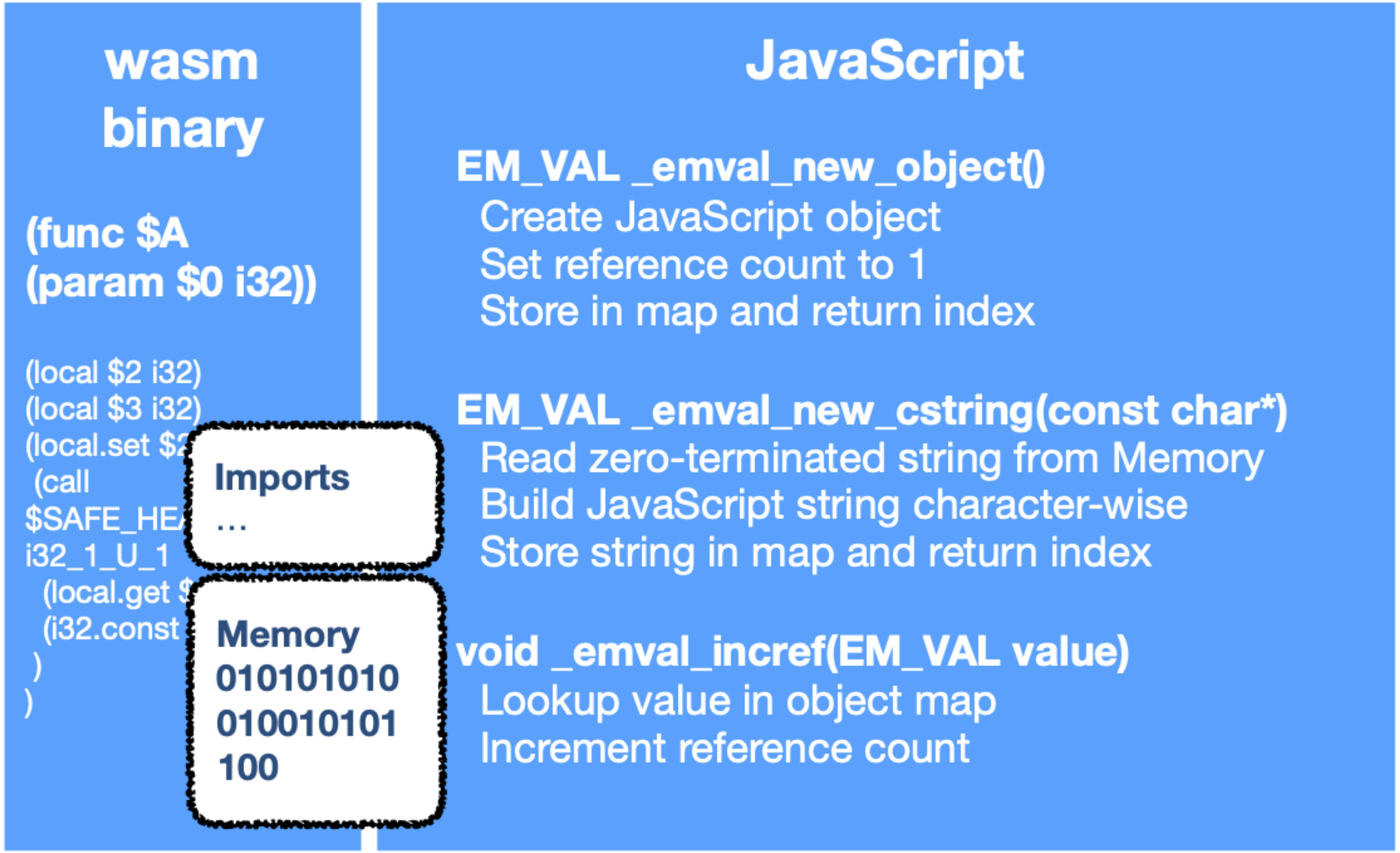
`emscripten::val` **based on WebAssembly imports implemented in JS**

```
EM_VAL _emval_new_object();
EM_VAL _emval_new_cstring(const char*);

void _emval_incref(EM_VAL value);
void _emval_decref(EM_VAL value);

void _emval_call_void_method(
    EM_METHOD_CALLER caller,
    EM_VAL handle,
    const char* methodName,
    EM_VAR_ARGS argv);
```

emscripten



`EM_VAL` = reference to JavaScript object stored in a table, possibly with reference count

emscripten

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  oscillator.set("type", val("triangle"));
  oscillator["frequency"].set("value", val(261.63)); // Middle C
}
```

```
namespace js = tc::js;
int main() {
    auto const ctx = js::AudioContext(tc::jst::create_js_object);
    auto const o = ctx->createOscillator();
    o->type(js::string("triangle"));
    o->frequency()->value(261.63);
}
```

What Do I Need?

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✅ Compile C++ for the Web — **WebAssembly & emscripten**

✅ Call JavaScript from C++ — **emscripten**

Type-safe calls to JS

typescripten

typescripten — https://github.com/think-cell/typescripten

- Compiles TypeScript interface declarations to C++ interfaces
- **i.e. type-safe, idiomatic calls to JavaScript libraries via emscripten**

JavaScript:

```
document.title = "Hello World from C++";
```

C++:

```
using namespace tc;
js::document()->title(js::string("Hello World from C++!"));
```

- Integration with emscripten in currently in progress

TypeScript

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Type definition libraries:

```
interface Document extends Node, NonElementParentNode, DocumentOrShadowRoot {
    readonly URL: string;

    readonly activeElement: Element | null;

    readonly anchors: HTMLCollectionOf<HTMLAnchorElement>;

    title: string;

    createElement<K extends keyof HTMLElementTagNameMap>(
        tagName: K, options?: ElementCreationOptions
    ): HTMLElementTagNameMap[K];
}
```

TypeScript

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interface Document extends Node, NonElementParentNode, DocumentOrShadowRoot {
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    title: string;

    createElement<K extends keyof HTMLElementTagNameMap>(
        tagName: K, options?: ElementCreationOptions
    ): HTMLElementTagNameMap[K];
}
```

https://github.com/DefinitelyTyped/DefinitelyTyped

Repository for over 7000 JavaScript libraries, e.g, AngularJS, bootstrap, tableau.com

TypeScript

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TypeScript ships with **super convenient** parser and resolver API:

```
function transform(file: string) : void {
    let program = ts.createProgram([file]);
    const sourceFile = program.getSourceFile(file);

    ts.forEachChild(sourceFile, node => {
        if (ts.isFunctionDeclaration(node)) {
            // do something
        } else if (ts.isVariableStatement(node)) {
            // do something else
        }
    });
}
```

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```
namespace tc::js {
    struct object_base {
        emscripten::val m_emval;
    };

    struct Document : virtual Node, ... {
        auto URL() noexcept;
        auto activeElement() noexcept;
        auto title() noexcept;
        void title(string v) noexcept;
        // ...
    };

    inline auto Document::title() noexcept { return m_emval["title"].template as<string>(); }
    inline void Document::title(string v) noexcept { m_emval.set("title", v); }

    inline auto document() noexcept {
        return emscripten::val::global("document").template as<Document>();
    }
}
```

typescripten

```
namespace tc::js {
    struct object_base {
        emscripten::val m_emval;
    };

    struct Document : virtual Node, ... {
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    inline auto Document::title() noexcept { return m_emval["title"].template as<string>(); }
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    }
}
```

typescripten

Do we support all TypeScript constructs?

typescripten

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```
interface A {
    func(a: { length: number }) : void;
}
```

typescripten

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interface A {
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No.

Need to support common constructs in interface definition files.

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Do we support all TypeScript constructs?

```
interface A {
    func(a: { length: number }) : void;
}
```

No.

Need to support common constructs in interface definition files.

```
interface A {
    func(a: TypeWithLengthProperty) : void;
}
```

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Supported TypeScript constructs

- Implementation of built-in types `tc::js::any`, `tc::js::undefined`, `tc::js::null`, `tc::js::string`
- Optional members, type guards
- Support for union types `A|B|C` as `tc::js::union_t<A, B, C>`
- Mixed enums like

```
enum E {
    a,
    b = "that's a string",
    c = 1.0
}
```

- Passing function callbacks and lambdas to JavaScript as `tc::js::function<R (Args...)>`
- Generic types, e.g., `tc::js::Array<T>` or `tc::js::Record<K, V>`

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Self-hosting, i.e., compiles interface definition for TypeScript API that it uses itself

typescripten

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Self-hosting, i.e., compiles interface definition for TypeScript API that it uses itself

Compiles all JavaScript standard libs and DOM library

typescripten

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typescripten itself uses generated interfaces to TypeScript API

```
function transform(file: string) : void {
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    const sourceFile = program.getSourceFile(file);

    ts.forEachChild(sourceFile, node => {
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            // do something
        } else if (ts.isVariableStatement(node)) {
            // do something else
        }
    });
}
```

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typescripten itself uses generated interfaces to TypeScript API

```
void transform(js::string const& file) noexcept {
    js::Array<js::string> files(jst::create_js_object, tc::single(file));

    auto const program = js::ts::createProgram(files, ...);
    auto const sourceFile = program->getSourceFile(file);

    js::ts::forEachChild(sourceFile,
        js::lambda(
            [](js::ts::Node node) noexcept {
                if (js::ts::isFunctionDeclaration(node)) {
                    // do something
                } else if (js::ts::isVariableStatement(node)) {
                    // do something else
                }
            }
        )
    );
}
```

typescripten

Semantical differences

- ODR or multiple definitions
- Type system
- Overloading rules

```
    class Array<T> {
        constructor(length: number);
        constructor(...items: T[]);
    }

    new Array<number>(5);
```

- Non-existing built-in types (union, intersection, literal types)

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Priorities

- Always generate valid C++
- Incomplete translation is acceptable

typescripten

Design Decisions

```
document.title = "Hello World from C++!";
```

typescripten

Design Decisions

```
tc::js::document.title = "Hello World from C++!";
```

typescripten

Design Decisions

```
    tc::js::document.title = "Hello World from C++!";
```

- Make expensive operations obvious

typescripten

Design Decisions

```
tc::js::document()->setTitle("Hello World from C++!");
```

- Make expensive operations obvious
  - no pseudo structs

typescripten

Design Decisions

```
tc::js::document()->setTitle(tc::js::string("Hello World from C++!"));
```

- Make expensive operations obvious
  - no pseudo structs
  - no implicit conversions

typescripten

Design Decisions

```
tc::js::document()->title(tc::js::string("Hello World from C++!"));
```

- Make expensive operations obvious
  - no pseudo structs
  - no implicit conversions
- Avoid naming collisions

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Declaration order does not matter in TypeScript

```
type FooBar = test.Foo | test.Bar;

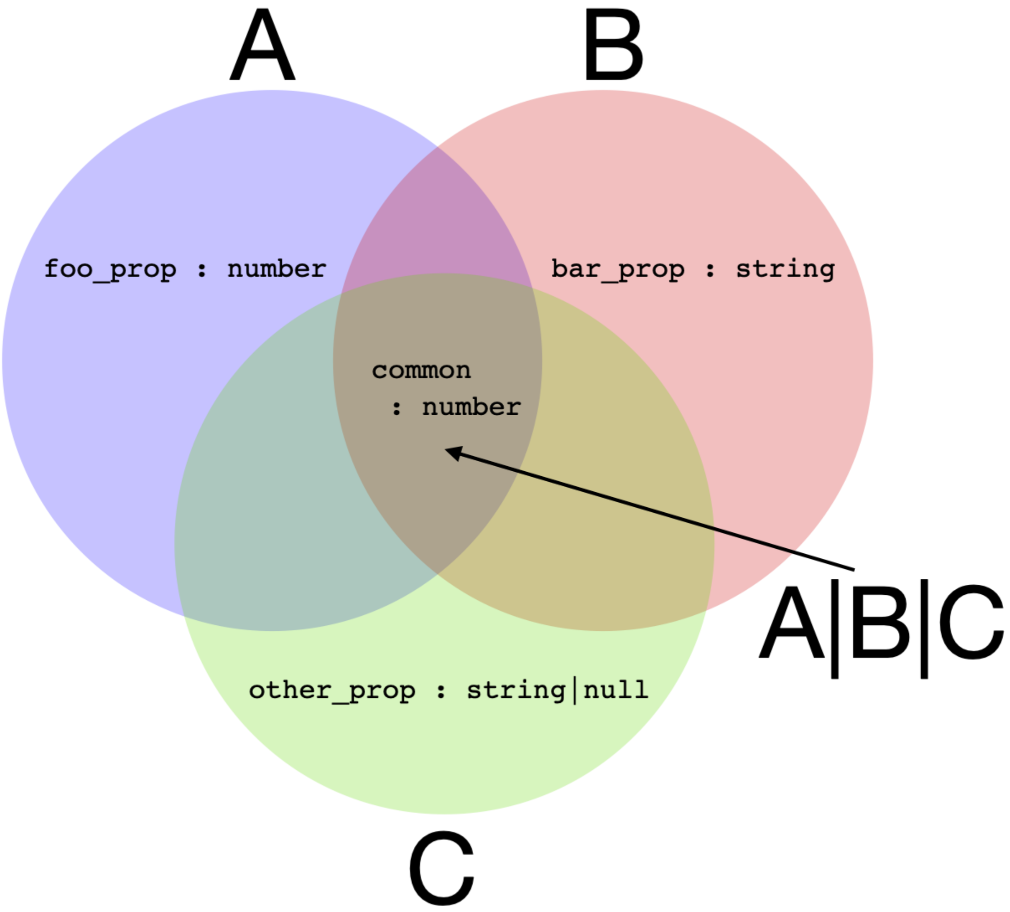
declare namespace test {
    export interface Foo {
        a: string;
    }

    export interface Bar {
        b: number;
    }
}
```

Union types are not like C++ unions

- don't have a discriminating enumeration value
- instead, intersection of properties

`A|B|C` has members that are *in the intersection* of members of A, B **and** C



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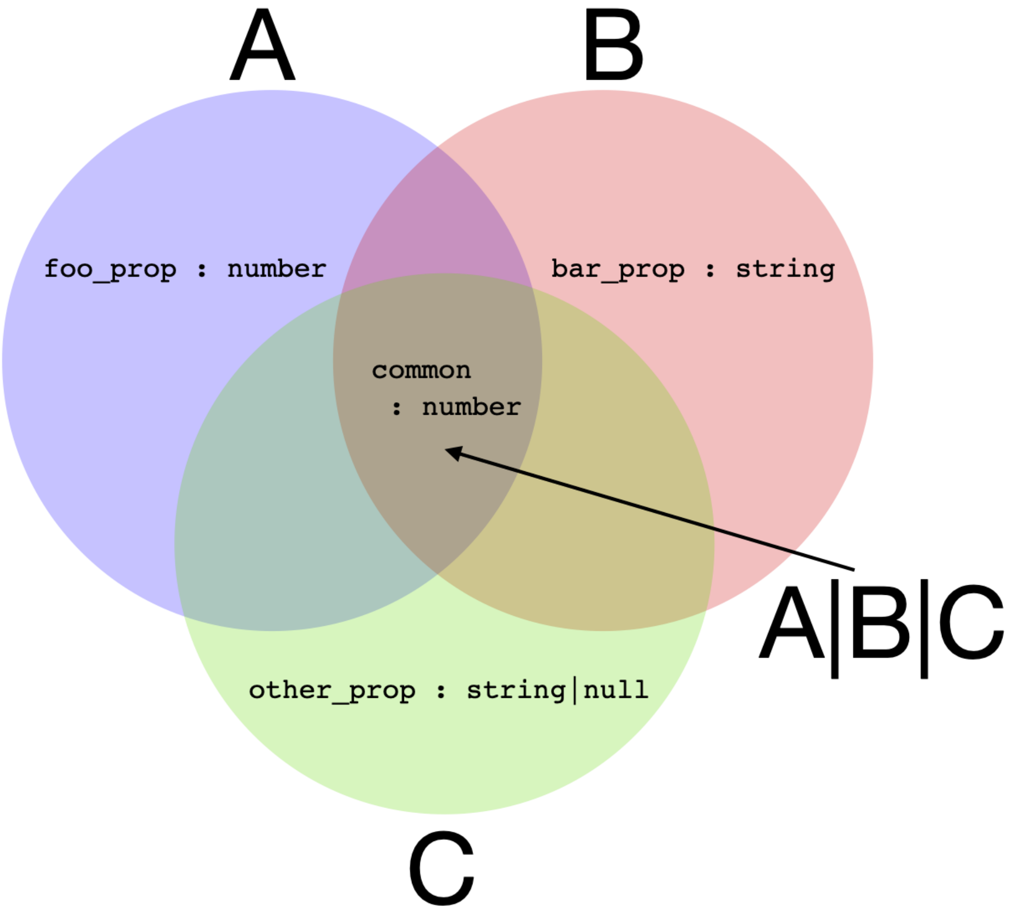
`A|B|C` has members that are *in the intersection* of members of A, B **and** C

`A|B|C` constructible from any value that has all members shared by A, B **and** C

```
class D {
    common: number = 0.0;
}

let u : A|B|C = new D();
```



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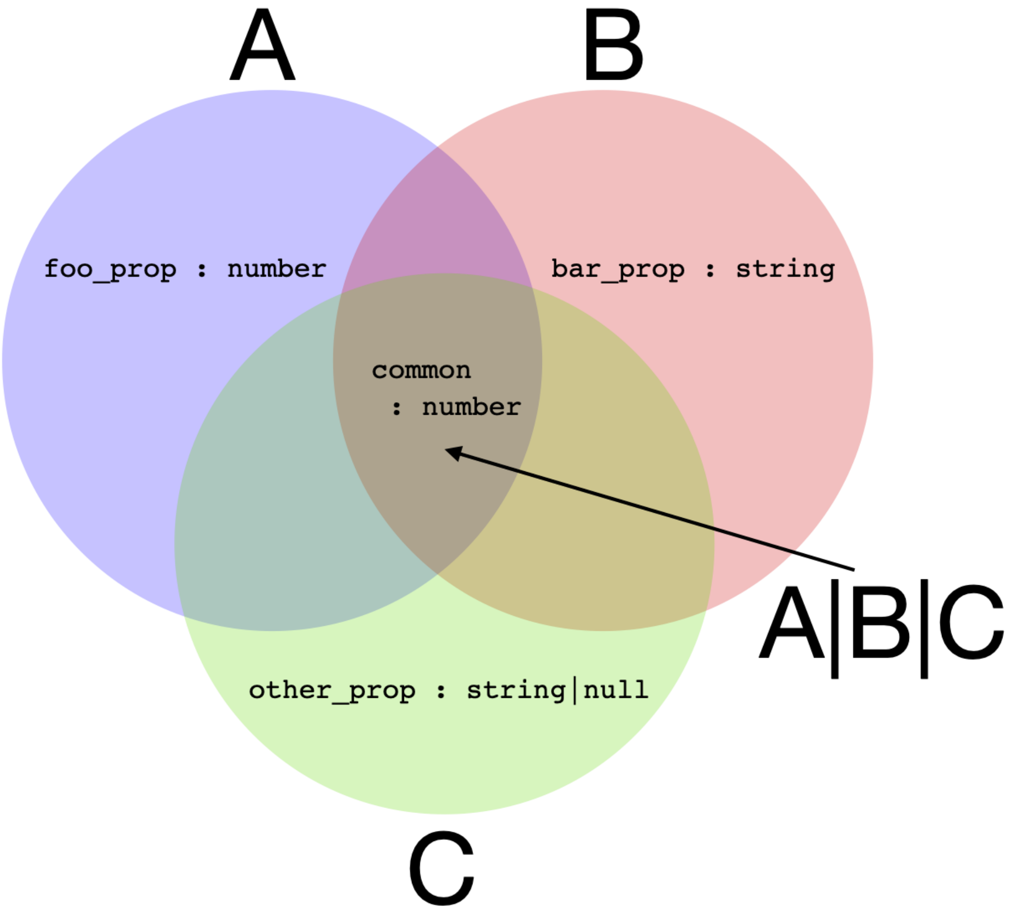
A type is just a set of properties = structural typing



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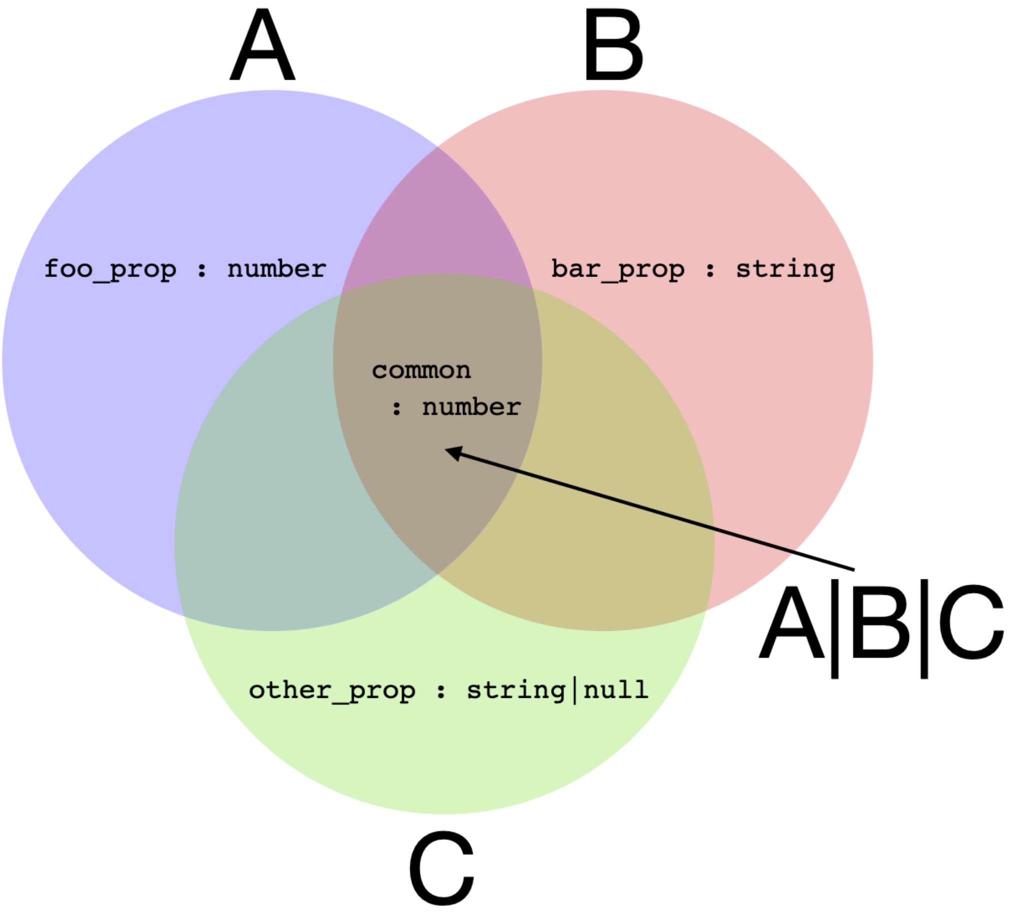
C++ does not support structural typing

`union_t<A,B,C>` converts to *common base classes* of A, B **and** C



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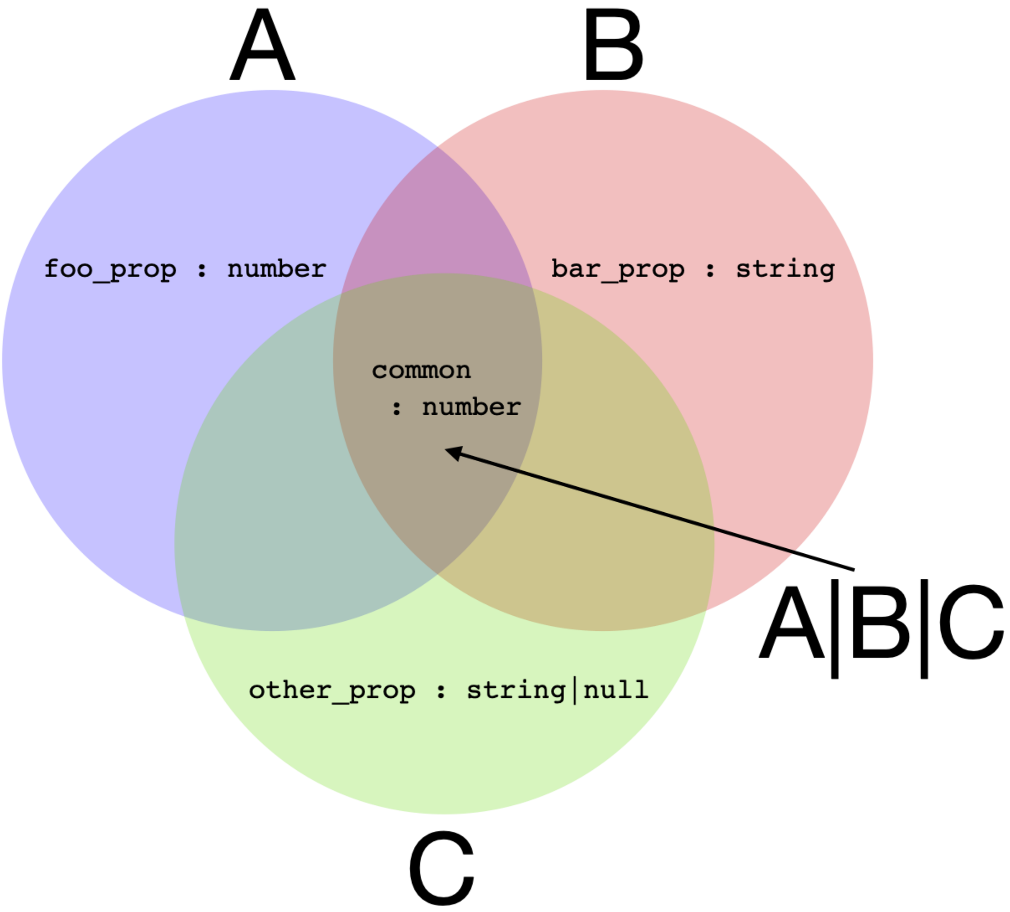
`union_t<A,B,C>` converts to wider union `union_t<A,B,C,D>`



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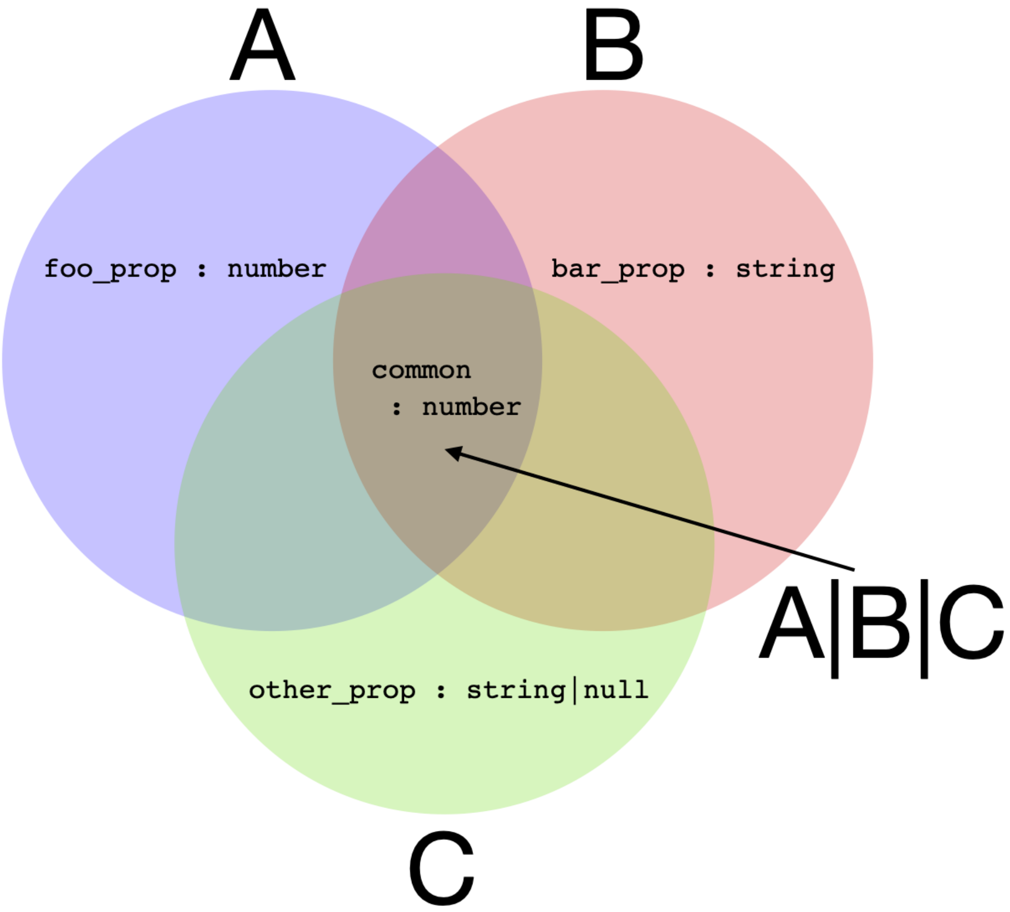

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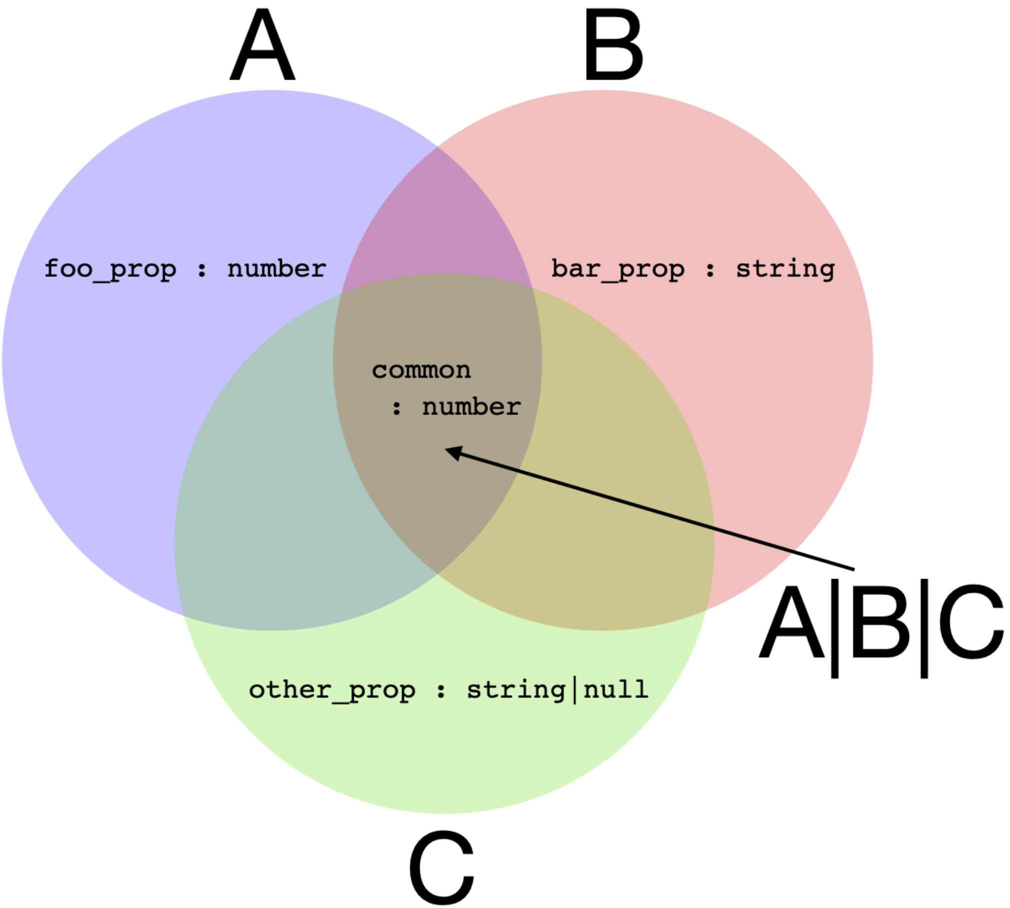
Not as limiting as it sounds



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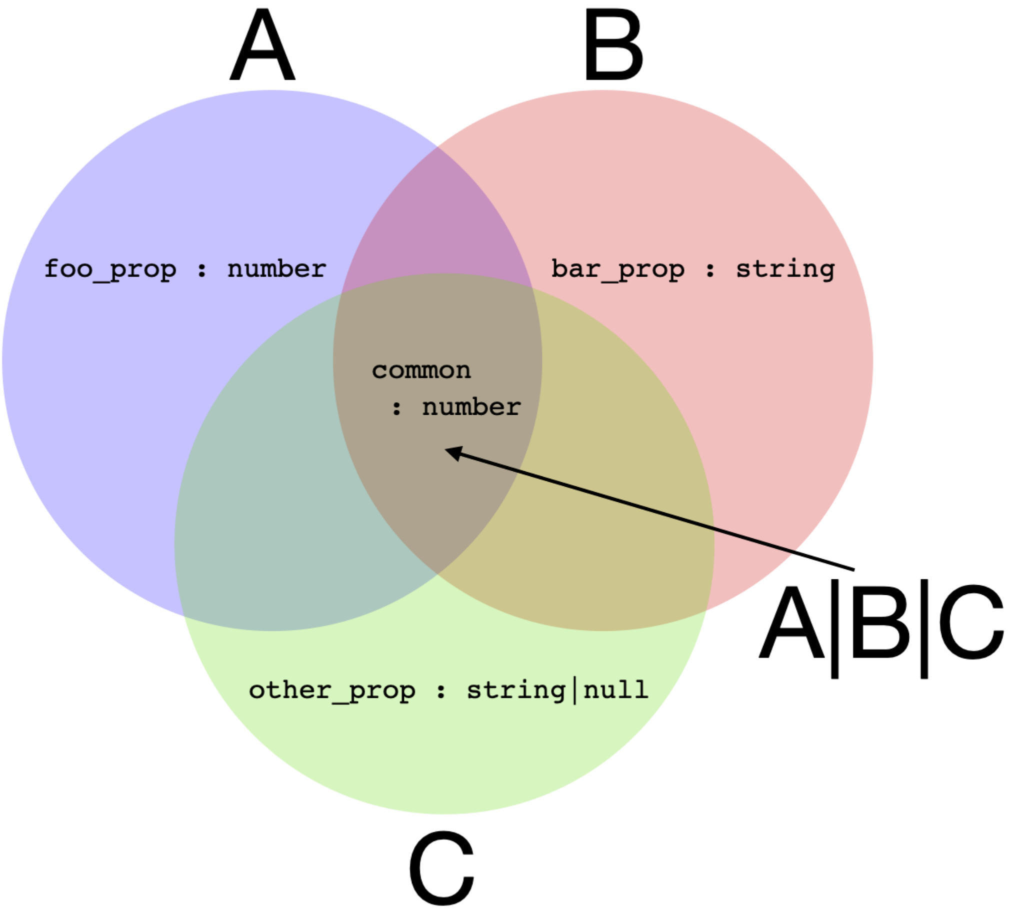
Not as limiting as it sounds

```
interface HasCommonProp {
    common: number;
};

interface A extends HasCommonProp {}
interface B extends HasCommonProp {}
interface C extends HasCommonProp {}
```



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Mixed enumerations with custom marshaling

```
export enum FunnyEnum {
    foo = "foo",
    bar = 1.5
}
```

typescripten

Mixed enumerations with custom marshaling

```
export enum FunnyEnum {
    foo = "foo",
    bar = 1.5
}
```

```
enum class FunnyEnum { foo, bar };

template<> struct MarshalEnum<FunnyEnum> {
    static inline auto const& Values() {
        static tc::dense_map<FunnyEnum, js::any> vals{
            {FunnyEnum::foo, js::string("foo")},
            {FunnyEnum::bar, js::any(1.5)}
        };
        return vals;
    }
};
```

typescripten

Mixed enumerations with custom marshaling

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        };
        return vals;
    }
};
```

Code Example #2

typescripten

Reference-counted function objects are complicated

```
class SomeButton {
    constructor() {
        const button = document.createElement(...);
        button.addEventListener("click", () => this.OnClick());
    }

    function OnClick(ev: MouseEvent) : void {
        /* do something */
        /* but in which states will this be called? */
    }
}
```

- No deterministic destruction
- On ownership of reference-counted objects
- makes thinking about states complicated

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Ugly syntax but simple state machine

```
struct SomeButton {
    SomeButton() {
        const button = js::document()->createElement(...);
        button->addEventListener("click"_s, OnClick);
    }

    ~SomeButton() {
        button->remove();
        // Our callback will also be destroyed! 🎉
    }

    TC_JS_MEMBER_FUNCTION(S, OnClick, void, (js::MouseEvent ev)) {
        // do something
    }
};
```

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```
// 1. Create RAII wrapper OnClick
static emscripten::val OnClickWrapper(void* pvThis, emscripten::val const& emvalThis,
    emscripten::val const& emvalArgs) noexcept;

jst::function<void (js::MouseEvent)> OnClick{&OnClickWrapper, this};
```

typescripten

```
// 1. Create RAII wrapper OnClick
static emscripten::val OnClickWrapper(void* pvThis, emscripten::val const& emvalThis,
    emscripten::val const& emvalArgs) noexcept;

jst::function<void (js::MouseEvent)> OnClick{&OnClickWrapper, this};
```

```
// 2. jst::function ctor calls to JS and creates JS function object
Module.CreateJsFunction = function(iFuncPtr, iThisPtr) {
    const fnWrapper = function() {
        if(iFuncPtr !== null) {
            return Module.tc_js_CallCpp(iFuncPtr, iThisPtr, this, arguments);
        }
    };
    fnWrapper.detach = function() {
        iFuncPtr = null;
    }
    return fnWrapper;
}
// 3. JS function object held as emscripten::val
```

typescripten

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```
// 1. Create RAII wrapper OnClick
static emscripten::val OnClickWrapper(void* pvThis, emscripten::val const& emvalThis,
    emscripten::val const& emvalArgs) noexcept;

jst::function<void (js::MouseEvent)> OnClick{&OnClickWrapper, this};
```

```
// 2. jst::function ctor calls to JS and creates JS function object
Module.CreateJsFunction = function(iFuncPtr, iThisPtr) {
    const fnWrapper = function() {
        if(iFuncPtr !== null) {
            return Module.tc_js_CallCpp(iFuncPtr, iThisPtr, this, arguments);
        }
    };
    fnWrapper.detach = function() {
        iFuncPtr = null;
    }
    return fnWrapper;
}
// 3. JS function object held as emscripten::val
```

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// 3. JS function object held as emscripten::val
```

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```
// 4. When called, JS function object passes function pointer back to generic C++ function
emscripten::val Call(PointerNumber iFuncPtr, PointerNumber iArgPtr,
    emscripten::val emvalThis, emscripten::val emvalArgs) noexcept {
    // 5. Casts function pointer to correct signature and calls it
}
```

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```

```
static emscripten::val OnClickWrapper(void* pvThis, emscripten::val const& emvalThis,
    emscripten::val const& emvalArgs) noexcept
{
    // 6. Cast this pointer, unpack arguments from emvalArgs and call OnClickImpl
}
```

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    emscripten::val const& emvalArgs) noexcept
{
    // 6. Cast this pointer, unpack arguments from emvalArgs and call OnClickImpl
}
```

```
void OnClickImpl(js::MouseEvent ev) noexcept {
    /* ... user code */
}
```

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TypeScript supports generic classes

```
js::HTMLCollectionOf<js::Element> htmlcollection =
    js::document()->body()->getElementsByTagName(js::string("div"));
```

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TypeScript supports generic classes

```
js::HTMLCollectionOf<js::Element> htmlcollection =
    js::document()->body()->getElementsByTagName(js::string("div"));
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Generic classes are translated to C++ templates

`interface Array<T> {}` translates to `template<typename T> struct Array {}`

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TypeScript supports generic classes

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Generic classes can have constraints

```
    enum Enum {}
    interface A<T extends Enum> {}
```

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TypeScript supports generic classes

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`interface Array<T> {}` translates to `template<typename T> struct Array {}`

Generic classes can have constraints

```
    enum Enum {}
    interface A<T extends Enum> {}
```

Expressible as non-type template parameter

```
    template<Enum E>
    struct A {};
```

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Generic classes support many kinds of constraints

```
class Node {}
interface A<T extends Node> {}
```

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Generic classes support many kinds of constraints

```
class Node {}
interface A<T extends Node> {}
```

might be expressed as

```
<typename T, std::enable_if_t<std::is_base_of<tc::js::ts::Node, T>::value>* = nullptr>
struct A {};
```

Again, the semantics are not identical.

Indexed-Access Types

```
document.addEventListener("click", (ev: MouseEvent) => {})
document.addEventListener("keydown", (ev: KeyboardEvent) => {})
```

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Indexed-Access Types

```
document.addEventListener("click", (ev: MouseEvent) => {})
document.addEventListener("keydown", (ev: KeyboardEvent) => {})
```

```
interface DocumentEventMap  {
    "click": MouseEvent;
    "keydown": KeyboardEvent;
}
addEventListener<K extends keyof DocumentEventMap>(
    type: K,
    listener: (this: Document, ev: DocumentEventMap[K]) => any
): void;
```

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Indexed-Access Types

```
interface DocumentEventMap  {
    "click": MouseEvent;
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Indexed-Access Types

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addEventListener<K extends keyof DocumentEventMap>(
    type: K,
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): void;
```

Use enums, tag types?

```
enum class DocumentEventMap { click, keydown };
void addEventListener(Event e, ...);

template<DocumentEventMap e>
void addEventListener(...);

document()->addEventListener<DocumentEventMap.click>(...);
```

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Better solution thanks to user-defined literals

```
jst::function<void (js::MouseEvent)> fn = ...;
document()->addEventListener("click"_s, fn);

jst::function<void (js::KeyboardEvent)> fn2 = ...;
document()->addEventListener("keydown"_s, fn2);
```

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```
interface DocumentEventMap  {
    "click": MouseEvent;
    "keydown": KeyboardEvent;
}
```

translates to

typescripten

```
interface DocumentEventMap  {
    "click": MouseEvent;
    "keydown": KeyboardEvent;
}
```

translates to

```
using hana = boost::hana;
struct DocumentEventMap {
    template<typename __TYPESCRIPTEN_DUMMY_ARG = tc::js::any>
    static auto constexpr keyof() noexcept {
        return hana::make_map(
            hana::make_pair("__typescripten_dummy_key"_s,
                hana::type_c<__TYPESCRIPTEN_DUMMY_ARG>
            ),
            hana::make_pair("click"_s, hana::type_c<MouseEvent>),
            hana::make_pair("keydown"_s, hana::type_c<KeyboardEvent>)
        );
    }
};
```

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```
interface DocumentEventMap  {
    "click": MouseEvent;
    "keydown": KeyboardEvent;
}
```

translates to

```
using hana = boost::hana;
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                hana::type_c<__TYPESCRIPTEN_DUMMY_ARG>
            ),
            hana::make_pair("click"_s, hana::type_c<MouseEvent>),
            hana::make_pair("keydown"_s, hana::type_c<KeyboardEvent>)
        );
    }
};
```

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```
addEventListener<K extends keyof DocumentEventMap>(
    type: K, listener: (this: Document, ev: DocumentEventMap[K]) => any, ...
): void;
```

translates to

```
template<typename K>
auto addEventListener(K type, tc::jst::function<
    tc::js::any(
        typename decltype(
             +(DocumentEventMap::keyof()[K{}])
        )::type
    )> listener
) noexcept;
```

Live Coding #3

✅ Compile C++ for the Web — **WebAssembly & emscripten**

✅ Call JavaScript from C++ — **emscripten**

✅ Type-safe calls to JS — **typescripten**

typescripten

typescripten will be superseded by *WebAssembly Interface types*

Still in proposal phase https://github.com/WebAssembly/interface-types

Longer Introduction: https://hacks.mozilla.org/2019/08/webassembly-interface-types/

As in ISO C++, maybe good idea to experiment with implementation

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Performance Test

1.000.000 function calls WebAssembly to JavaScript

JS function increments a number

- `extern "C" function` from WebAssembly to JavaScript
- `EM_ASM_DOUBLE` embedded JS code
- *typescripten* call via `emscripten::val`

```
inline auto _impl_js_j_qMyLib_q::_tcjs_definitions::next() noexcept {
    return emscripten::val::global("MyLib")["next"]().template as<double>();
}
```

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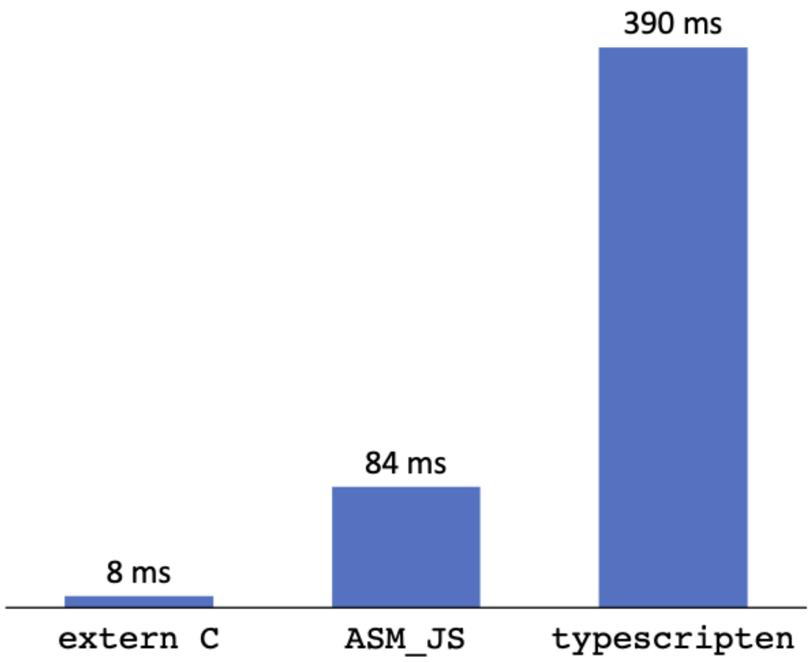
Performance Test

1.000.000 function calls WebAssembly to JavaScript

JS function increments a number



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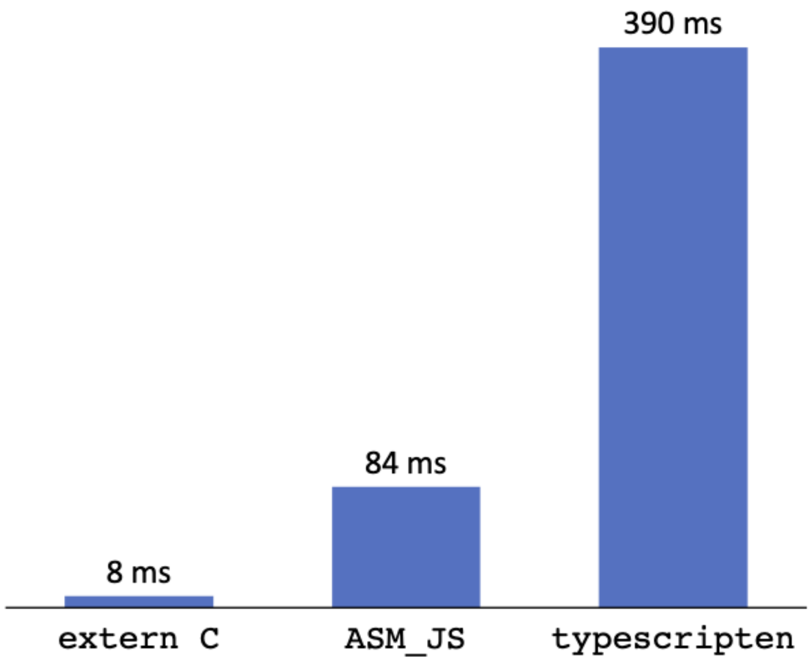

Cost of converting C-strings to JavaScript strings

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Next Challenges:

- emscripten integration
- Test typescripten against DefinitelyTyped Repository
- Generic constraints and most requested language features

```
interface HTMLCollectionOf<T extends Element> extends HTMLCollectionBase {
    item(index: number): T | null;
}
```

- literal types and their unions

```
interface Oscillator {
    type: "triangle" | "square";
}
```

- Performance

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Check it out at https://github.com/think-cell/typescripten

Contributors are very welcome

Thank you!

And yes, we are recruiting: `hr@think-cell.com`