

Duck-Tape Chronicles

Rust/C++ Interop

VICTOR CIURA



Cppcon
The C++ Conference

20
25



September 13 - 19

+
25

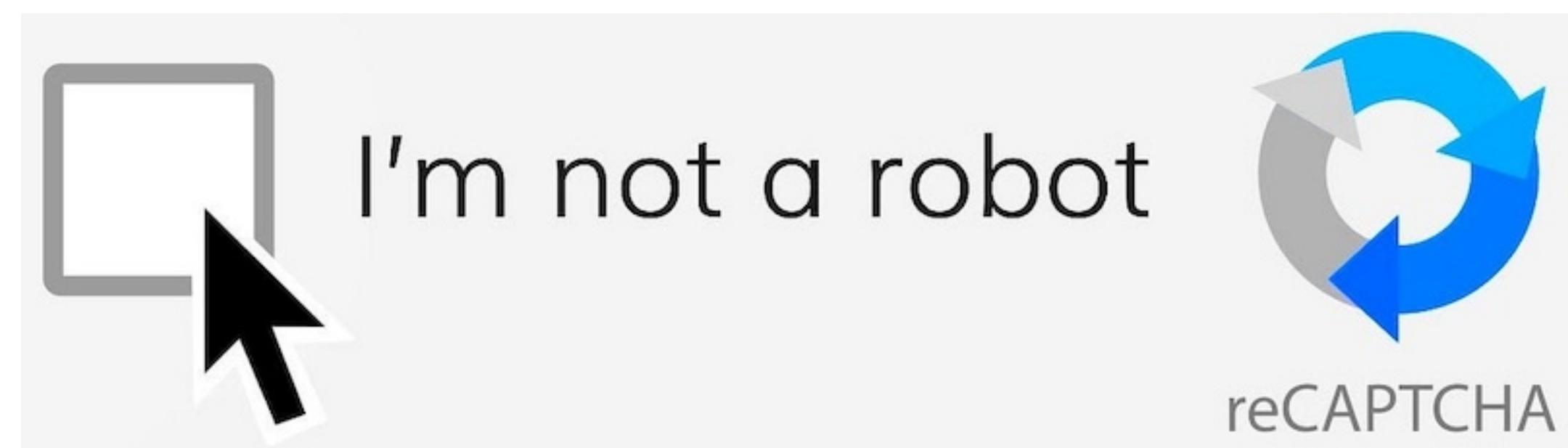


A full week of 8am-10pm sessions



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No LLMs were hurt
in the making of this presentation



This presentation was prepared by a *human* agent.
No hallucinations. But errors and 🔥 hot-takes are allowed.

**Why do you care?
Why are you here?**

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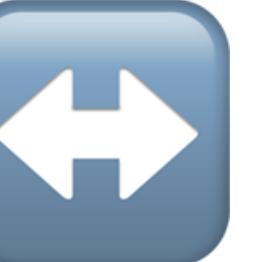
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they NEED it in order to call into existing libs they don't yet have.

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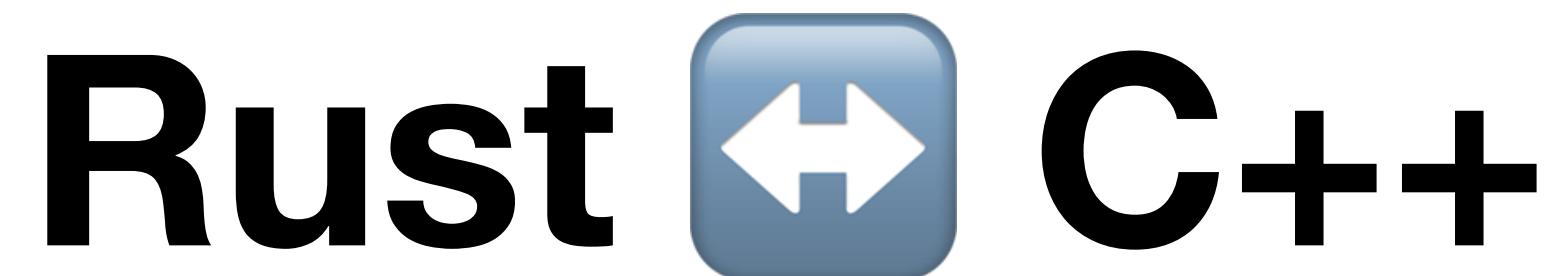
But when **C++ folks** look into Rust interop, it's more than curiosity...
you know some degree of desperation has occurred 🔥

Rust code everywhere is increasing at an accelerated rate...

Rust  C++

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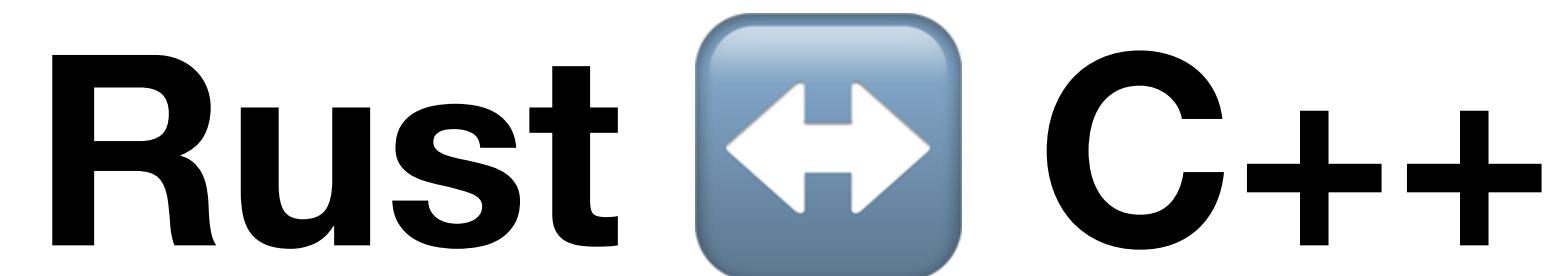
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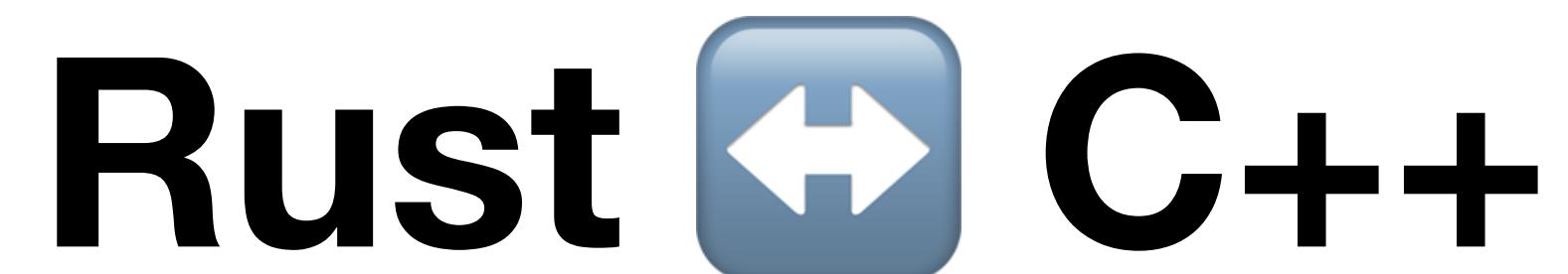
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They need to play nice together... for a looong time!

Who thinks interop is about... C FFI



Who thinks interop is about... C FFI
glue code



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glue code
coge generators



Who thinks interop is about... C FFI
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ABI compat



What you're going to get out of this talk

- This presentation aims to highlight:
 - some of the major interop challenges
 - existing solutions out there
 - tease out the avenues at the forefront of this pursuit

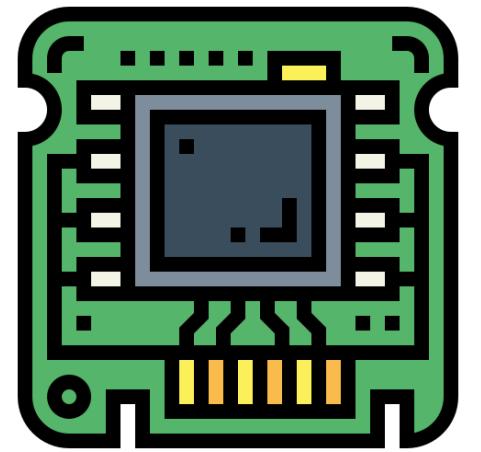


What you're going to get out of this talk

- This presentation aims to highlight:
 - some of the major interop challenges
 - existing solutions out there
 - tease out the avenues at the forefront of this pursuit
- General high-fidelity interoperability has yet to be achieved 
- Just "*making things work*" is not enough in the domain space of C++ and Rust
- Many of the explored solutions so far fail to deliver on all needed requirements



Rust extreme range of operation



Rust / C++ interoperability

Choose... none some?



Rust / C++ interoperability

- No perf overhead (avoid marshaling costs, eg. copying strings)

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- Ergonomics - with safety

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- Debuggable
- Hybrid build systems (CMake, cargo, MSBuild, bazel, buck...)



Compiler



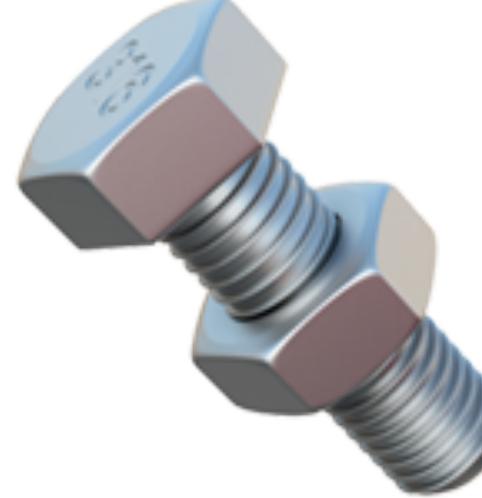
Linker



Packaging



ABI guarantees



Interop Library



Debugger



Build systems & CI



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Episode 1^{3/4}

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Victor Ciura
~~Principal Engineer~~
Rambling Idiot
Rust Tooling @ Microsoft

About me



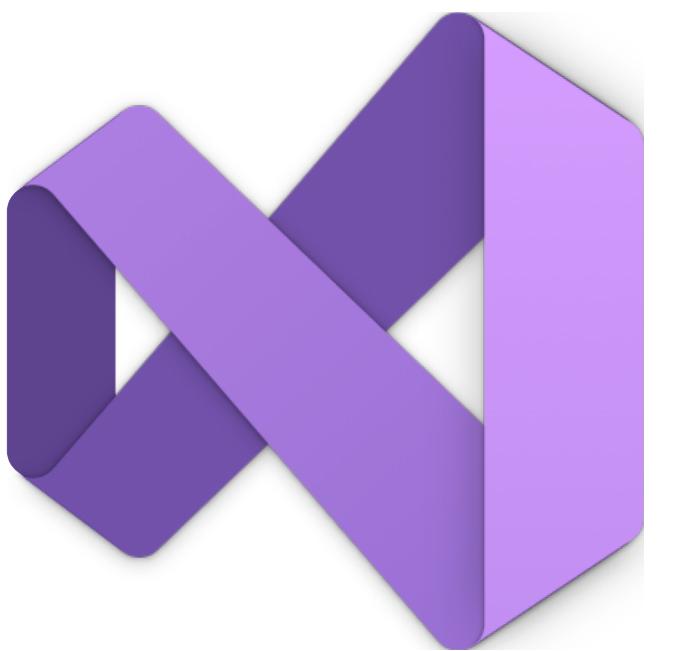
Advanced Installer



Clang Power Tools



Oxidizer SDK



Visual C++



Rust Tooling
Microsoft

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Disclaimer

I'm just an engineer, with some opinions on stuff...



What's out there...

C - The Original Duck Tape



- C is the [lingua franca](#) FFI systems language
- Every API consumable from most languages
- The only ABI-stable "universal interop glue"



- Poor abstraction
- No safety
- Naked structs (public fields)
- Raw pointers
- Manual lifetimes

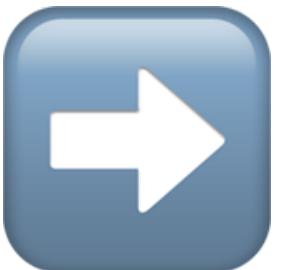


bindgen

Allows Rust to call into C APIs

C headers ➔ Rust FFI bindings

```
typedef struct Widget {  
...  
} Widget;  
  
void action(Widget * w);
```



```
#[repr(C)]  
pub struct Widget {  
...  
}  
  
extern "C" {  
    pub fn action(w: *mut Widget);  
}
```

Source generation (build step)

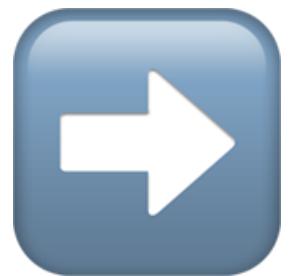
cbindgen

Allows C code to call Rust APIs

.rs → C headers

```
#[repr(C)]
pub struct Widget {
...
}

#[unsafe(no_mangle)]
pub extern "C" fn action(w: *mut Widget) {
...
}
```



```
typedef struct Widget {
...
} Widget;

void action(Widget * w);
```

Source generation (build step)

bindgen / cbindgen

- Works directly on source files (not IDL)
- Source generation (build step)
- Types: `repr(C)` ABI only
- Pass by value: for C types
- ~~Structs with private fields~~
- ~~C++ classes~~
- ~~std::unique_ptr, std::optional~~
- ~~Box<T>, Option<T>~~
- ~~Rust enums~~
- ~~&str, String~~
- ~~std::string~~
- ~~&[T]~~ unsafe{ } required to convert to/from C representation

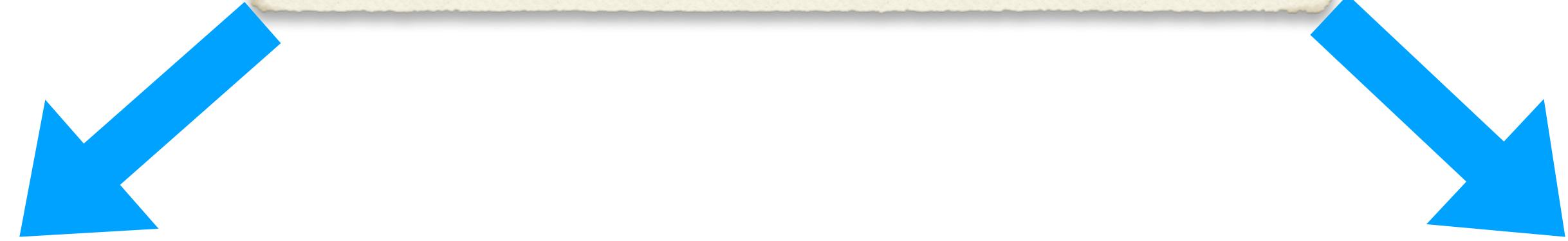
Macro-based **IDL**

Needs to be separately maintained (manually)

```
#[cxx::bridge]
mod ffi {
    struct Widget {
        things: Vec<String>
    }
}
```

```
#[repr(C)]
struct Widget {
    things: Vec<String>
}
```

```
struct Widget {
    rust::Vec<rust::String> things;
};
```



- Types: standard types (mostly), slices, IDL structs
- C++ classes
- std::unique_ptr, std::optional
- Box<T>, Option<T>
- &str, String
- std::string
- std::vector
- Vec<T>
- &[T]
 - cxx doesn't know the memory layout of user types
 - **✗ Pass-by-value => need to Box<T> or unique_ptr<T>**
 - relies heavily on **pinning** (reduced ergonomics)

```
struct Widget {  
    id: u32,  
    things: Vec<String>  
}  
  
impl Widget {  
    fn new_empty(id: u32) -> Self {  
        Self {  
            id: id,  
            things: vec![],  
        }  
    }  
    fn work() -> f32 {  
        ...  
    }  
}
```

Custom **IDL** (.zng)

```
type crate::Widget {  
    #layout(size = 32, align = 8)  
  
    fn new_empty(u32) -> crate::Widget;  
    fn work() -> f32;  
}  
  
#include "generated.h"  
  
void cpp_caller() {  
    auto w = rust::crate::Widget::new_empty(42);  
    w.work();  
}
```

- Custom **IDL** (.zng)
 - Needs to be separately **maintained** (**manually**)
 - Types: standard types (mostly), slices, IDL structs
-  **Pass-by-value:** have to manually annotate types with: `#[layout(size, align)]`
- no need for indirection/boxing and heap allocation
- Reduced need for **pinning**
 - Favors Rust-friendly APIs and developer experience,
accepting ***occasional runtime cost*** to get there

- Bold new project with the goal of high-fidelity lang interop between Rust and C++

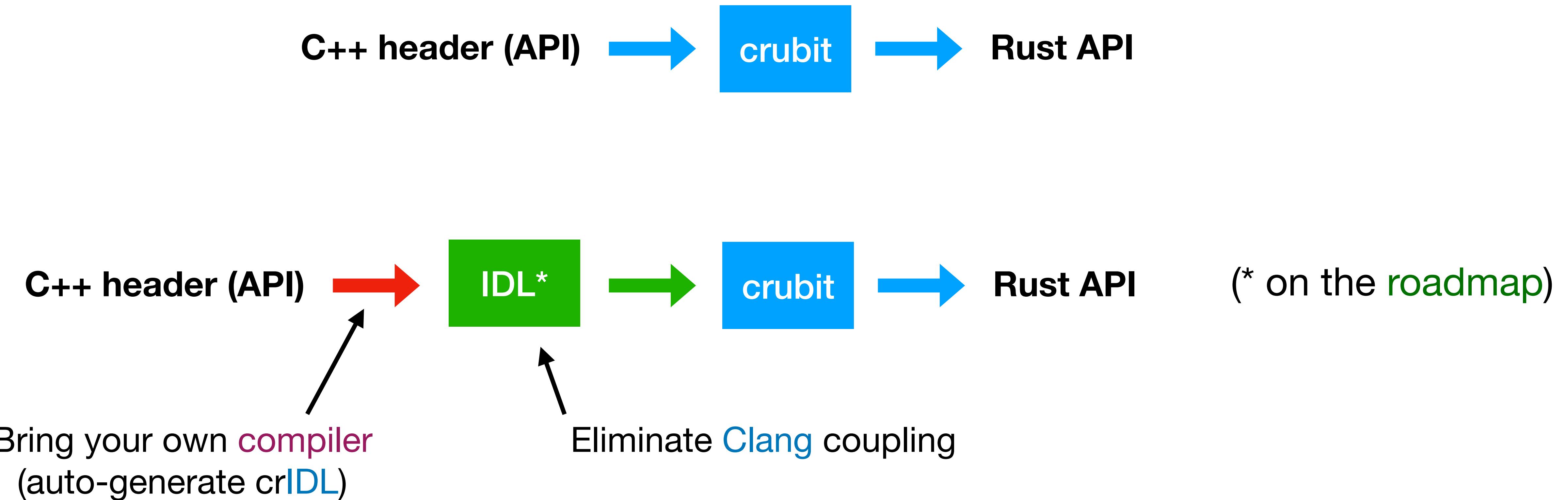
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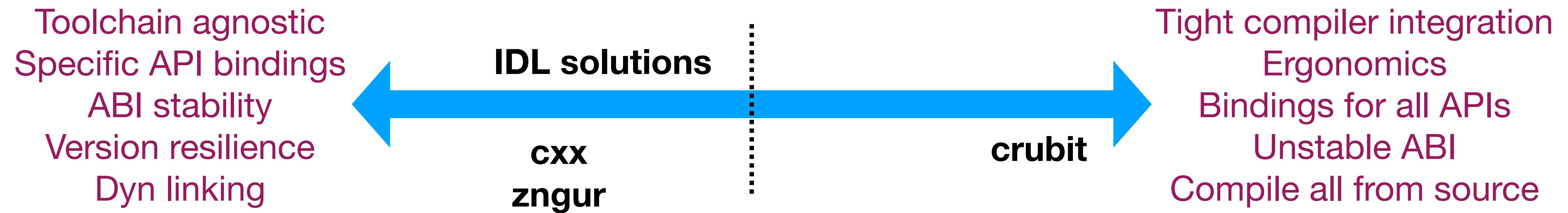
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 - Optional IDL (TBD - on the roadmap)

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- Pass by value: AllTheThings™ (that's where deep compiler integration comes in)



Tradeoffs...

Projects have very diverse interop needs, so no solution fits all (equally)



Language Semantics

Some C++ features not having direct Rust equivalents:

- Overloaded assignment operator
- Overloaded dereference operator
- Overloaded new and delete operators
- Function overloading
- Argument-dependent lookup
- Default function parameters
- Implicit conversions
- SFINAE
- In-place initialization
- Move constructors



Language Semantics

Profound semantic differences between language constructs

- Rust semantics is a **subset** of C++ semantics
- Generally, Rust is less expressive than C++

=>

- Using Rust code from C++ is **easier**
- Using C++ code from Rust much **harder**



Level: **HARD!!!**

- C++ features not having direct Rust equivalents (eg. [overloading](#))
- [unsafe](#)
- [Lifetimes](#)
- [Aliasing \(refs\)](#)
- Movable types that are non memcopy
- ...

Level: I CAN DO IT

- Rust semantics is a **subset** of C++ semantics
- Rust's **strong type system**
 - easy to grasp **intended semantics** of functions, types
- Querying **rustc** - ⚠ Rust ABI is **not** stable: these need to be **refreshed** on each update
 - determine the exact **size** & **alignment** of every Rust type
 - struct fields
 - key **trait** implementations:
 - **Drop** → C++ dtor
 - **Clone** → C++ copy ctor

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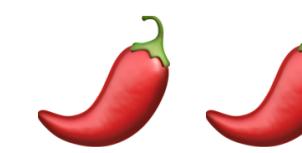
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(see [Carbon](#))

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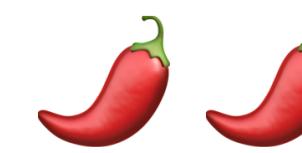
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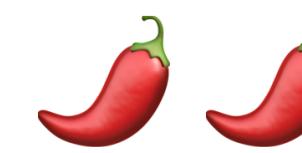
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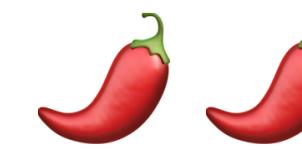
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 - it's just **differently mangled symbol names**

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 - Need a way to name-mangle such that separate functions map to the correct overloads

The ABI Menace

What is ABI, anyway?

ABI isn't a property of a programming language

It's really a property of a system and its toolchain

ABI is something defined by the *platform*

Eg.

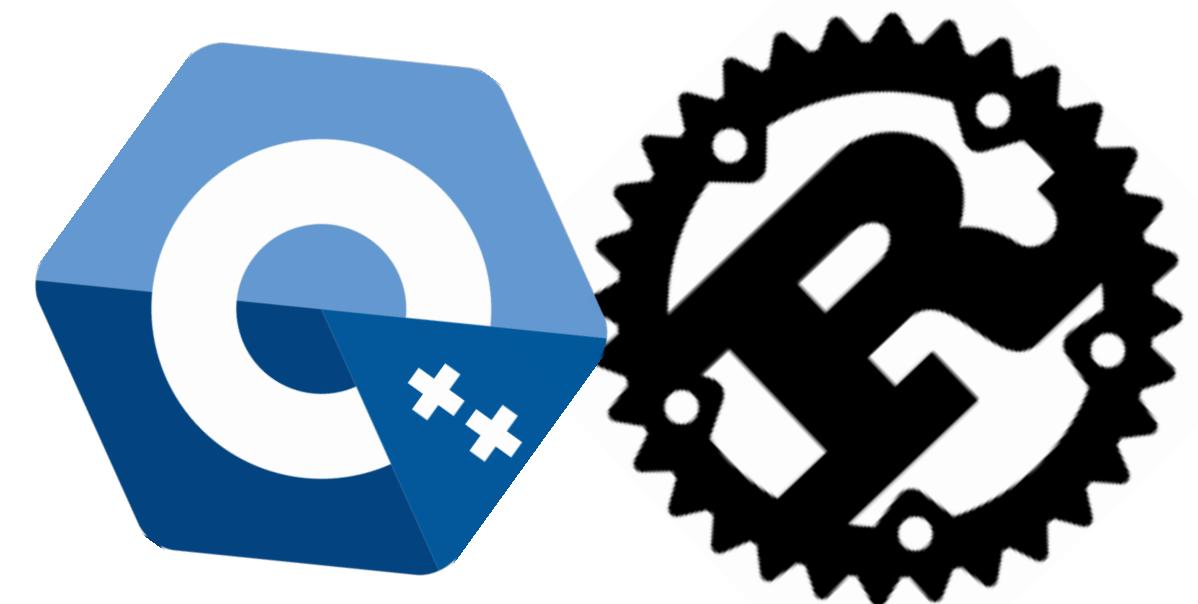
Compilers determine class layout: ✗ portable

- Layout of types
 - size & alignment (stride)
 - offsets & types of fields
 - v-table entries
 - closures
- Calling conventions
- Name mangling (symbols)
- Metadata (if applicable)

ABI Stability - When?

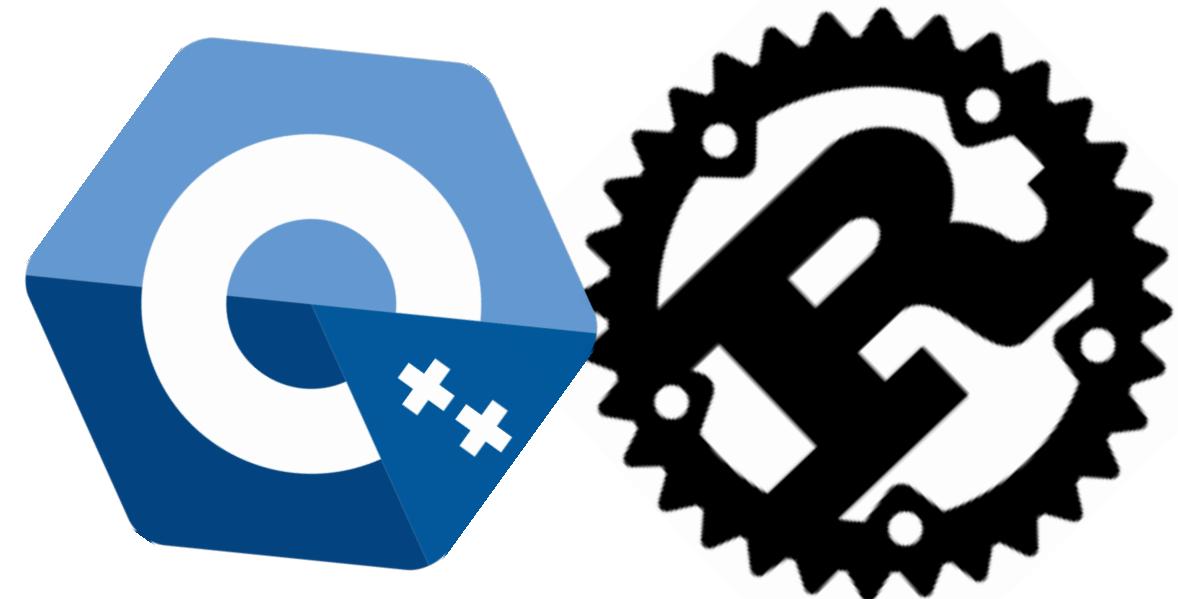
- ➊ Don't shut the door on **future compiler & library improvements**
- ➋ **Stabilizing the ABI (too early)™** might miss optimization opportunities
 - ➌ implement a faster custom calling convention
 - ➌ implement optimal structure layout
 - ➌ improve the way a std utility works
 - ➌ make changes affecting v-table
 - ➌ (re)use existing padding

ABI Stability - Why?



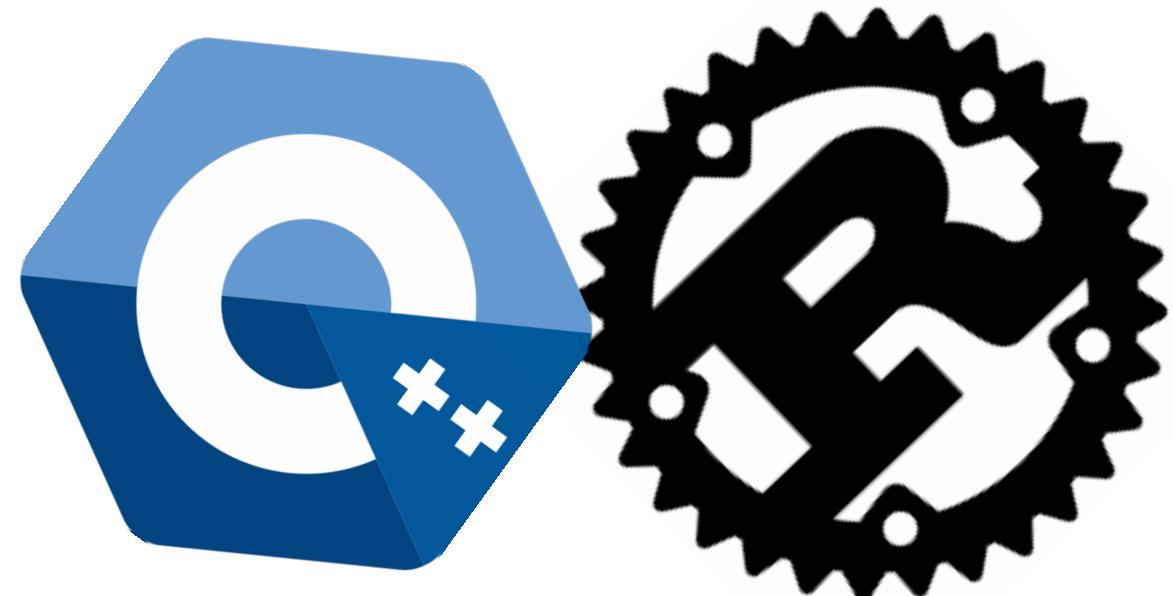
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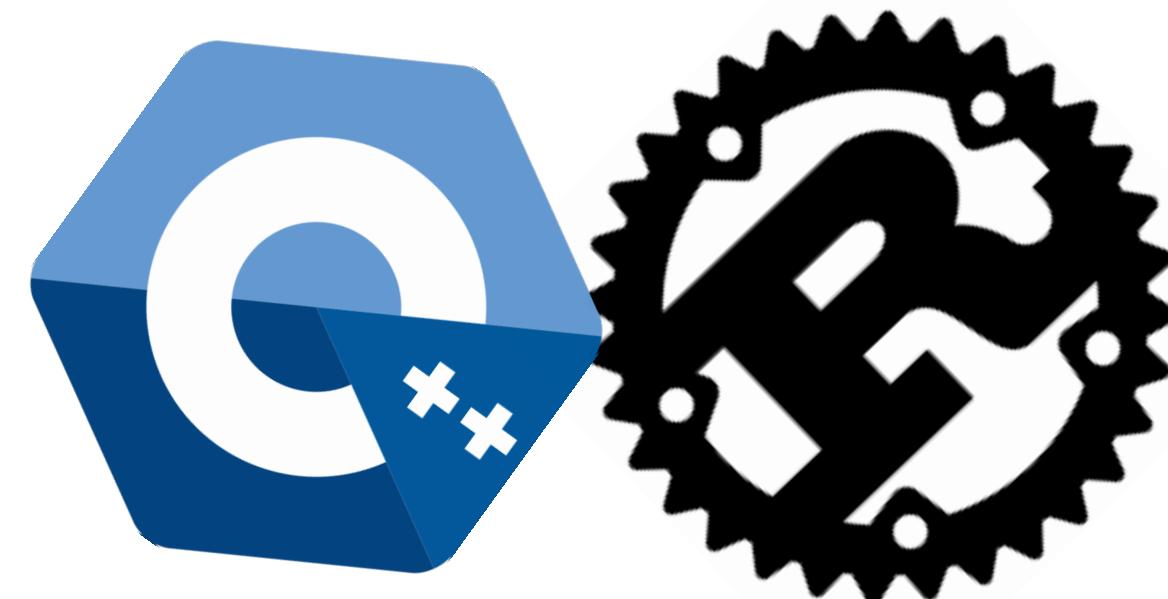


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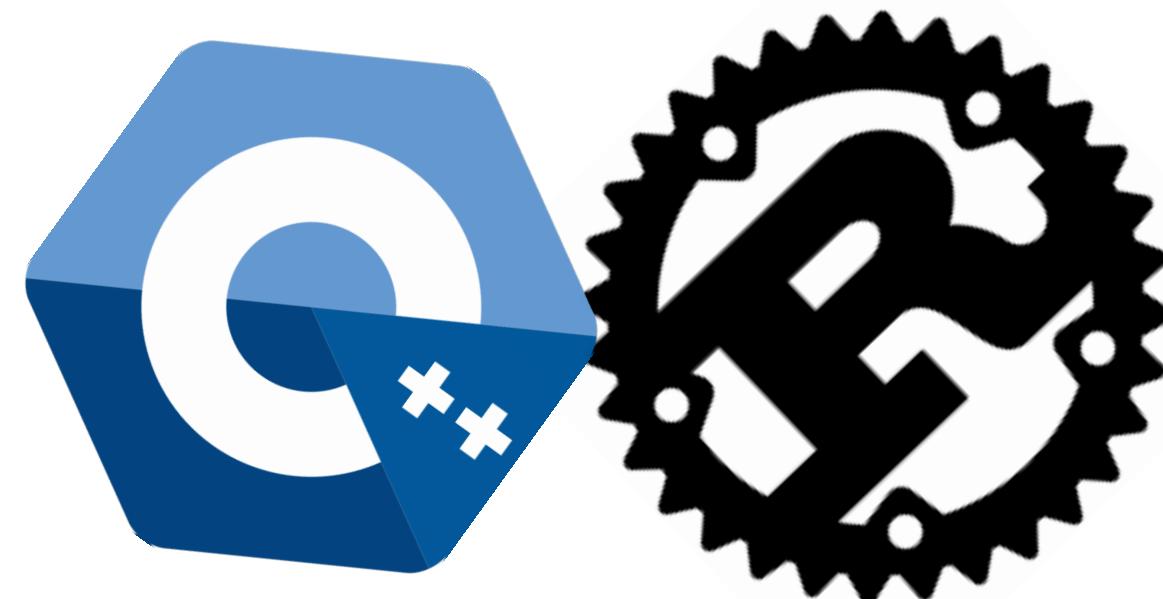


ABI Stability - Why?



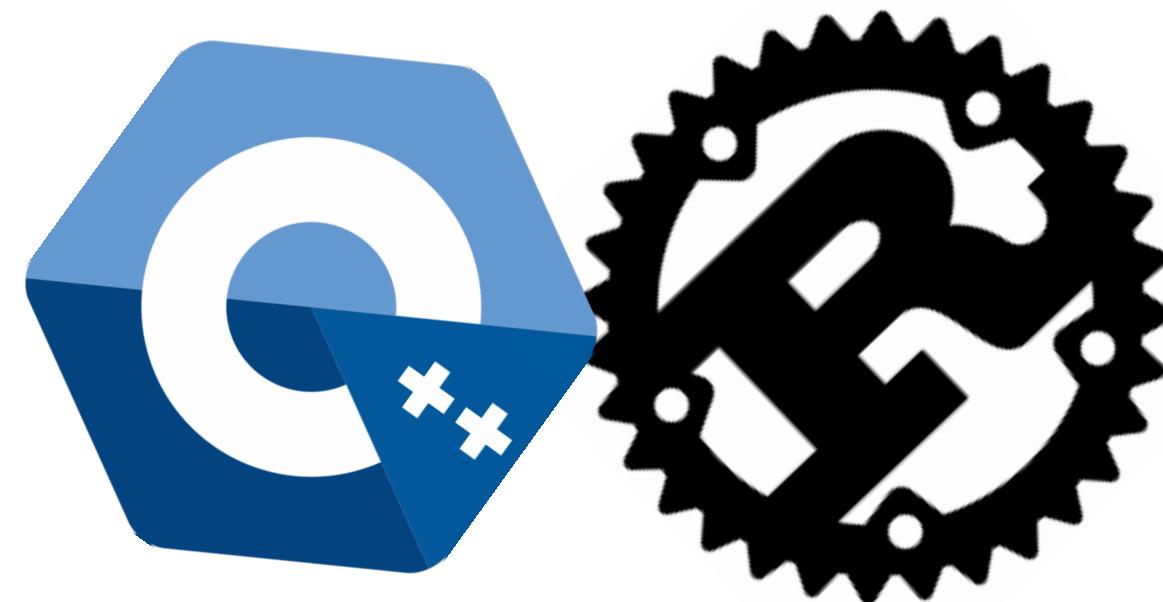
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- Use libraries compiled with a **different compiler version**

ABI Stability - Why?



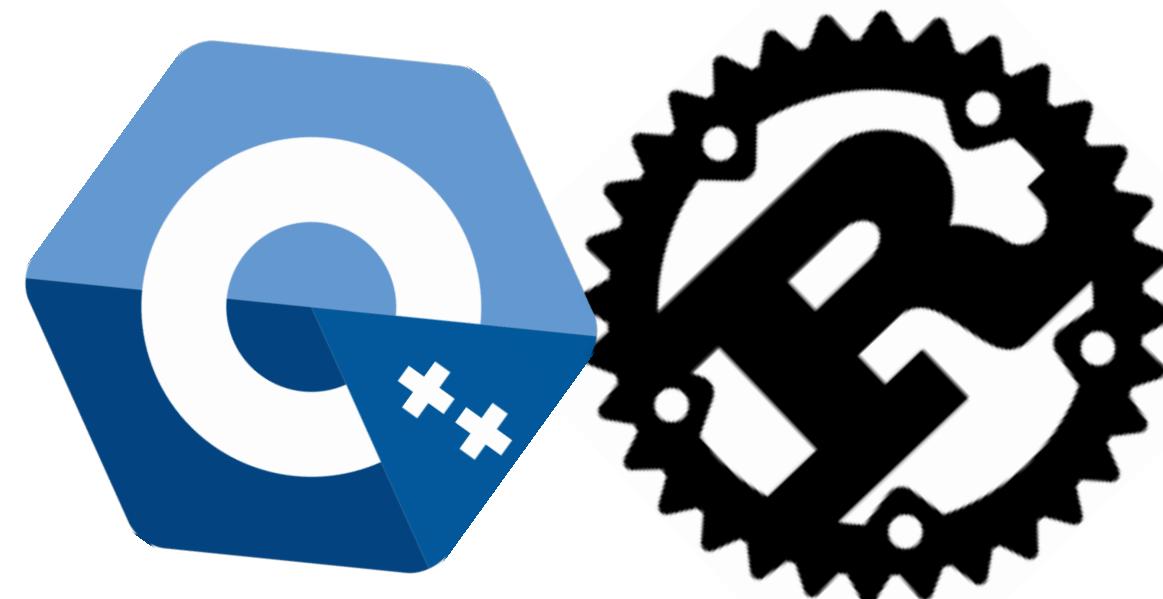
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ABI Stability - Why?



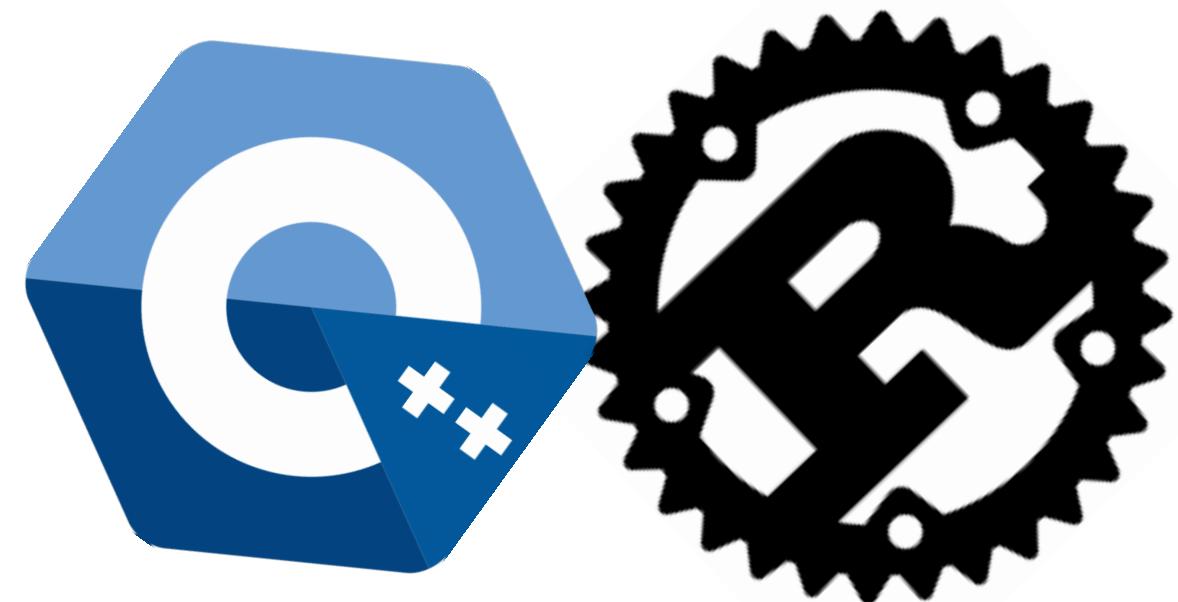
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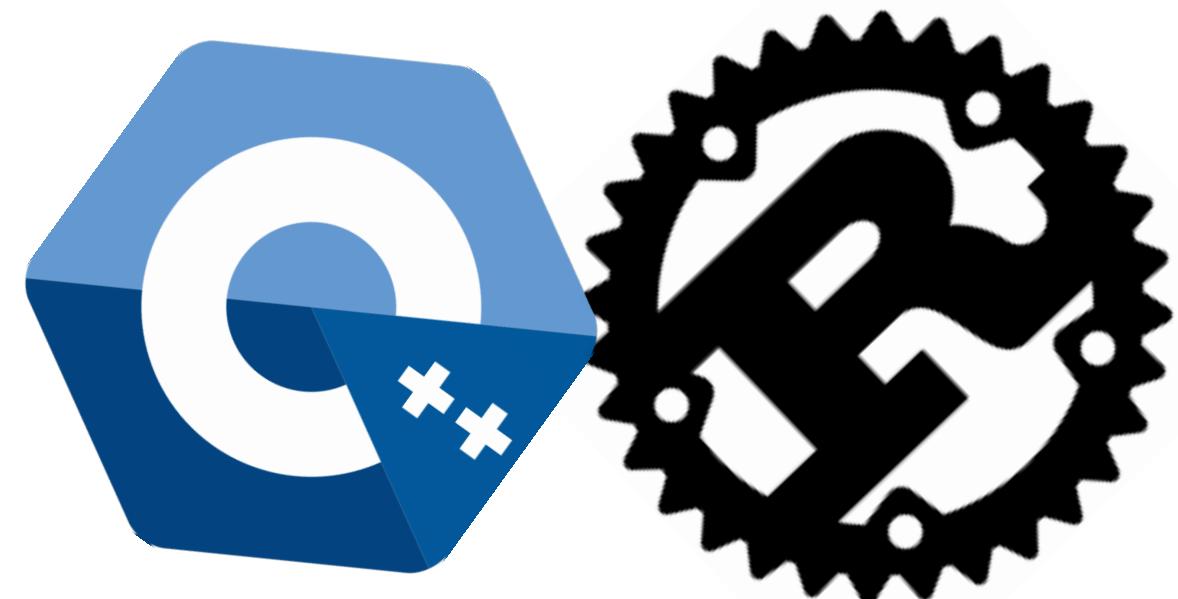
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- **Plugins/extensions** (dynamically loaded)

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- **Plugins/extensions** (dynamically loaded)
- **Language interop** (hybrid projects)

The (early) 90s are calling...

- Old-school interop: COM, CORBA, XPCOM, ...
- COM
 - MIDL for interop
 - metadata
 - ABI resilience

Design for Library Evolution

Principles for ABI-stable library evolution:

- make all promises **explicit**
- delineate what can and cannot change in a stable ABI
- provide a performance model that **indirects** only when necessary
- let the authors of libraries & consumers be **in control**

Doug Gregor

*Implementing Language Support for
ABI-Stable Software Evolution in Swift and LLVM*

youtube.com/watch?v=MgPBetJWkmc

Struct Layout

C++ compilers could provide a class' data members with [layout metadata](#)
=> allow representation of Rust struct fields in C++

Retrieve [layout](#) via the C++ [AST](#) and the [rustc query API](#)

Layout

Type Layout should be as-if we had the whole program:

- *Widget library* should layout the type without indirection
- Expose **metadata** with layout information:
 - size/alignment of type
 - offsets of each of the public fields
 - overlapping sub-objects
 - padding tricks & vtables
- Attributes, annotations, or compiler synthesized

```
size_t Widget_size = 32;  
size_t Widget_align = 8;  
size_t Widget_field1_offset = 0;  
size_t Widget_field2_offset = 8;
```

Client/External Code

Client code (external) **indirects** through **layout metadata**

- **Access** a field:
 - read the metadata for the **field offset**
 - add that offset to the base object
 - cast the new pointer and load the field
- **Store** an instance on the **stack**:
 - read the metadata for instance **size**
 - emit **alloca** instruction, to setup as needed

Library Code

Library code (internal) eliminates all ~~indirection~~

- performance: **indirects** only when necessary
- Access a field:
 - ~~read the metadata for the field offset~~
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 - ~~read the metadata for instance size~~
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Dynamically-sized

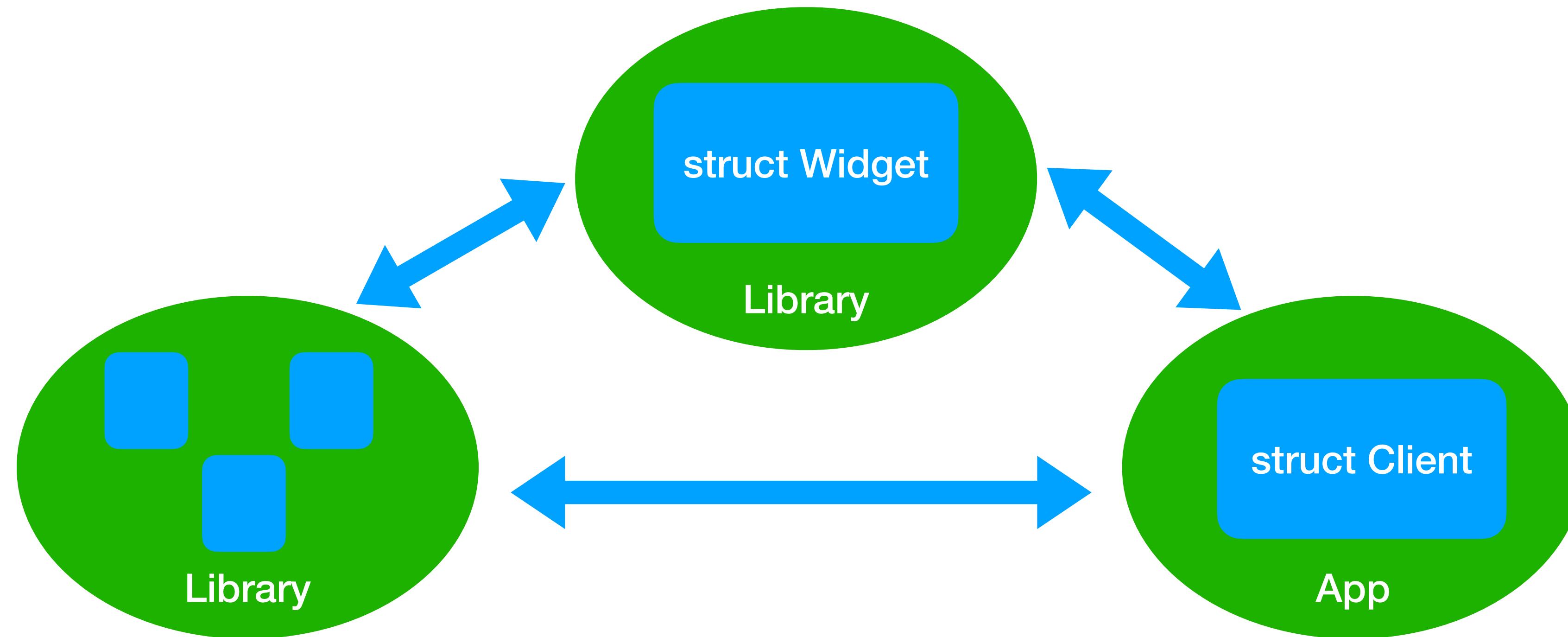
- Support for **dynamically-sized** things on the **stack** is key (eg. LLVM)
- Compilers can use of this for of **ABI-stable value types**:
 - you have local variable of some struct defined in an **ABI-stable library**
 - so you don't know it's size until **load time**
- Dynamic allocs can handle this nicely (with **minimal perf impact**)
- C++ desperately wants all objects to have **compile-time-constant size**
 - the notion of **sizeof/alignof** being **runtime values** clashes with the C++ model

Interop Domains

By explicitly modeling the **boundaries** between software modules that **evolve separately** vs. **together**:

- introduce appropriate **indirections** across **separately-evolved** software modules
- while **optimizing away that indirection** within software modules that are **always compiled together**

Interop Domains



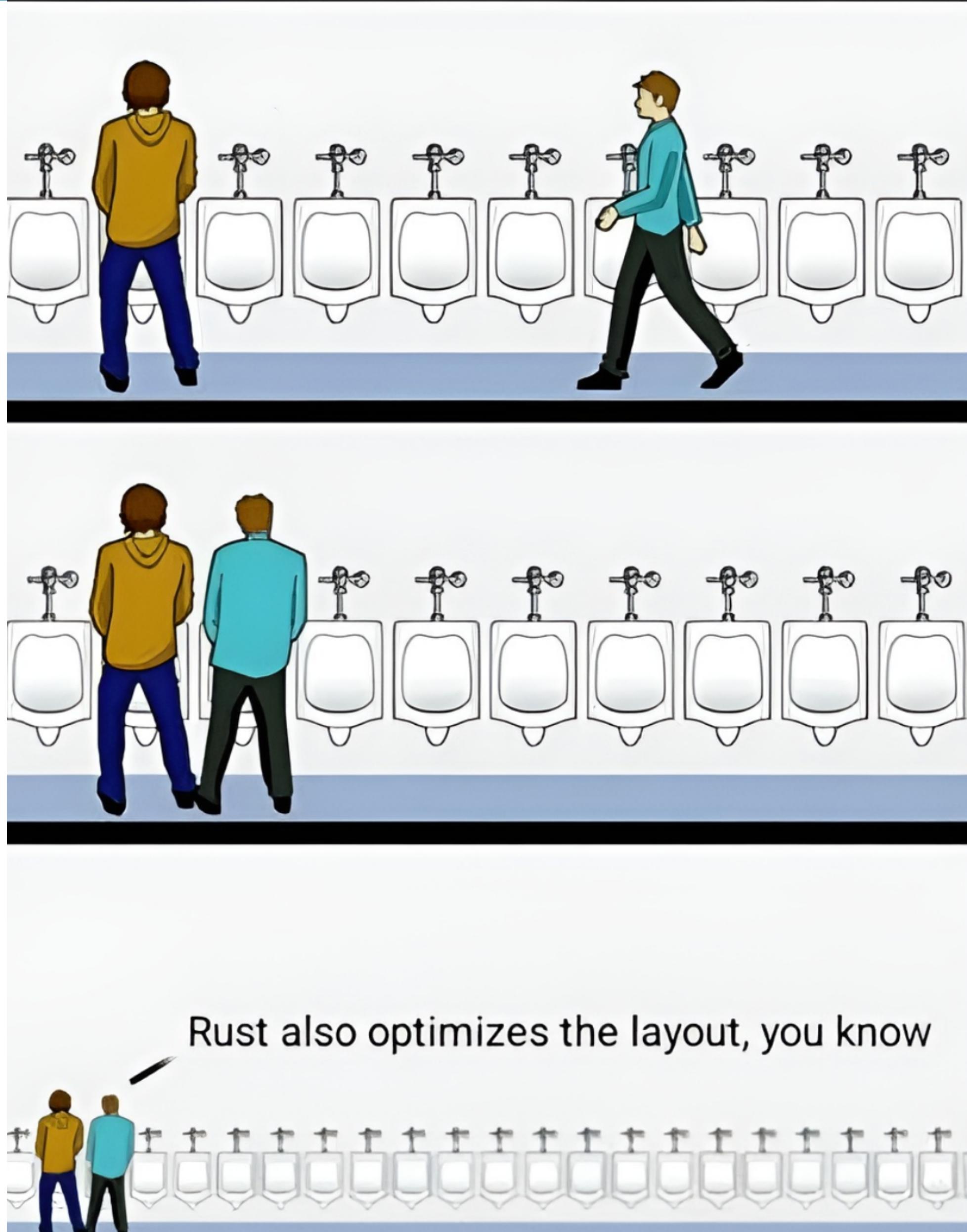
An **interop domain** contains code that will always be **compiled together**

Domains can control where the costs of interop are paid

Optimization vs. Resilience

- Across resilience domains => maintain **stable ABI**
- Within a resilience domain => all implementation details are **fair game**
 - no indirections (direct access, no computed metadata)
 - no guarantees made
- Optimizations need to be aware of resilience **domain boundaries**
- A program can have just 1 resilience domain

Tail Padding & Rust ABI



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- A field with `[[no_unique_address]]` may have its tail padding reused for a neighbor field
- Prevents Rust from turning a C++ child reference into a base class reference
 - doing so would allow overwriting the tail padding (and thereby the child fields)

Rust ABI Stability

Rust dev: "Can we have stable ABI?"

Rust dev: "We have stable ABI at home."

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Stable ABI at home: `#[repr(C)]`

Status quo: `repr(C)` - fake it, till you make it 😊

- Using the C calling convention for function definitions and calls `extern "C" fn`
- Using the C data layout for a type `#[repr(C)]`
- Definitions of C types like `char`, `int`, `long`, etc. `std::ffi::c_*`
- Exporting an item under a stable linking symbol `#[no_mangle]`
- Limited to **C types**, mostly
- No slices

`u8, i64, c_int, c_char, ...`
`&T, &mut T`
`*const T, *mut T`
`struct`

The Future™: calling convention and data layout

- Stable calling convention that supports common data types
 - `&str` `&[u8]` etc.
- Standard data layout that supports enums (with data), etc.
 - `enum` `struct`
- Stable layout guarantees of common standard library types
 - `Option` `Result` etc.

`extern "crabi" fn`

`#[repr(crabi)]`

`#[repr(crabi)] in std`

crABI

github.com/joshtriplett/rfcs/blob/text/3470-crabi.md

The Future™: mechanism for exporting/importing, naming symbols and working with dynamic libraries

- Exporting items under stable linking symbols, supporting crates, modules, methods `# [export]`
- Use a crate as dynamic library, only importing the exported items `extern dyn crate`
- Cargo features for dynamically linking to Rust libraries `cargo dynamic deps`

The Future™: trait objects/vtables and typeid

- A standard data layout for dynamic trait objects (v-tables)
 - `&dyn T` `&mut dyn T` `Box<dyn T>`
- A way of dealing with types that depend on global state (eg. allocated objects)
 - `Box` `Vec`
- Stable typeid
 - `Any` `catch_unwind`
- Access to std structures like maps through dynamic std trait objects
 - `&dyn HashMap` etc.

The Future™: "*Don't stop me now!*" ♪♪

- Turning parts of std into an opt-in dynamic library with a stable ABI ([std as dylib](#))
- [Tools](#) to help with [detect](#)/maintaining ABI compatibility and tools to debug ABI issues
- Store signatures, data layouts in binaries ([introspection](#))

ABI Cafe 

faultlore.com/abi-cafe/book/

Pair Your Compilers At The ABI Café:
faultlore.com/blah/abi-puns/



I like to move it, move it...

Object Relocation

One particularly sensitive topic about handling C++ **values** is that they are all *conservatively* considered **non-relocatable**

I like to move it, move it...

Object Relocation

In contrast, a **relocatable value** would preserve its **invariant**, even if its bits were moved arbitrarily in memory

For example, an `int32` is relocatable because moving its 4 bytes would preserve its actual value, so the address of that value does not matter to its integrity

I like to move it, move it...

Object Relocation

C++'s assumption of **non-relocatable values** hurts everybody
for the benefit of a few questionable designs

I like to move it, move it...

Object Relocation

Only a *minority* of objects are genuinely **non-relocatable**:

Eg.

- objects that use internal **pointers**
- objects that need to update **observers** that store pointers to them

Trivially Relocatable

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- Relocating an object to a distinct physical location is a **destructive** move
 - **create** new object having original value at destination
 - **destroy** the source object

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 - anything with no self-references, eg. **std::vector**, **std::unique_ptr**, etc.

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- Trivial relocation **standardizes** this important optimization

I like to move it, move it...

Trivial Relocatability C++26

Safely relocate objects in memory

wg21.link/P2786

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Many types in C++ cannot be trivially moved or destroyed, but do support trivially moving an object from one location to another by copying its bits – an operation known as **trivial relocation**

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Optimizing containers to take advantage of this property of a type is **already in widespread use** throughout the industry, but is **undefined behavior** as far as the language is concerned

wg21.link/P2786

Trivially Relocatable

A class is trivially relocatable if:

- it has no virtual base classes
- all of its **sub-objects** are trivially relocatable
- it has no *deleted* destructor
- **AND:**
 - its move constructor, move-assignment operator, and destructor are *defaulted*
 - **OR**
 - it's tagged with the **trivially_relocatable_if_eligible** keyword



I like to move it, move it...

C++ and Rust have **opposite** ways of handling move:

- Rust likes to **move** by default
- C++ likes to **copy** by default
- Rust does **memcpy()** on the bytes of T, regardless of type
- C++ is by default needing **move functions** (ctor, =)
 - eg. std::string cannot be memcpyed due to SSO (self referential *)
- Rust **Pin** solves the issue with **self-referential** types
 - not ergonomic (pollutes the context)

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✗ place a C++ object on a Rust stack since it cannot be safely memcopy-moved
(relocated)

C++26: Make C++ types trivially relocatable ([annotate types](#))

Get standard library to be relocatable

=> allow most C++ types on the Rust stack (efficiency)



Improving Rust/C++ Interop with Trivial Relocatability:

camio.github.io/trivially_relocate_rust/trivially_relocate_rust.pdf

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Support for **destructive moves** in C++ would match the behavior of Rust **drop** mechanics

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Support for **destructive moves** in C++ would match the behavior of Rust **drop** mechanics

- **Rust move:** which is a blind memcpy
 - render the moved-from object inaccessible
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moveit

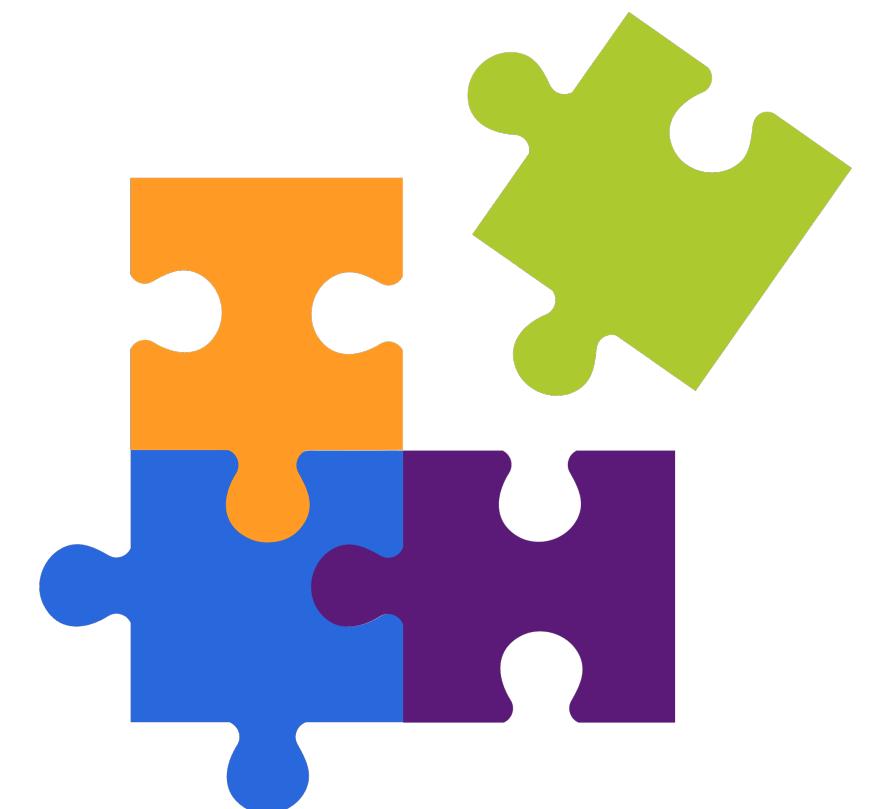
- safe in-place construction of Rust and C++ objects
- mirrors Rust's drop semantics in its destructive moves
- moved-from values can no longer be used afterwards

Let's talk compilers!

Compilers & Interop

Many of the tricks here require deep **compiler** involvement:

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- on Rust side (easy: 1 instance?)



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High-fidelity language semantics & mapping of vocabulary types:

- **front-ends** (C++, rustc)
- toolchain independent **IR**
- support libs?



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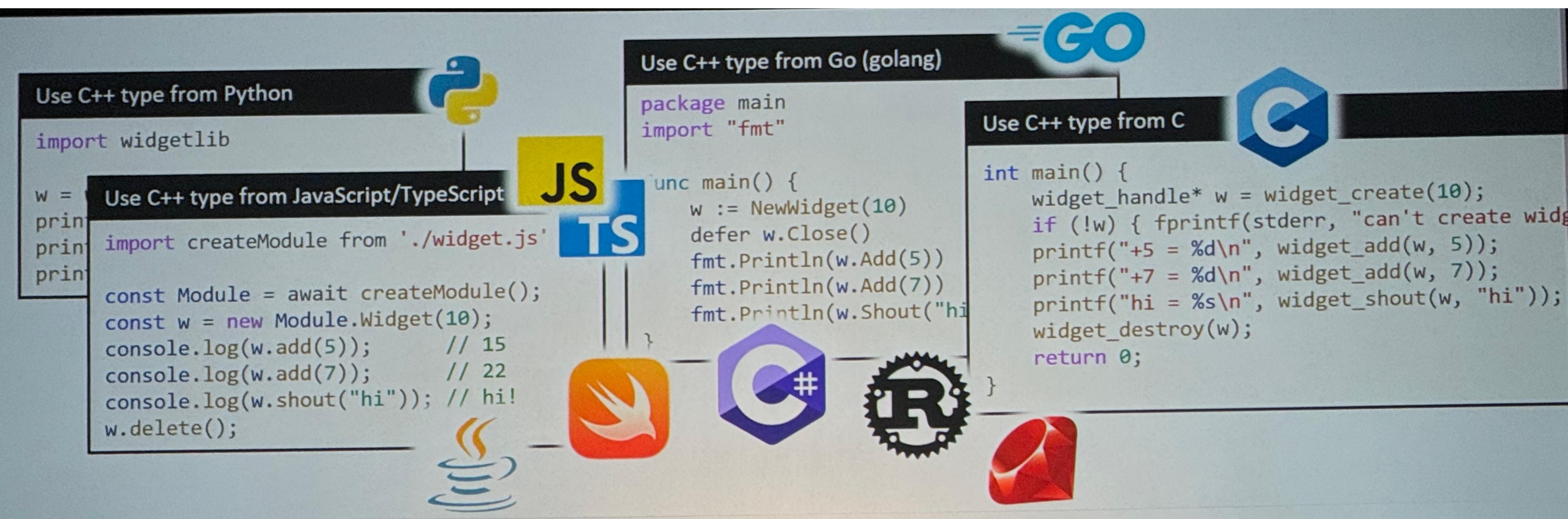
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Binary-level fidelity, ABI, linking, dylib, etc.

- platform integration
- post-build tooling
- codegen / **back-end**



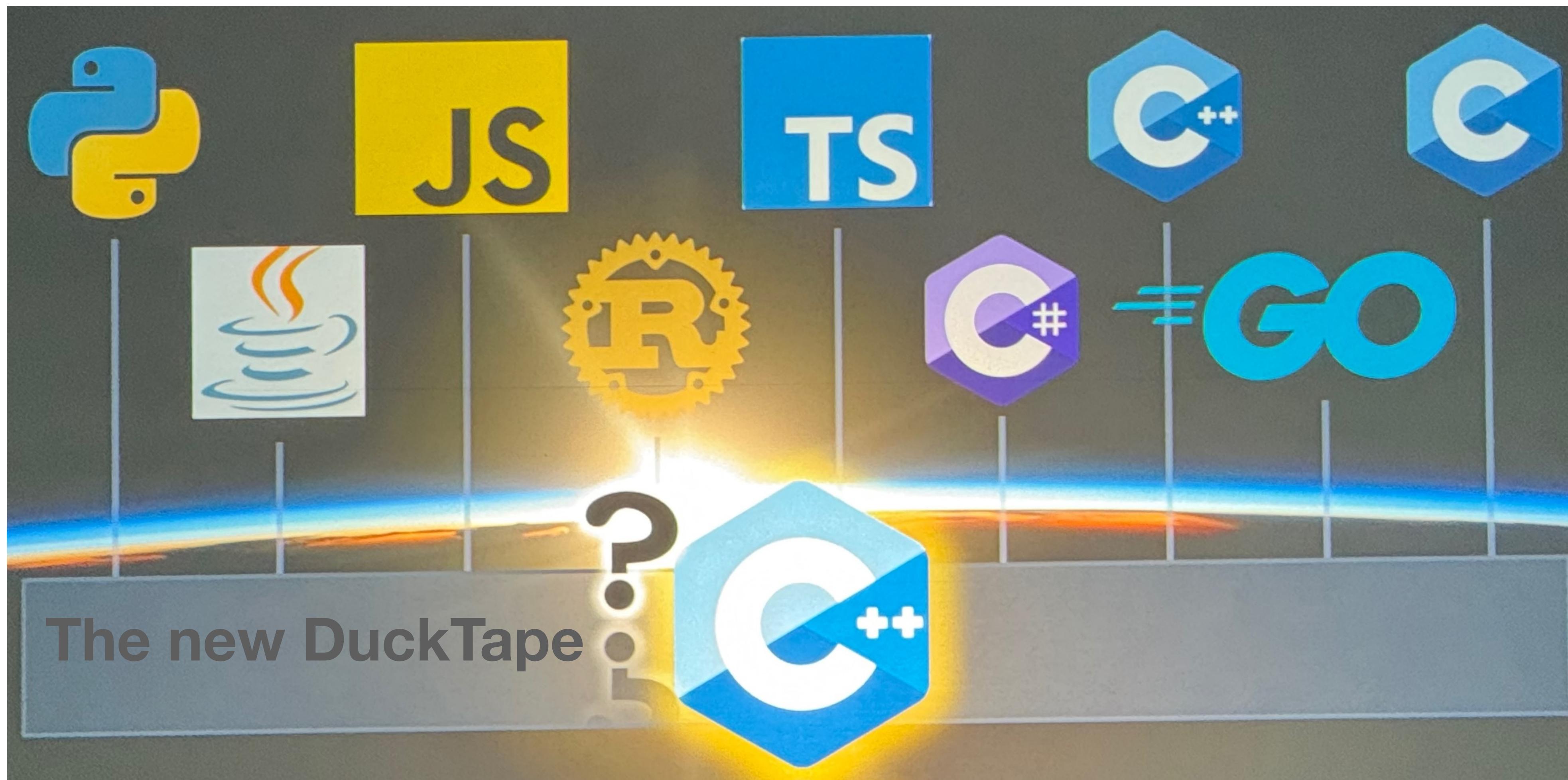
C++26 Reflection will be a game changer!



Herb Sutter: "Reflection: C++'s Decade-Defining Rocket Engine" (CppCon 2025)

Compilers & Interop

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Who's driving this thing?

Active Effort

This year, there have been effervescent talks in the Rust Project & community about this topic (in the broader interop context, not just C++)

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[Rust Foundation](#) joined INCITS in order to participate in the [C++ ISO standards process](#) ([Jon Bauman](#), David Sankel, et.al.)

Rust/C++ Interop Study Group

Interested? join the Rust Project [Zulip](#) server

- rust-lang.zulipchat.com
- [#t-lang/interop](#) channel

You'll find there some familiar Rust and C++ names 😊



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Meetings:

- Feb 26 First lang-team design meeting on the topic - [Notes](#)
- Apr 23 Short-sync on interop interest in industry
- May 15-17 Interop study group @ Rust-All-Hands - [Notes](#)
- Sep 2 Interop study group @ RustConf - [Notes](#)



Must watch



Zngur

Simplified Rust/C++ Integration

David Sankel

youtube.com/watch?v=k_sp5wvoEVM



Fine-grained Rust / C++ interop

Taylor Cramer and Tyler Mandry

The original annual Rust programming language conference.

Learn more at rustconf.com



hosted by:
 Rust
Foundation

Open Discussion

What does Rust/C++ [interop](#) mean for you?

What are the [interop](#) requirements/challenges of your project?



Duck-Tape Chronicles

Rust/C++ Interop

Episode 1^{3/4}

SOON Episode 2

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Victor Ciura
~~Principal Engineer~~
Rambling Idiot
Rust Tooling @ Microsoft