Duck-Tape Chronicles

Rust/C++ Interop

VICTOR CIURA

2025
September 13 - 19

A full week of 8am-10pm sessions

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⚠️ Disclaimer

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

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When Rust folks are looking into C/C++ interop, it's natural…
they NEED it in order to call into existing libs they don't yet have.

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

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

Who thinks interop is about... C FFI

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C FFI

glue code

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glue code

coge generators

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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
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  - tease out the avenues at the forefront of this pursuit

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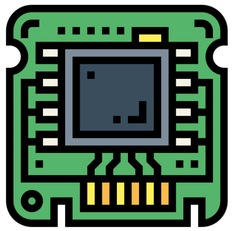
- General high-fidelity interoperability has yet to be achieved 🌶️
- Just "*making things work*" is not enough in the domain space of C++ and Rust
- Many of the explored solutions so far fail to deliver on all needed requirements

Rust extreme range of operation

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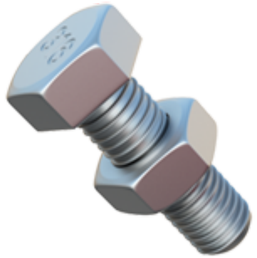
- Easily automated
- Debuggable
- Hybrid build systems (CMake, cargo, MSBuild, bazel, buck...)

Choose... ~~none~~ some?

Compiler



Interop Library

Debugger

Linker

ABI guarantees

Packaging

Build systems & CI

CppCon

September 2025

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Rust/C++ Interop

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

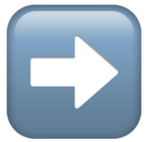
bindgen

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]~~

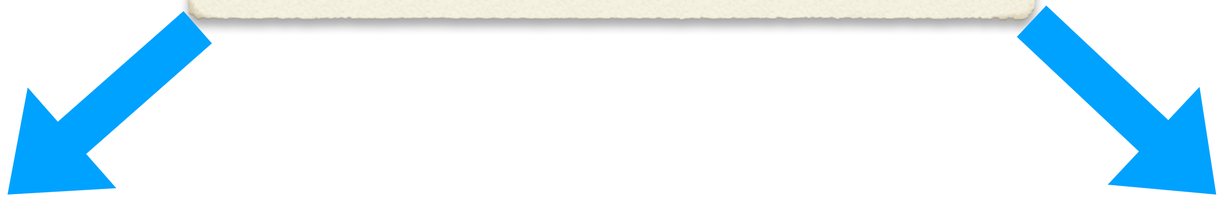
unsafe{} required to convert to/from C representation

CXX

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;
};
```

cxx

- 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 does'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)

zngur

```rust
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;
}
```

```cpp
#include "generated.h"

void cpp_caller() {
  auto w = rust::crate::Widget::new_empty(42);
  w.work();
}
```

zngur

- 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

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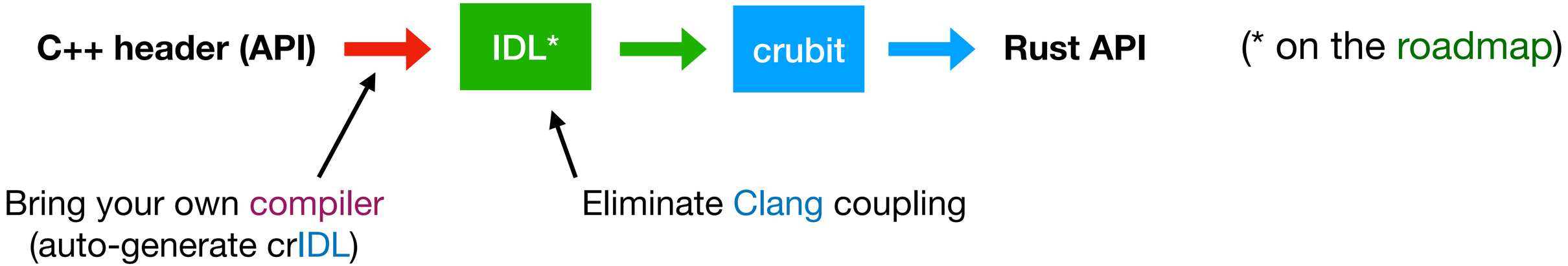
- C++ compiler diversity: ~~MSVC, GCC~~, Clang
  - Optional IDL (TBD - on the roadmap)
- Pass by value: AllTheThings™ (that's where deep compiler integration comes in)

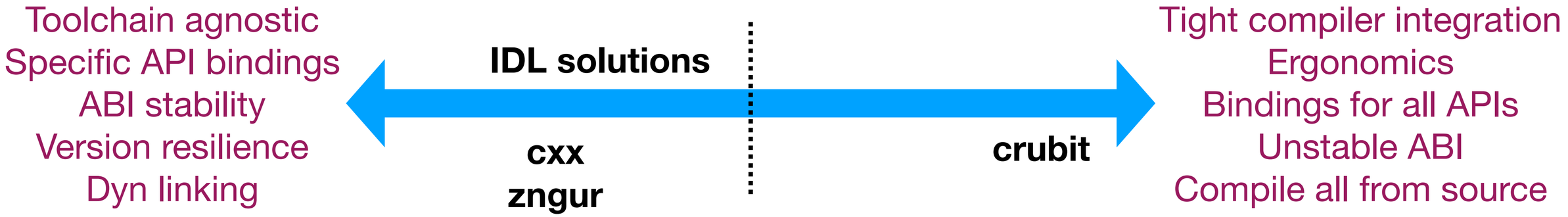
crubit


C++ header (API)
crubit
Rust API


C++ header (API)
IDL*
crubit
Rust API
(* on the roadmap)
Bring your own compiler
(auto-generate crIDL)
Eliminate Clang coupling

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

Calling C++ from Rust

Level: HARD!!!

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

Calling Rust from C++

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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- No fundamental need for a Rust to allow function overloads in the core language
- 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?

- Don't shut the door on future compiler & library improvements

- Stabilizing the ABI (too early)™ might miss optimization opportunities
  - implement a faster custom calling convention
  - implement optimal structure layout
  - improve the way a std utility works
  - make changes affecting v-table
  - (re)use existing padding

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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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  - cast the new pointer and load the field
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  - ~~read the metadata for instance size~~
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Dynamically-sized

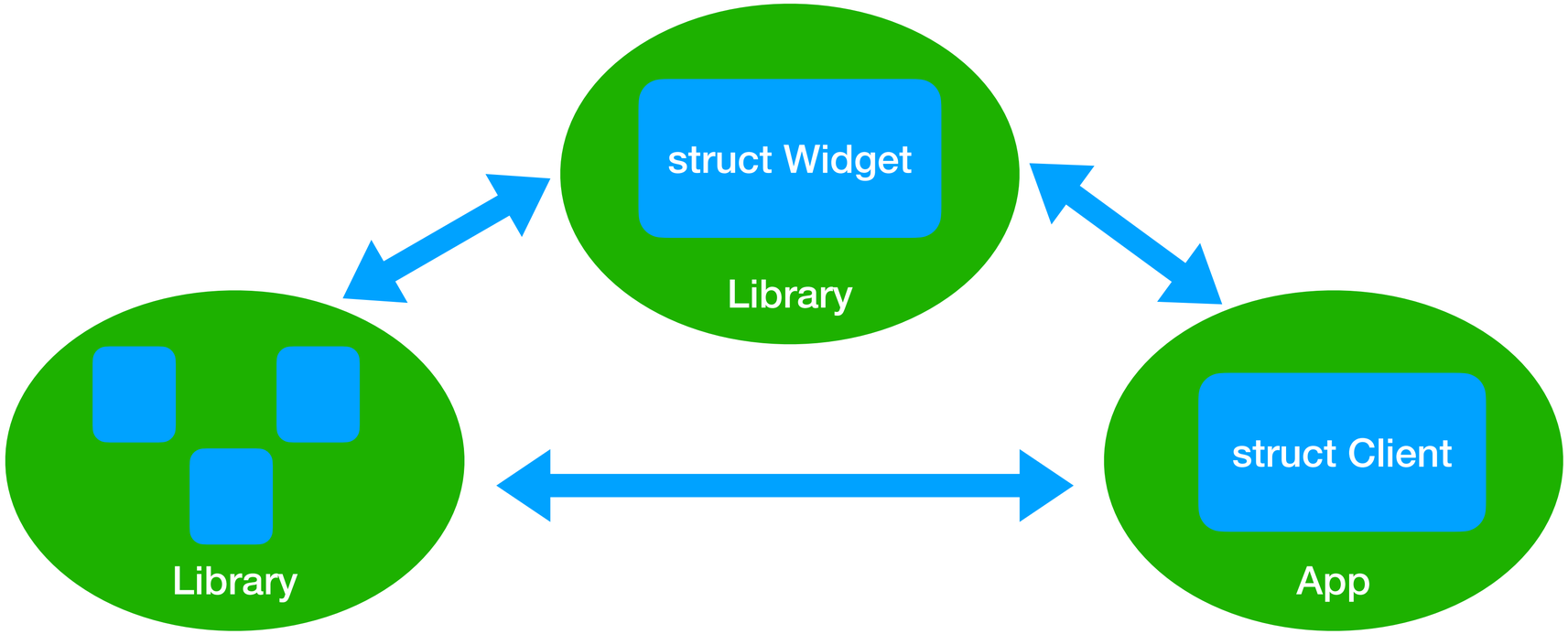
- Support for dynamically-sized things on the stack is key (eg. LLVM)
- Compilers can use of this for of ABI-stable value types:
  - you have local variable of some struct defined in an ABI-stable library
  - so you don’t know it’s size until load time
- Dynamic allocs can handle this nicely (with minimal 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

Interop Domains

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

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Tail Padding & Rust ABI

- C++ is allowed to reuse tail padding of structs, but Rust does not

- Rust treats tail padding as part of the value
  - users expect to be able to memcpy() of size_of::<T>() bytes
- C++ does not allow this
  - fields of a child class may be placed in tail padding of the base class

- 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?"

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

Rust ABI

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
```

Rust ABI

The Future™: calling convention and data layout

- Stable calling convention that supports common data types — `extern "crabi" fn`
  - `&str` `&[u8]` `etc.`
- Standard data layout that supports enums (with data), etc. — `#[repr(crabi)]`
  - `enum` `struct`
- Stable layout guarantees of common standard library types — `#[repr(crabi)] in std`
  - `Option` `Result` `etc.`

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

Rust ABI

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`

Rust ABI

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.`

Rust ABI

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**

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

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Object Relocation

C++'s assumption of non-relocatable **values** hurts everybody

for the benefit of a few questionable designs

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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- Trivial relocation standardizes this important optimization

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Trivial Relocatability C++26

Safely relocate objects in memory

wg21.link/P2786

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Trivial Relocatability C++26

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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 memcopy-ed due to SSO (self referential *)
- Rust Pin solves the issue with self-referential types
  - not ergonomic (pollutes the context)

I like to move it, move it...

❌ 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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- Rust move: which is a blind memcpy
  - render the moved-from object inaccessible
- C++ move: where a move is really like a mutating Clone operation
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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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- front-ends (C++, rustc)
- toolchain independent IR
- support libs?

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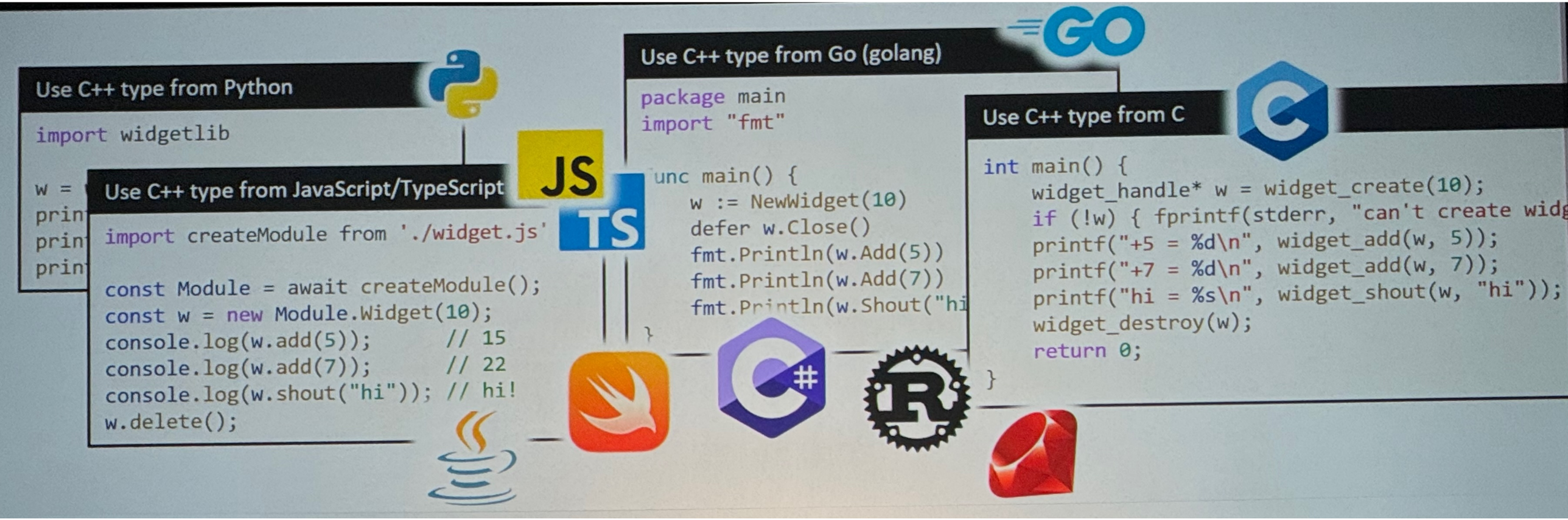
Binary-level fidelity, ABI, linking, dylib, etc.

- 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)

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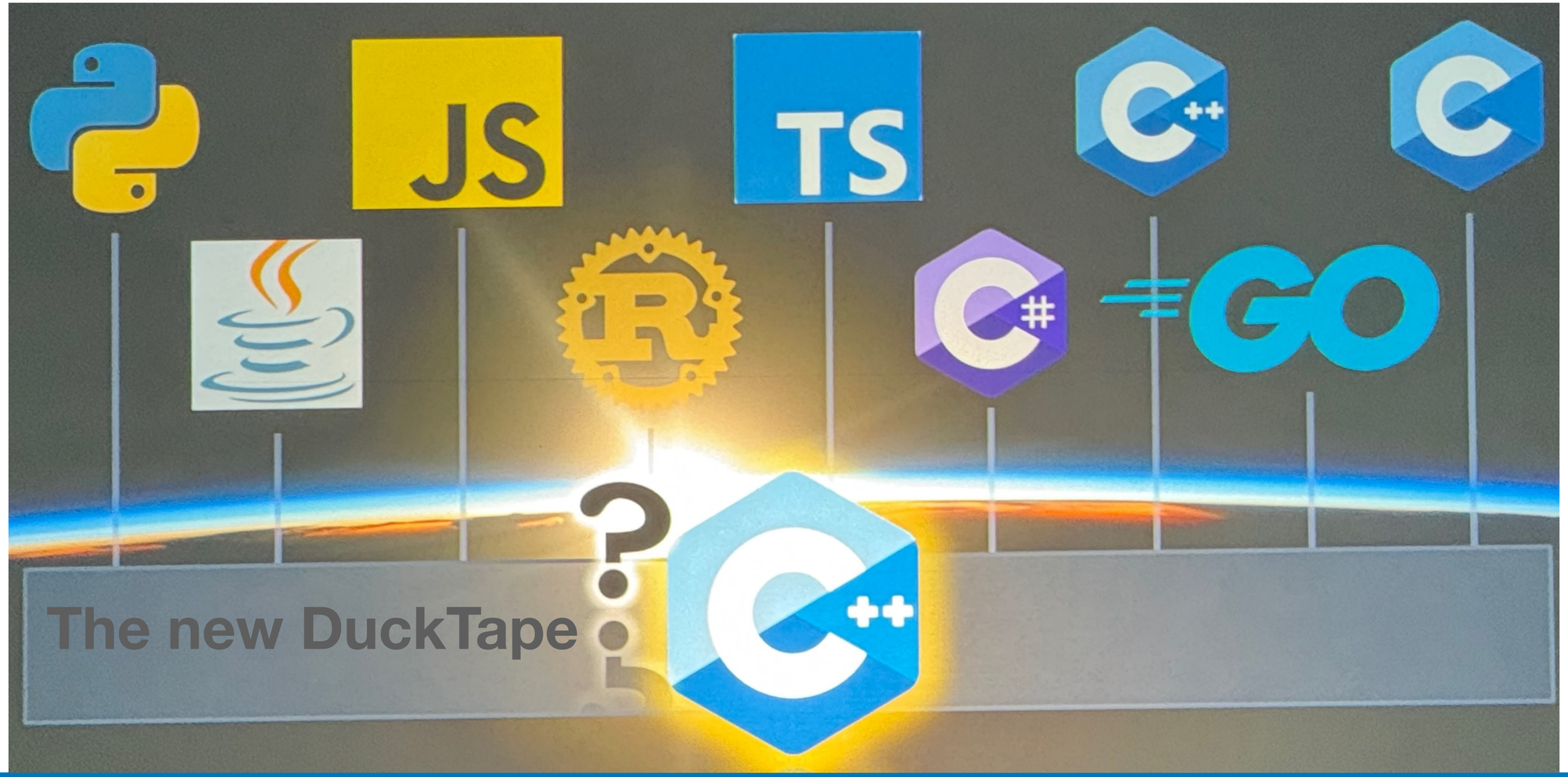

Who's driving this thing?

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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- Document the problem space of current interop challenges (identify the gaps)
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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 

youtube.com/watch?v=k_sp5wvoEVM

RustConf
2025 | Seattle + Online

Fine-grained Rust / C++ interop

Taylor Cramer and Tyler Mandry

We are crubit

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?

CppCon

September 2025

Duck-Tape Chronicles
Rust/C++ Interop

Episode 1[3/4]

Episode 2

Victor Ciura

Principal ~~Engineer~~
Rambling Idiot

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