Building Bridges

C++ Interop., Foreign Function Interfaces & ABI

Qt Quality Assurance

Gareth Williamson

Software Engineer

Qt Quality Assurance

Motivation

Why build a multi-language system?

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Why build a multi-language system?

Use the right tool for the job

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Use the right tool for the job

Performance Critical Code

Expressive API

Motivation

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Re-use existing code

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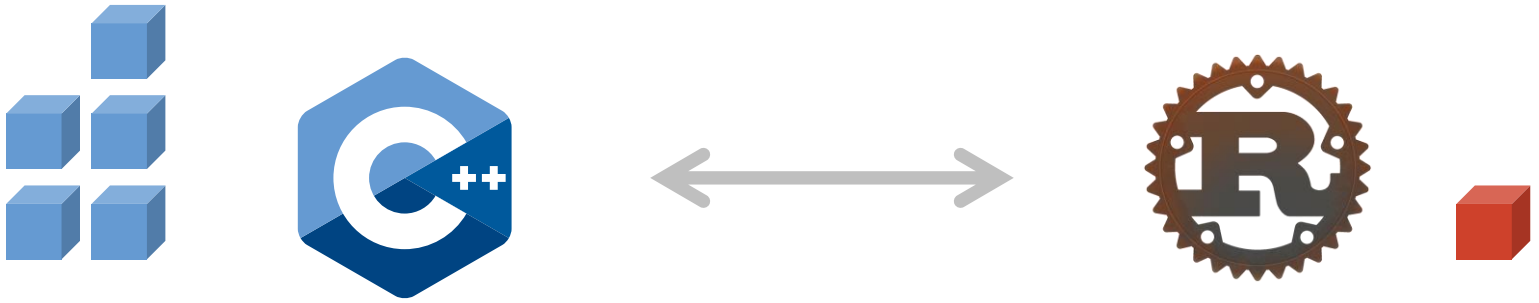
Why build a multi-language system?

Use the right tool for the job

Re-use existing code



Existing Codebase

New Library

Motivation

How can we build a multi-language system?

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How can we build a multi-language system?

Inter-process

Motivation

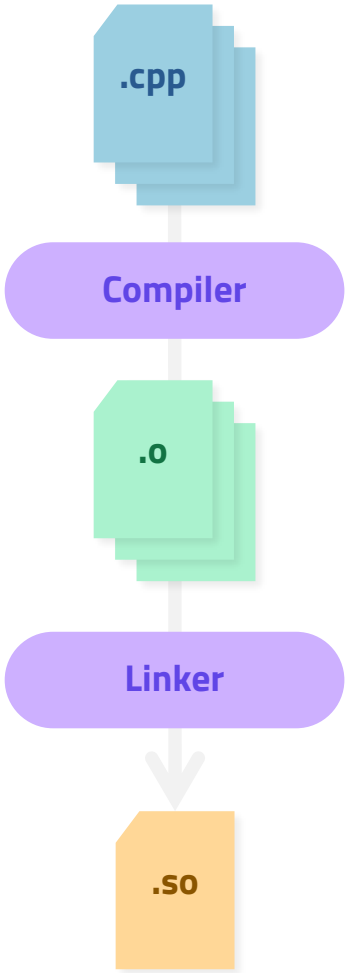
How can we build a multi-language system?

Inter-process

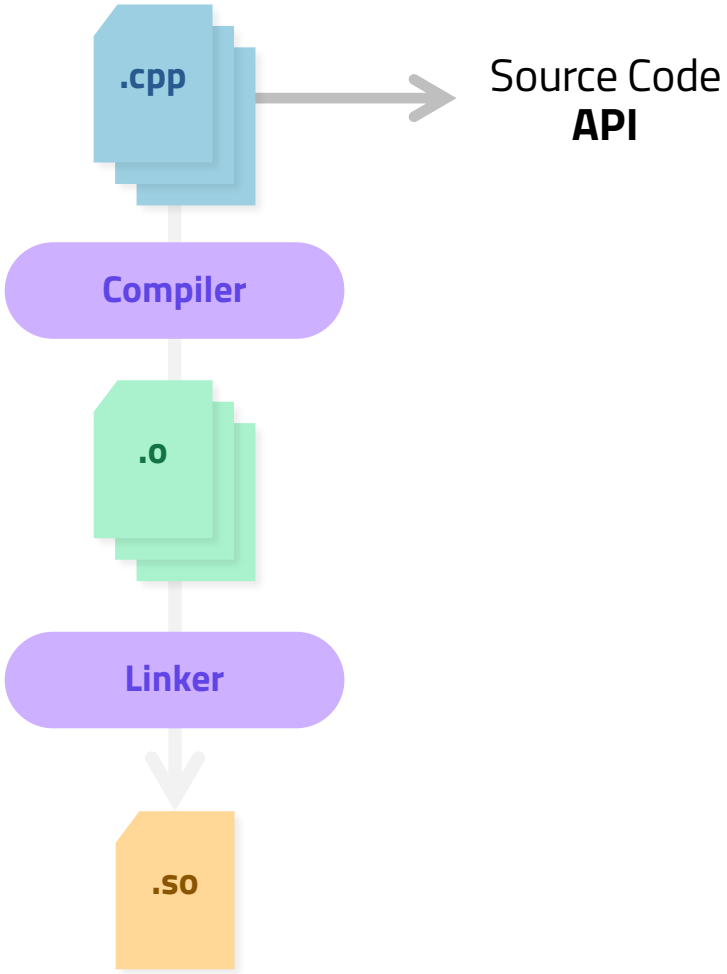
Link Object Code

Application Binary Interface

ABI



ABI



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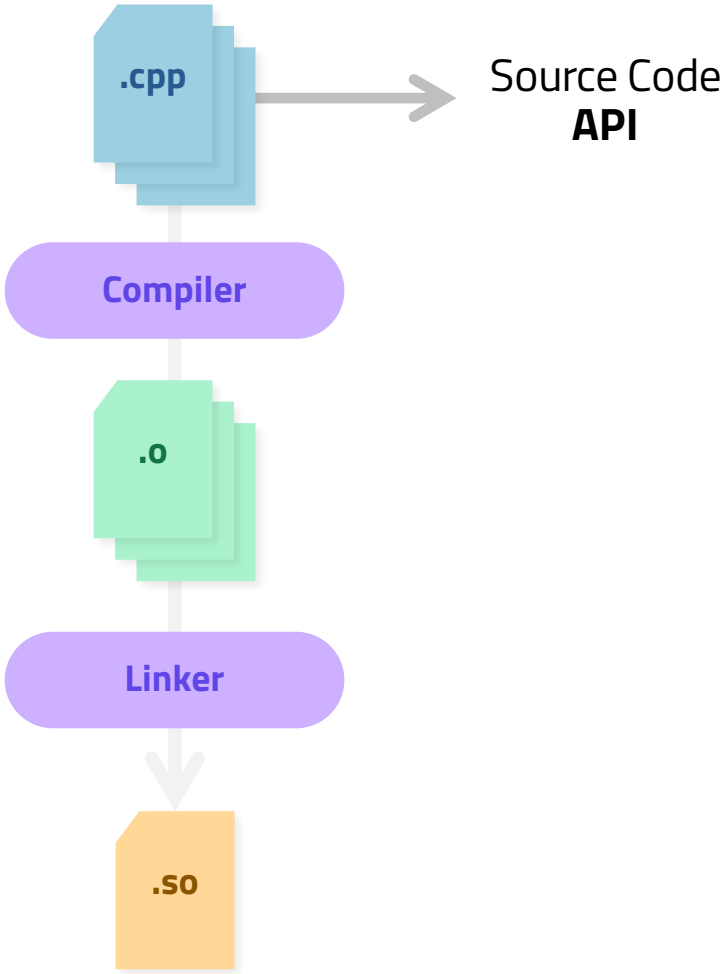
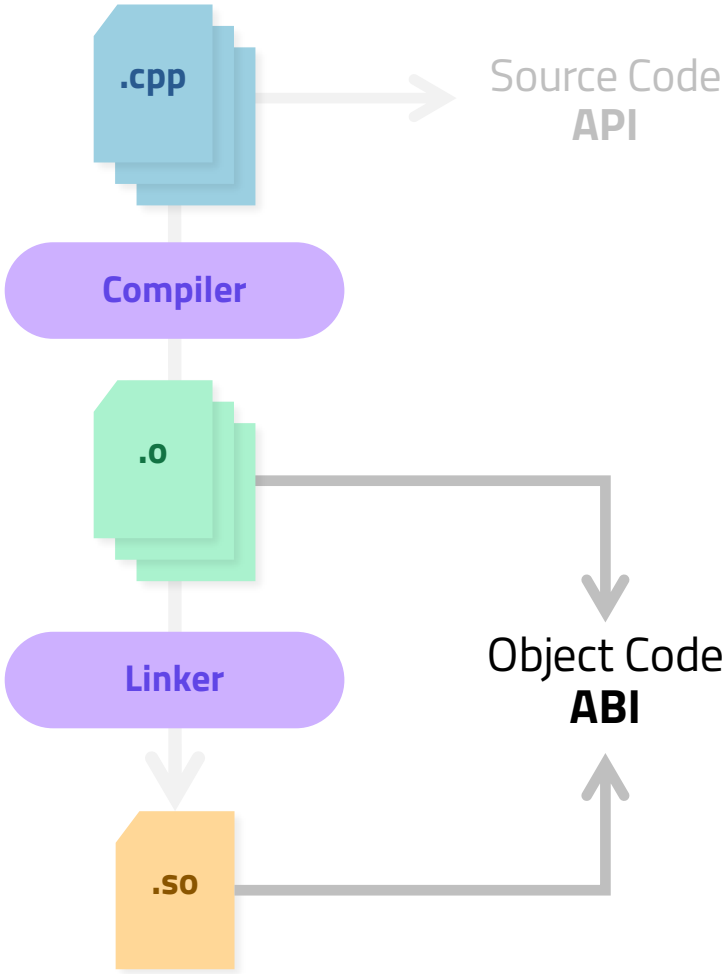


API is the **source code** level interface

ABI



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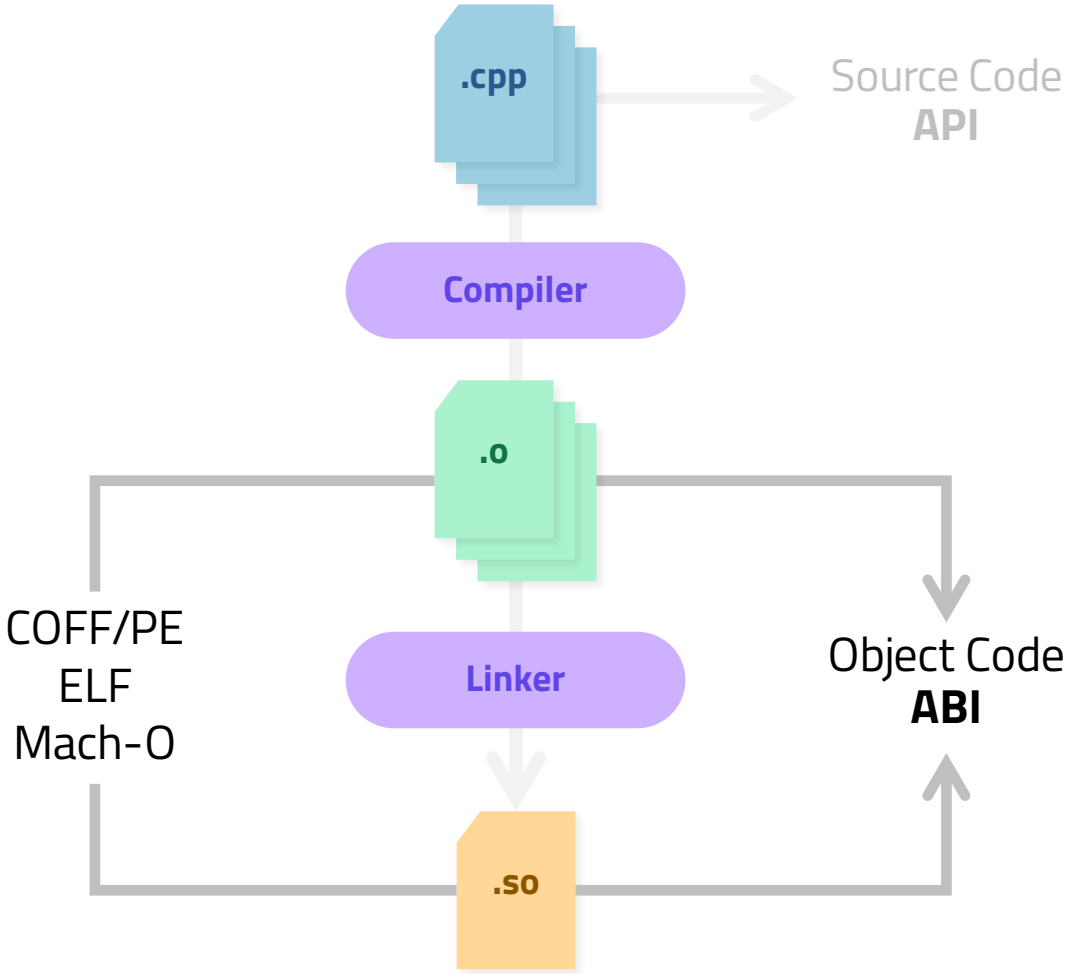

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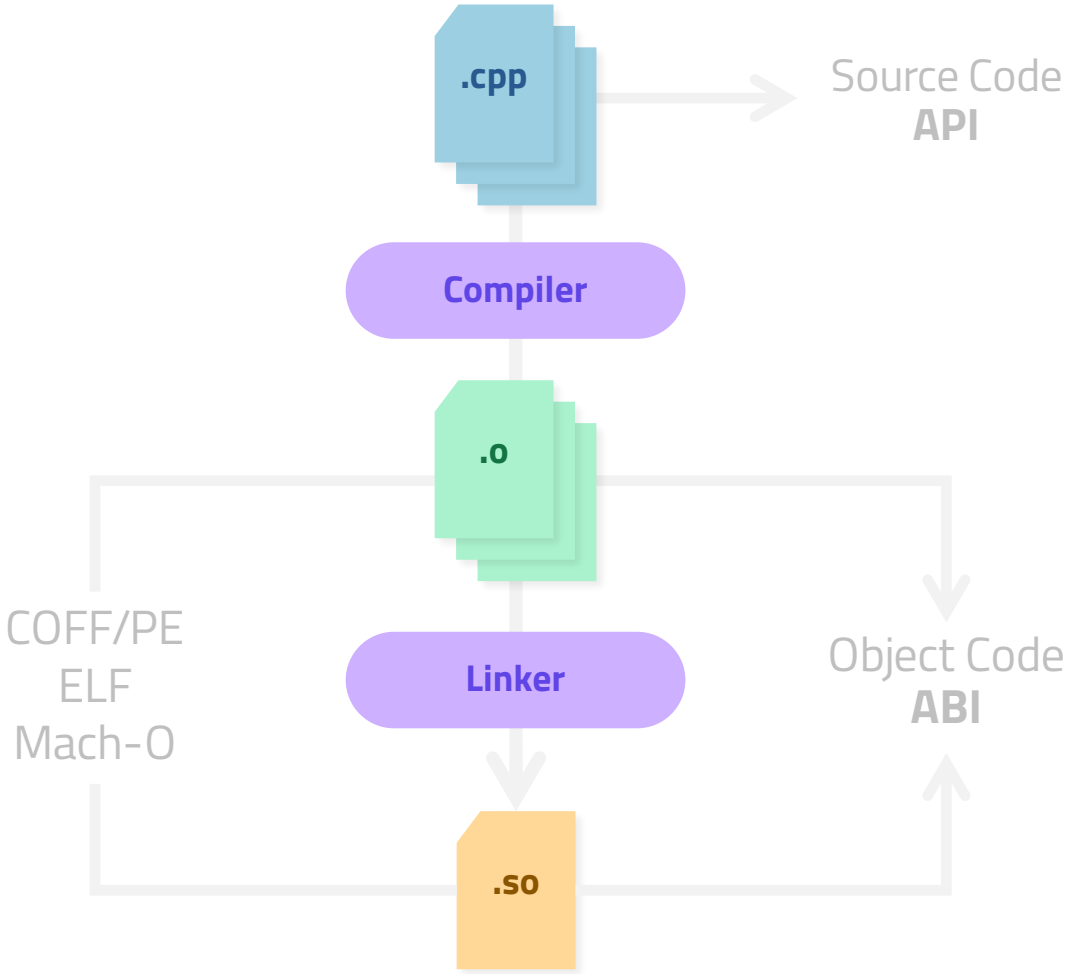
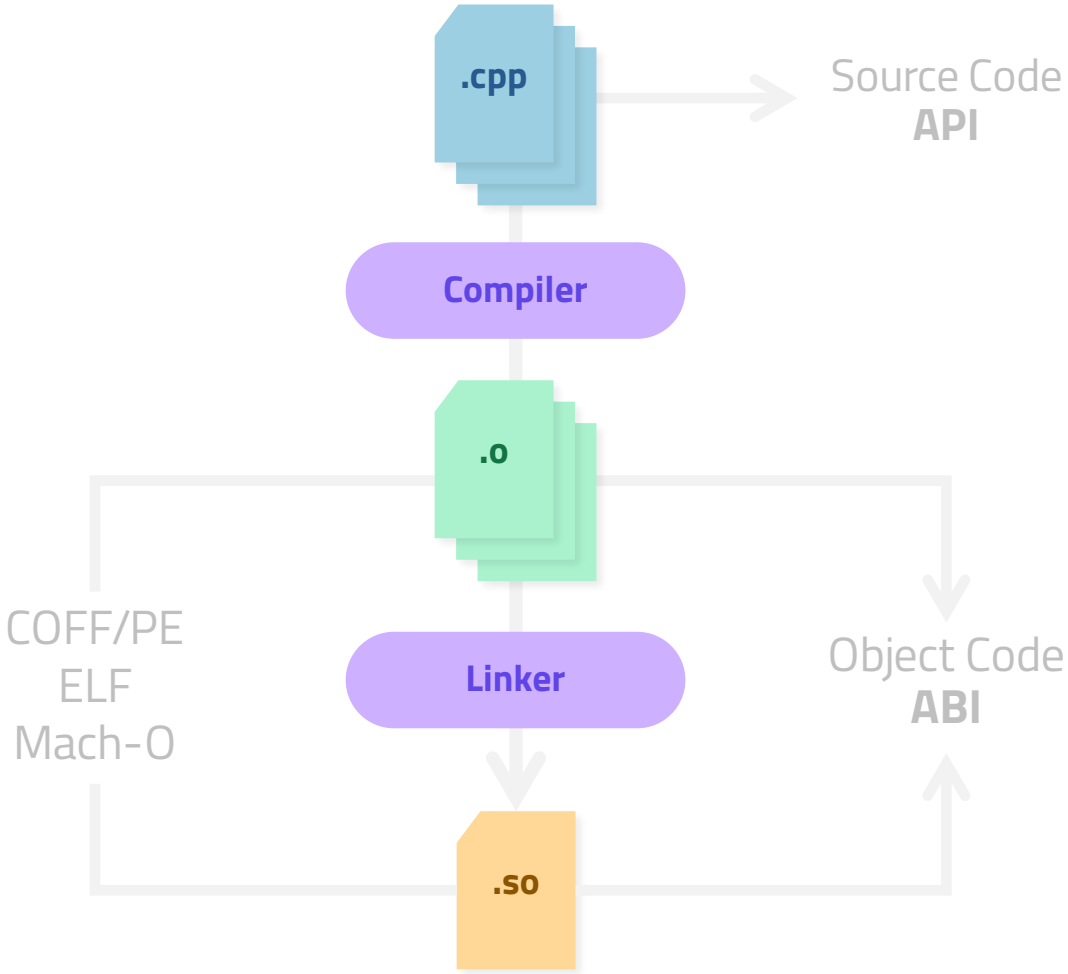


API is the **source code** level interface

ABI is the **object code** level interface

ABI



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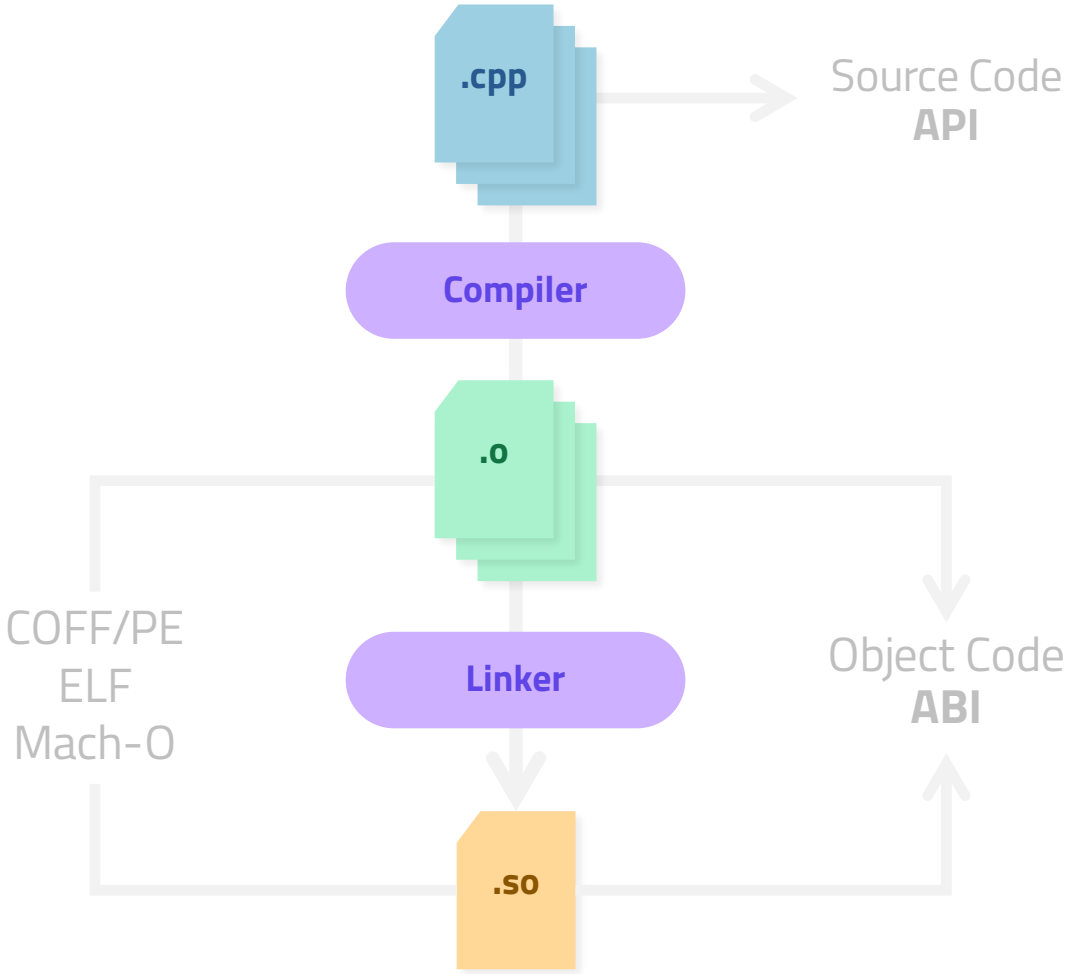
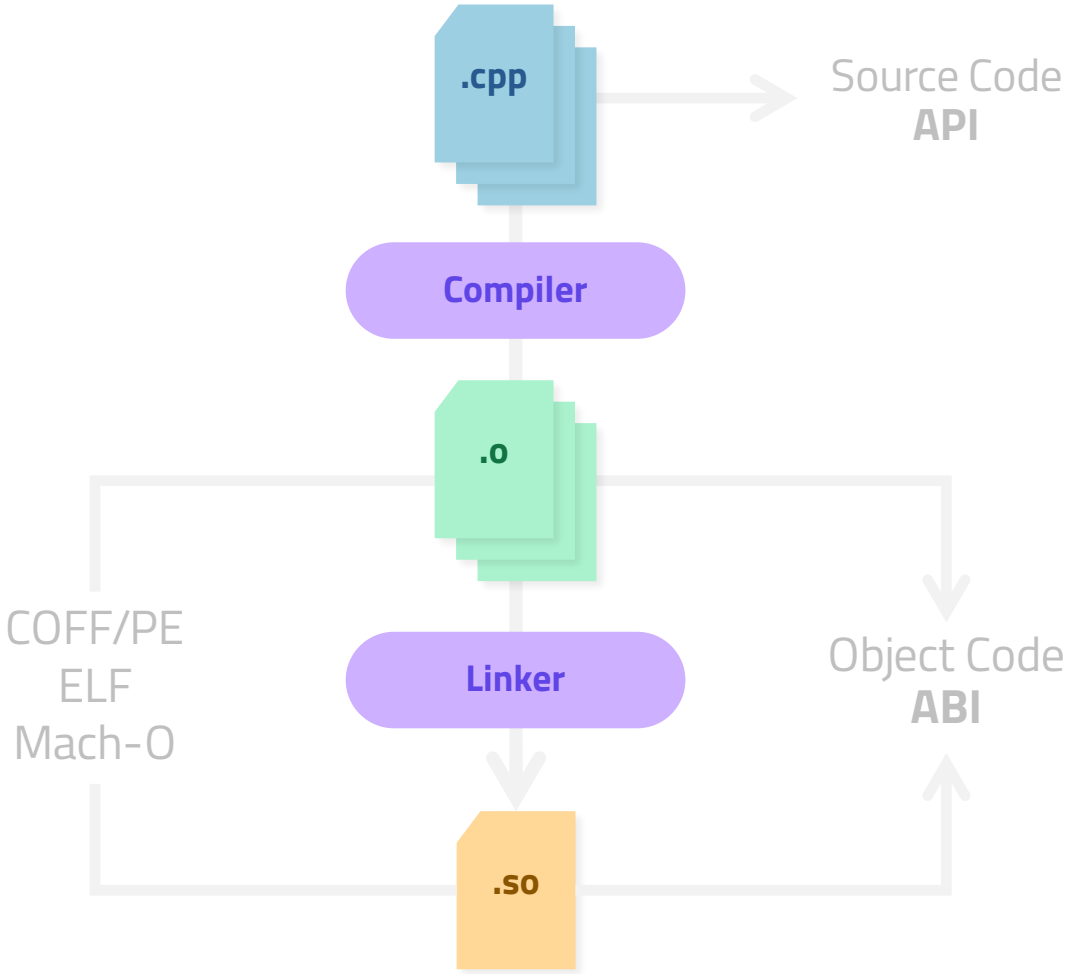


What's inside object files?

ABI



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Machine Code

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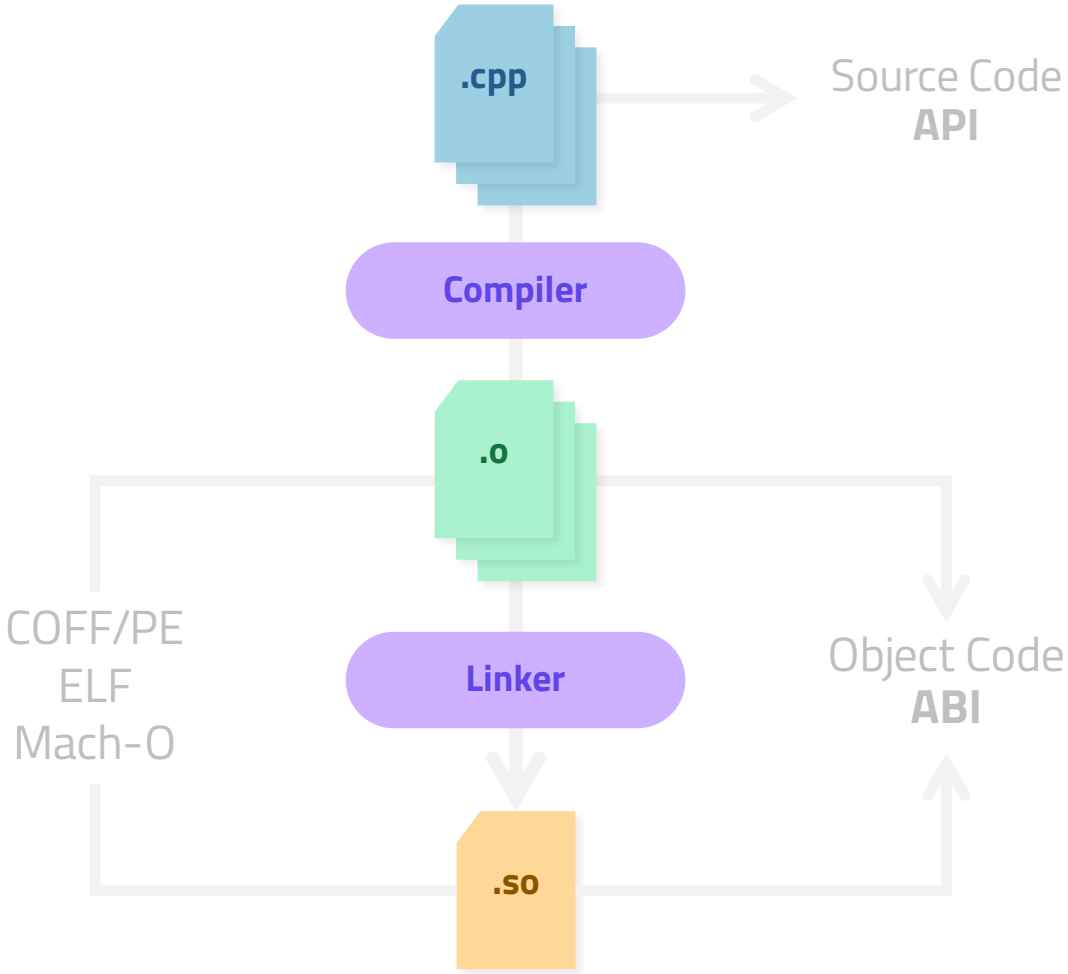

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Machine Code

Static Data

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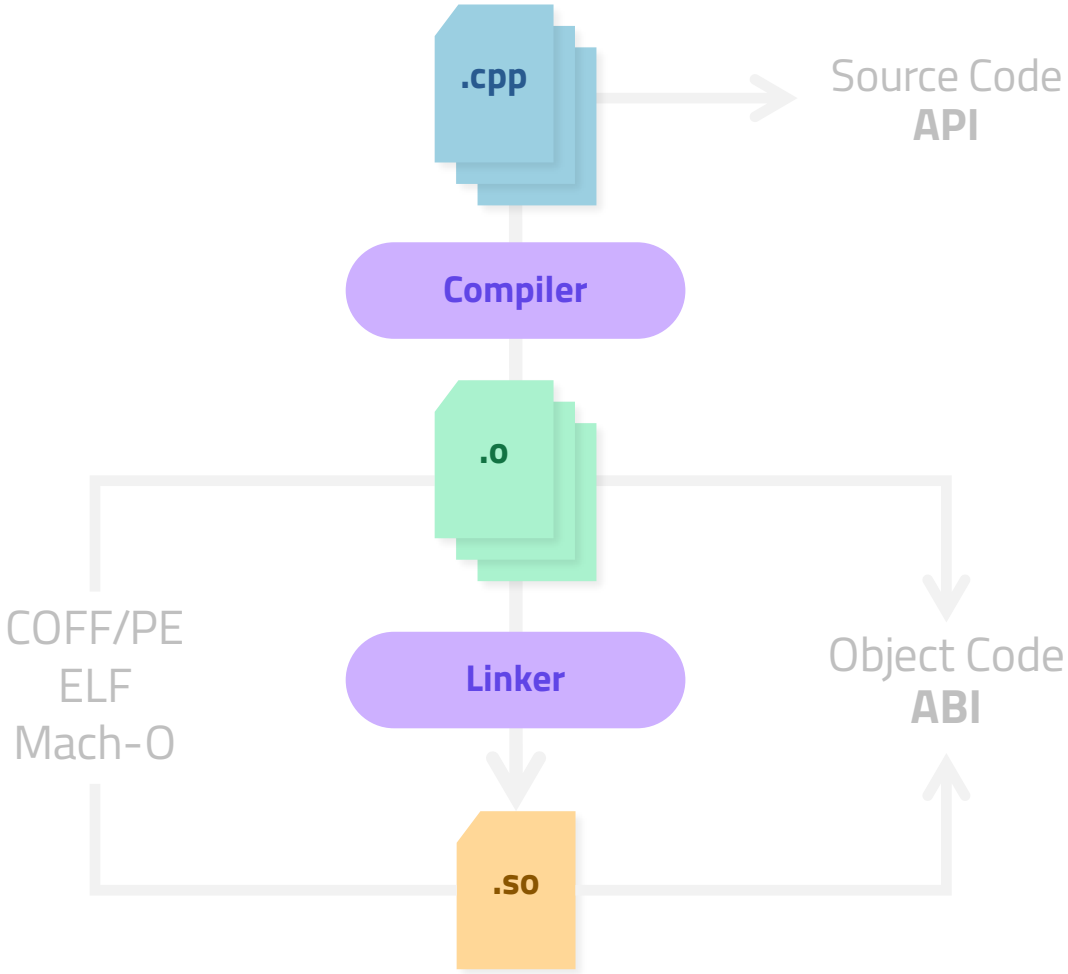


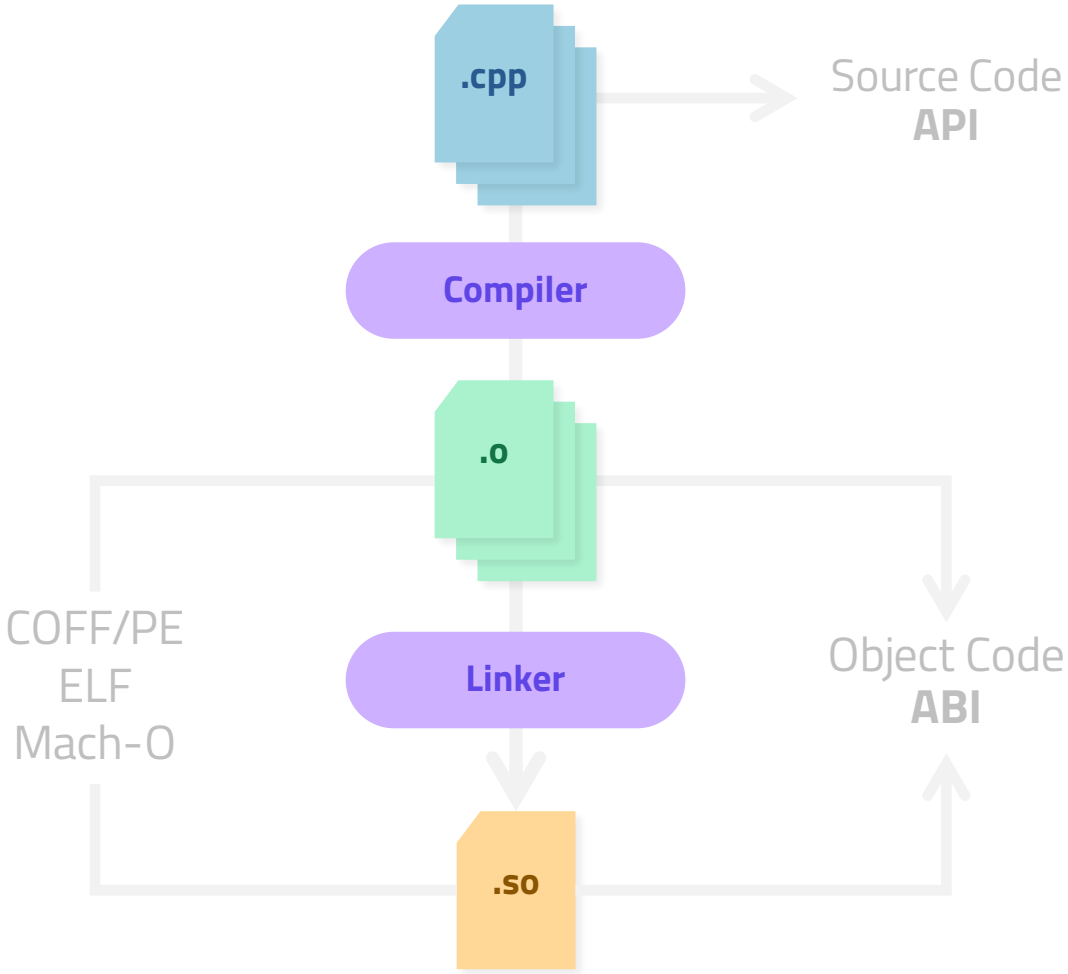
What's inside object files?

Machine Code

Static Data

Symbol Table

ABI



What's inside object files?

Machine Code

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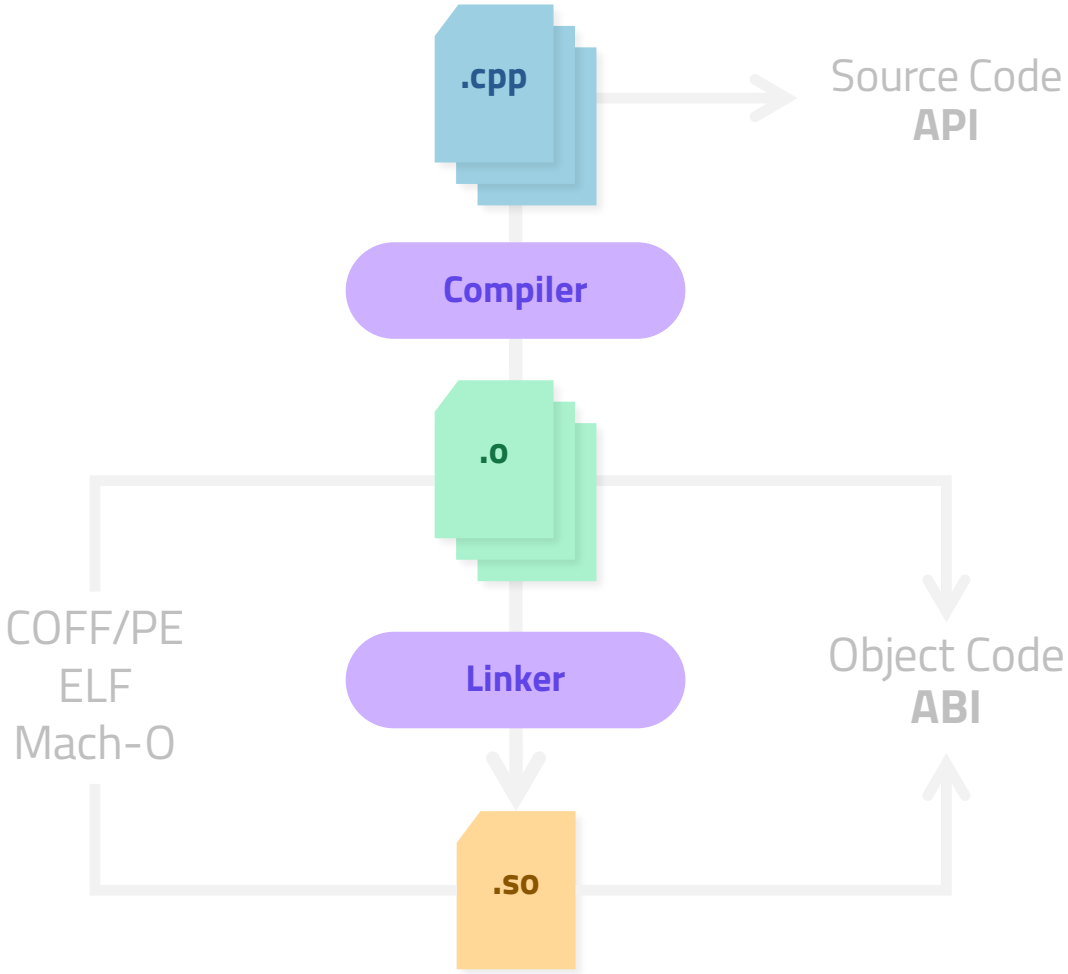
Symbol Table

```
linux $ nm --extern-only lib.so | c++filt
```

ABI



What's inside object files?

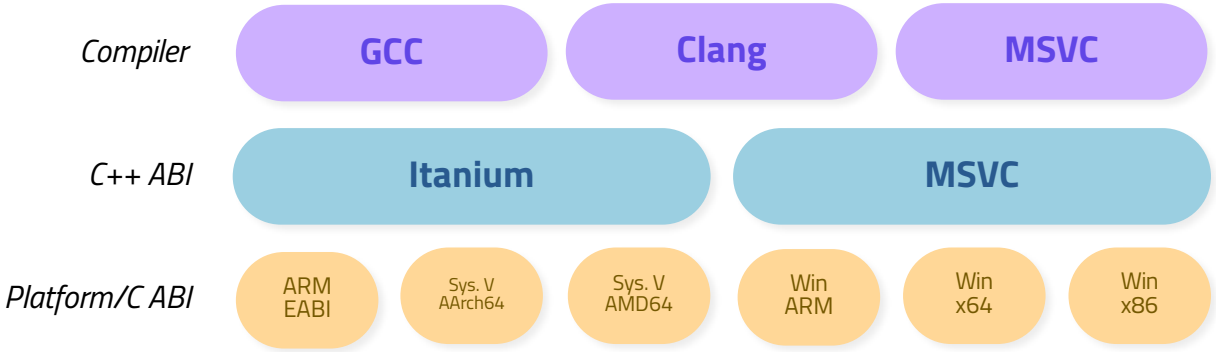
Machine Code

Static Data

Symbol Table

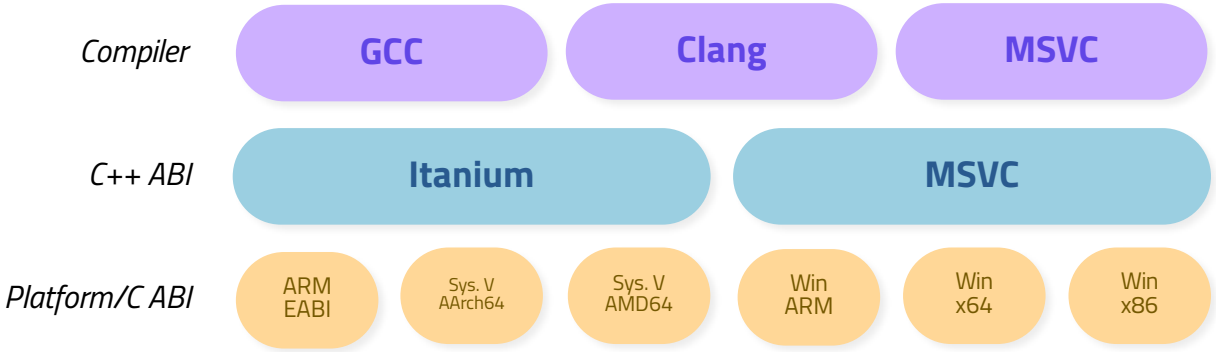
```
  linux $ nm --extern-only lib.so | c++filt

windows $ dumpbin /exports lib.dll
```

ABI



ABI

The Layers of ABI



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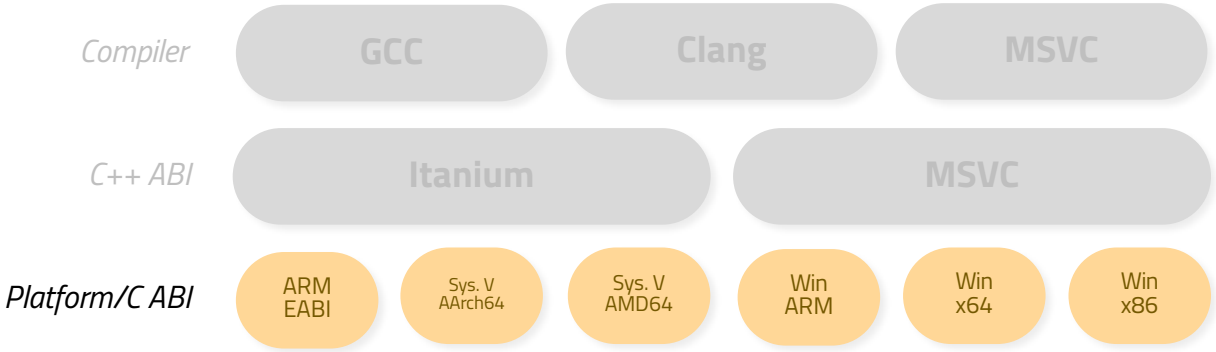
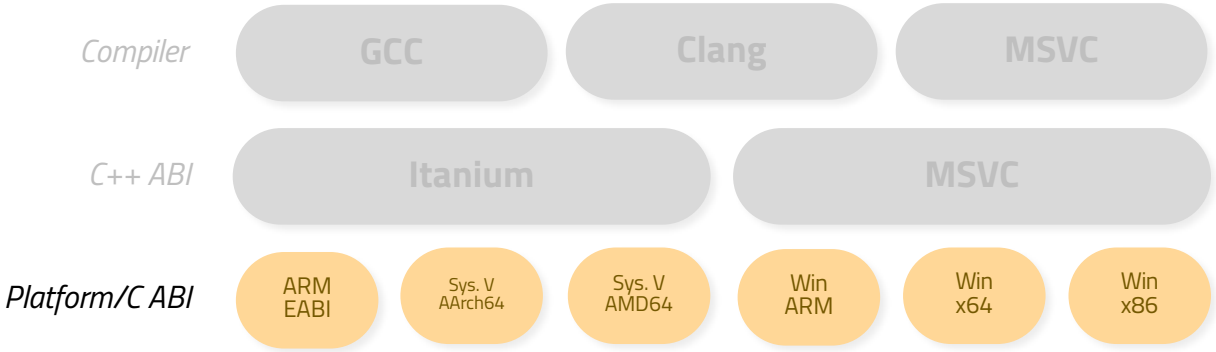


The Layers of ABI

Processor Architecture

ABI

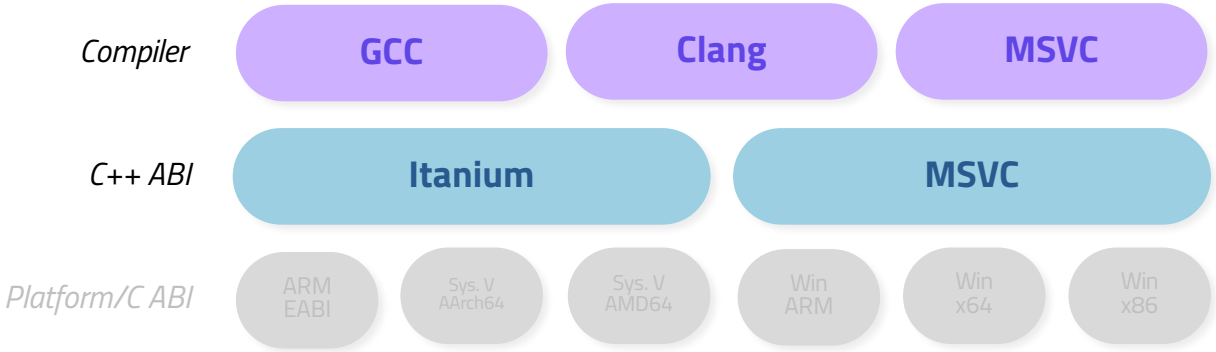


The Layers of ABI

Processor Architecture

Operating System

ABI



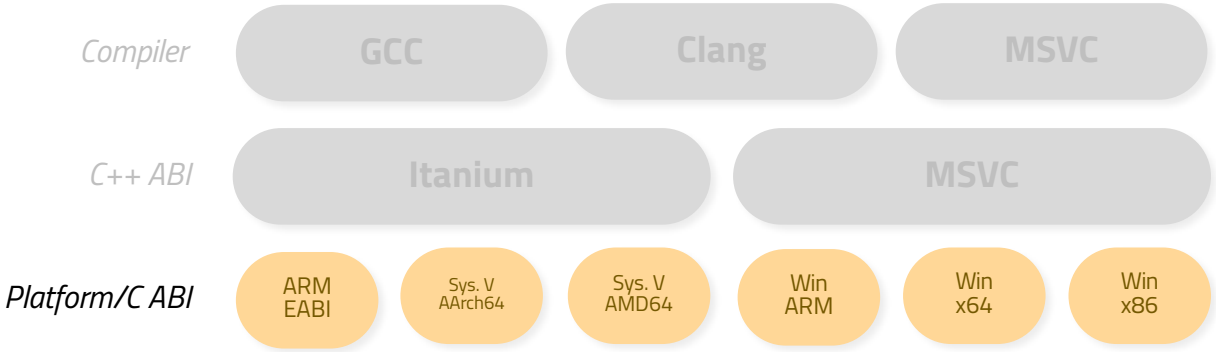
The Layers of ABI

Processor Architecture

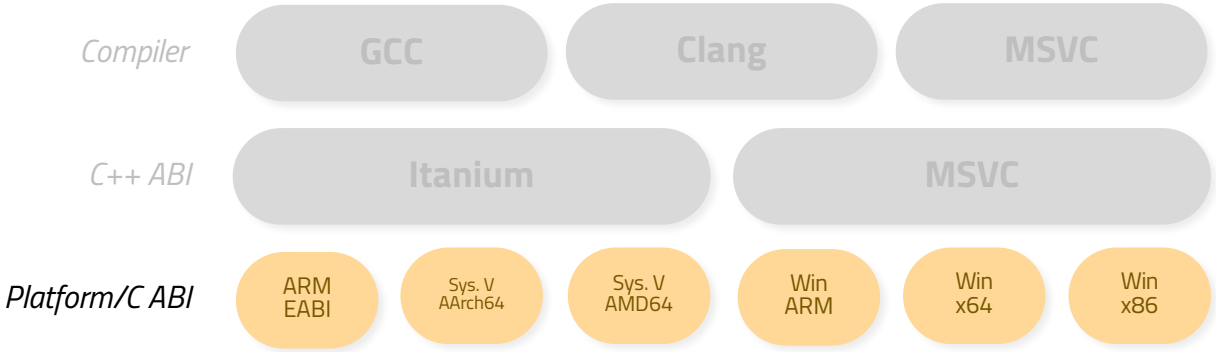
Operating System

Compiler

Platform/C ABI

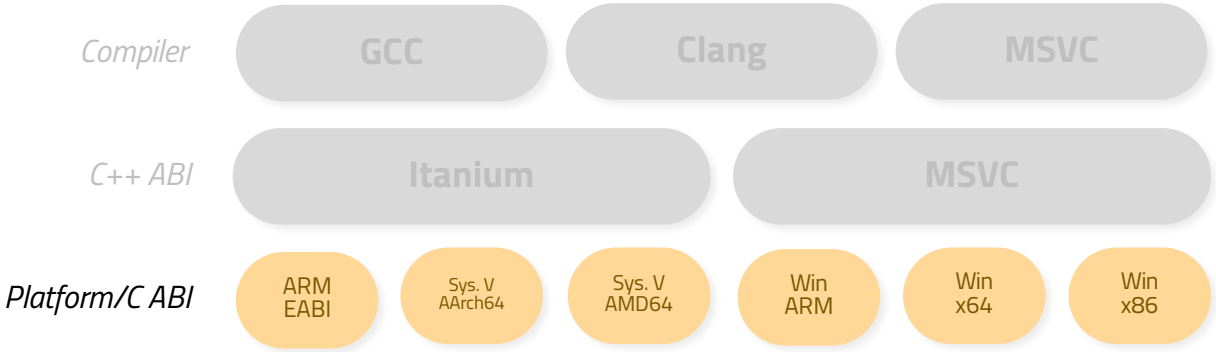


Platform/C ABI



Platform/C ABI is the
lowest common denominator

Platform/C ABI



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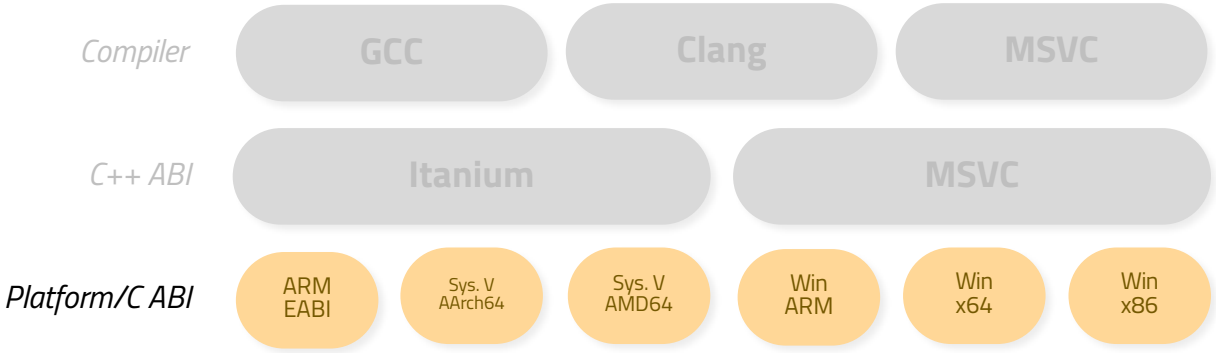

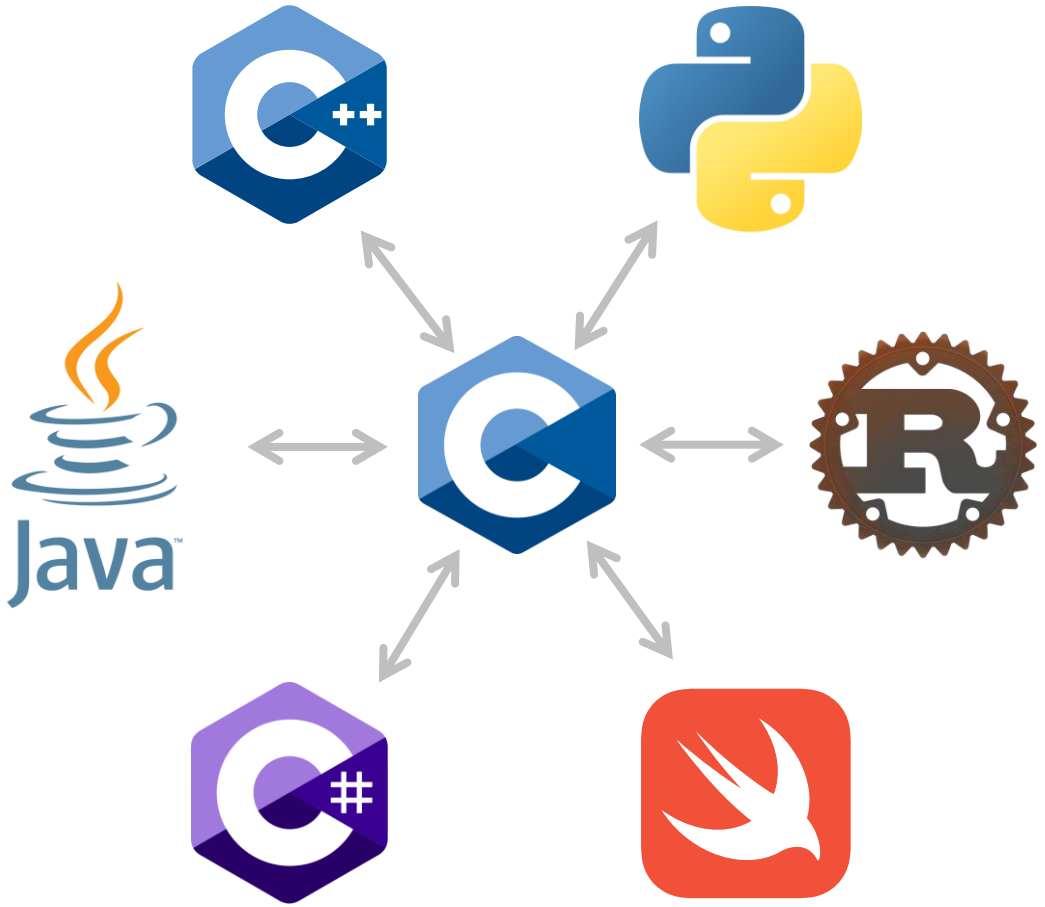

Python/C

Python/C

```
01
02 import ctypes
03
04 libc = ctypes.cdll.LoadLibrary("libc.so.6")
05
06 libc.printf.restype = ctypes.c_int
07 libc.printf.argtypes = [
08     ctypes.c_char_p,
09     ctypes.c_char_p,
10 ]
11
12 libc.printf(b"Hello, %S\n", "World!")
13
14
```

Python ctypes

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Python ctypes

Load Shared Libraries

Python/C

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Python ctypes

Basic C Types

Python/C

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12 libc.printf(b"Hello, %S\n", "World!")
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```

Python ctypes

C-like Function Signatures & Calls

Python/C

```
01
02
03 import ctypes
04
05 class Point(ctypes.Structure):
06     _fields_ = [
07         ("x", c_int),
08         ("y", c_int),
09     ]
10
11 point = Point(10, 20)
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```

Python ctypes

Python/C

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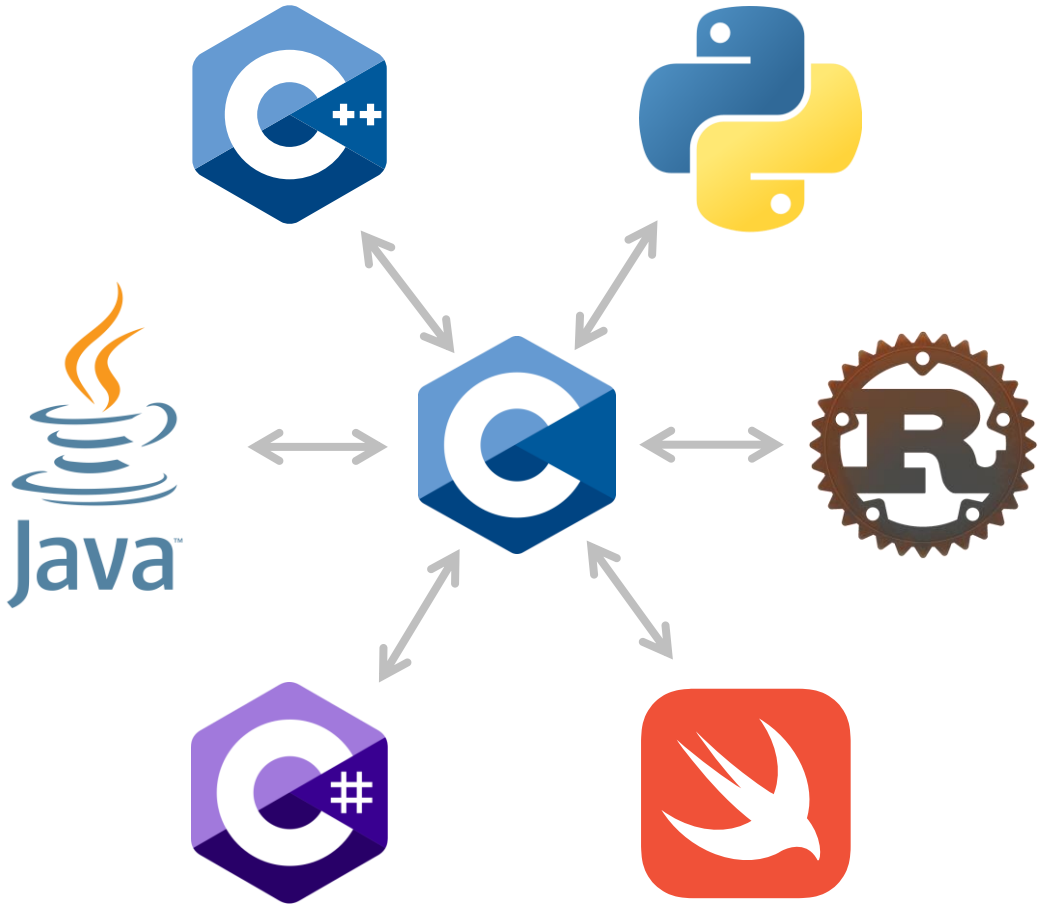
Python ctypes

Most languages have similar APIs

Platform/C ABI

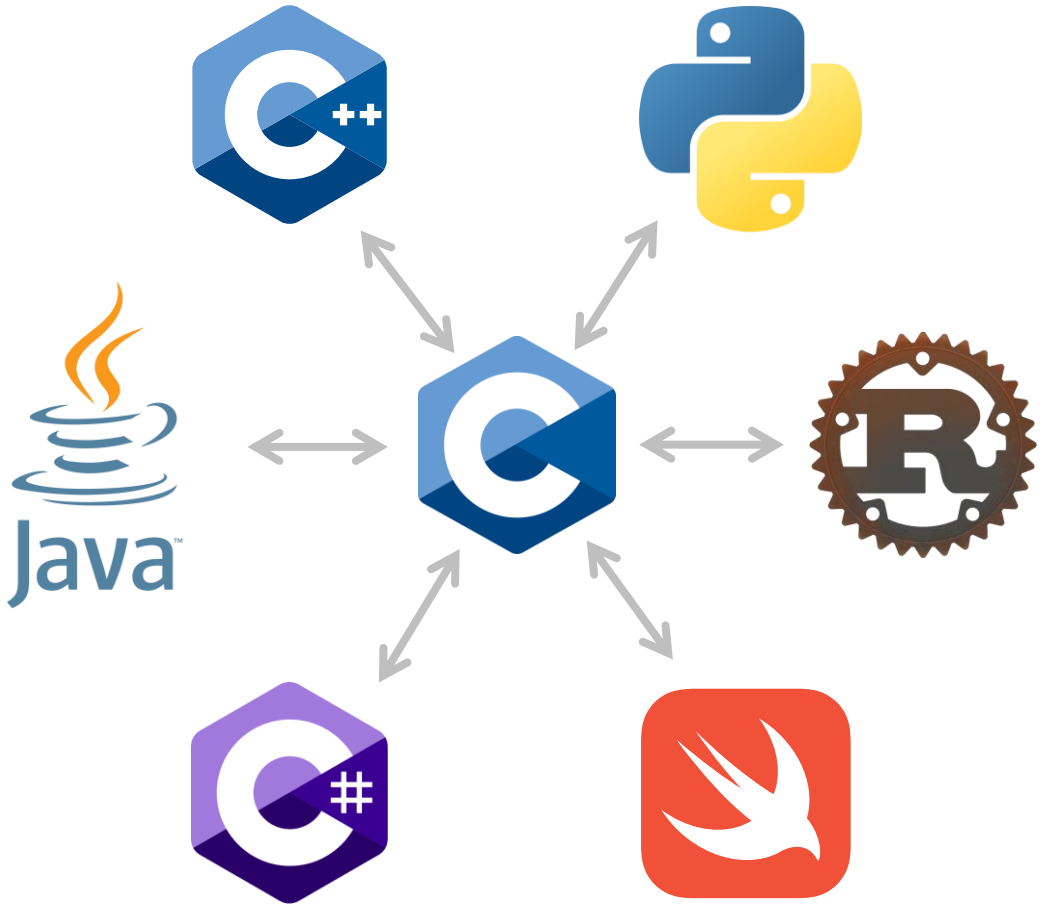
Platform/C ABI



Platform/C ABI

Platform/C ABI

A good foundation for cross-lang. interop.



Platform/C ABI

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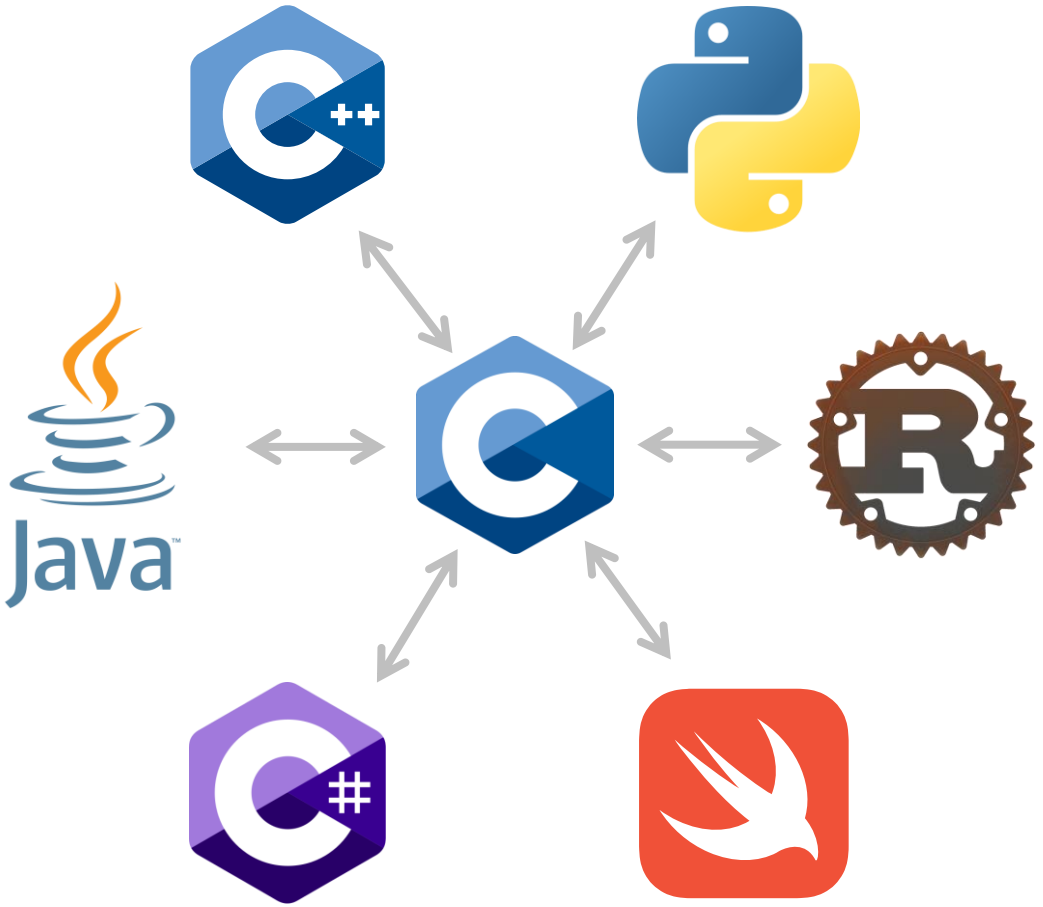
A good foundation for cross-lang. interop.

Calling Convention & Type Layout



Platform/C ABI: Calling Convention

Calling Convention

Calling Convention

Caller & Callee Saved Registers

Platform/C ABI

Calling Convention

Caller & Callee Saved Registers

Passing Parameters & Return Values

Platform/C ABI

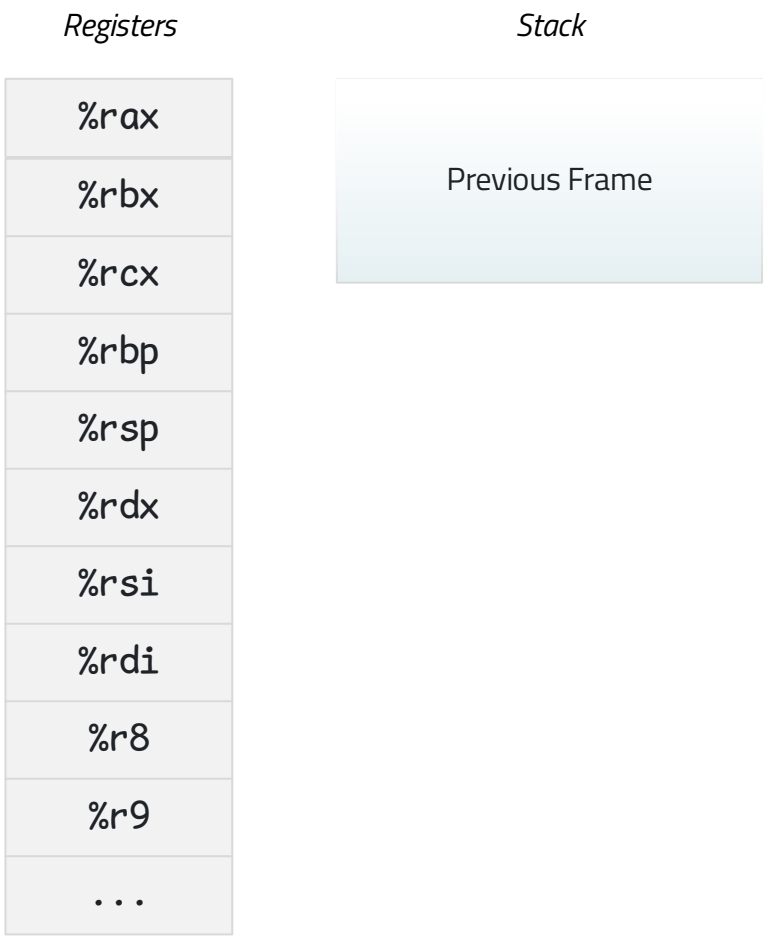
Calling Convention

Caller & Callee Saved Registers

Passing Parameters & Return Values

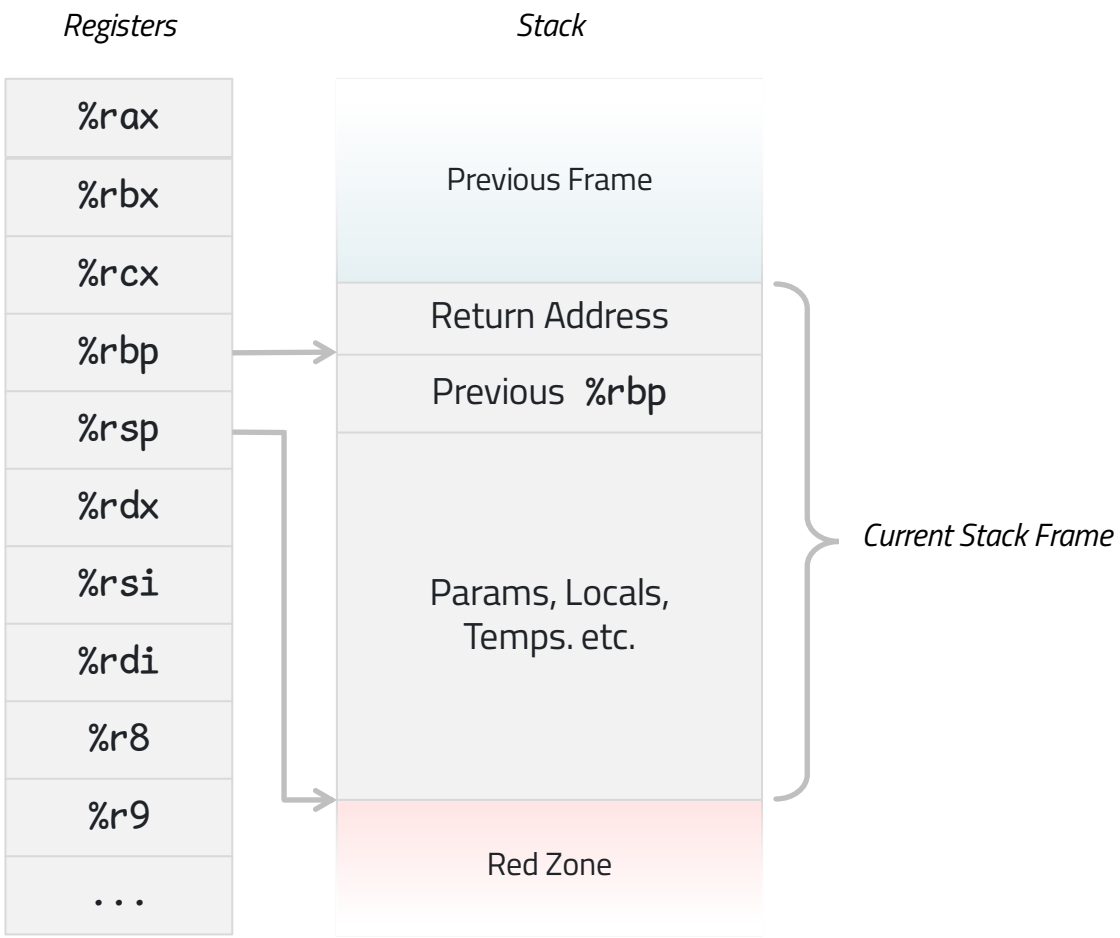
Stack Frame Layout

Platform/C ABI



System V AMD64 ABI

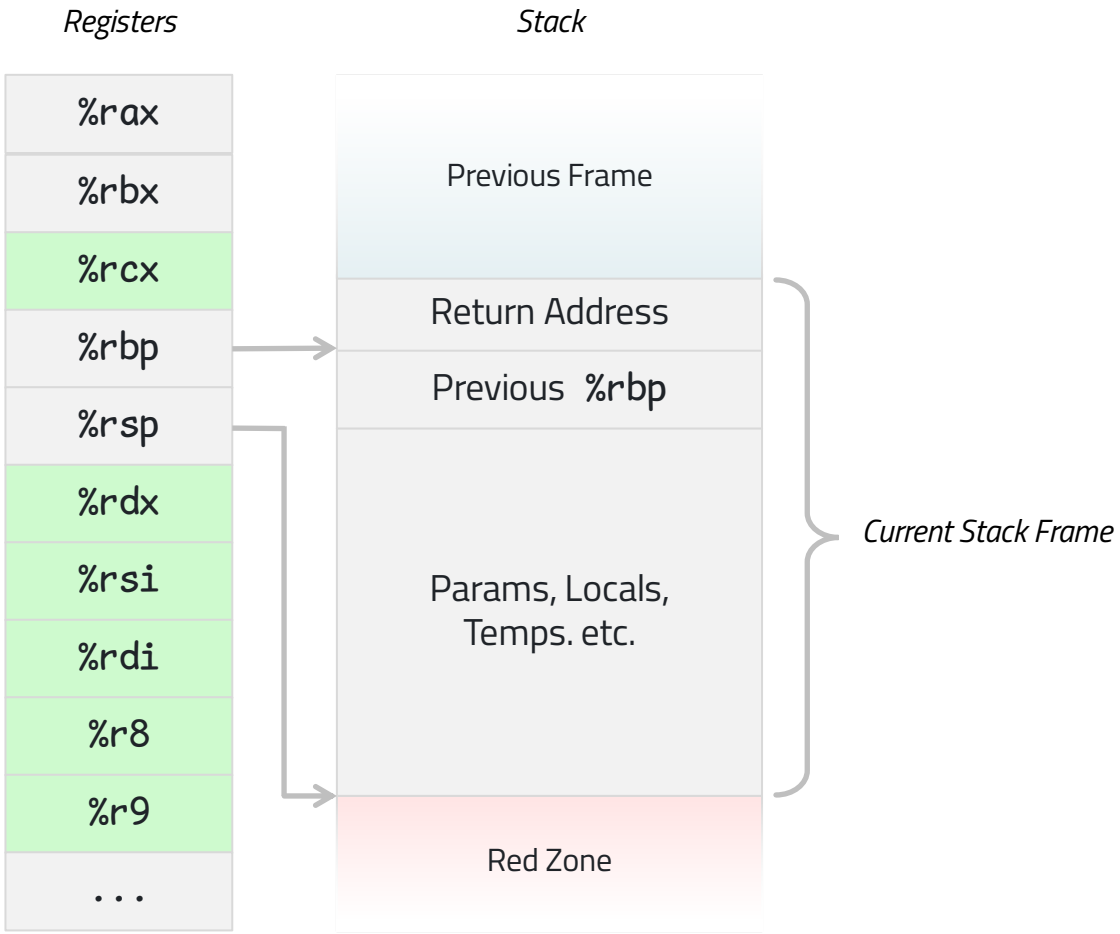
Platform/C ABI



System V AMD64 ABI

Push Return Address & Base-Pointer on Stack

Platform/C ABI

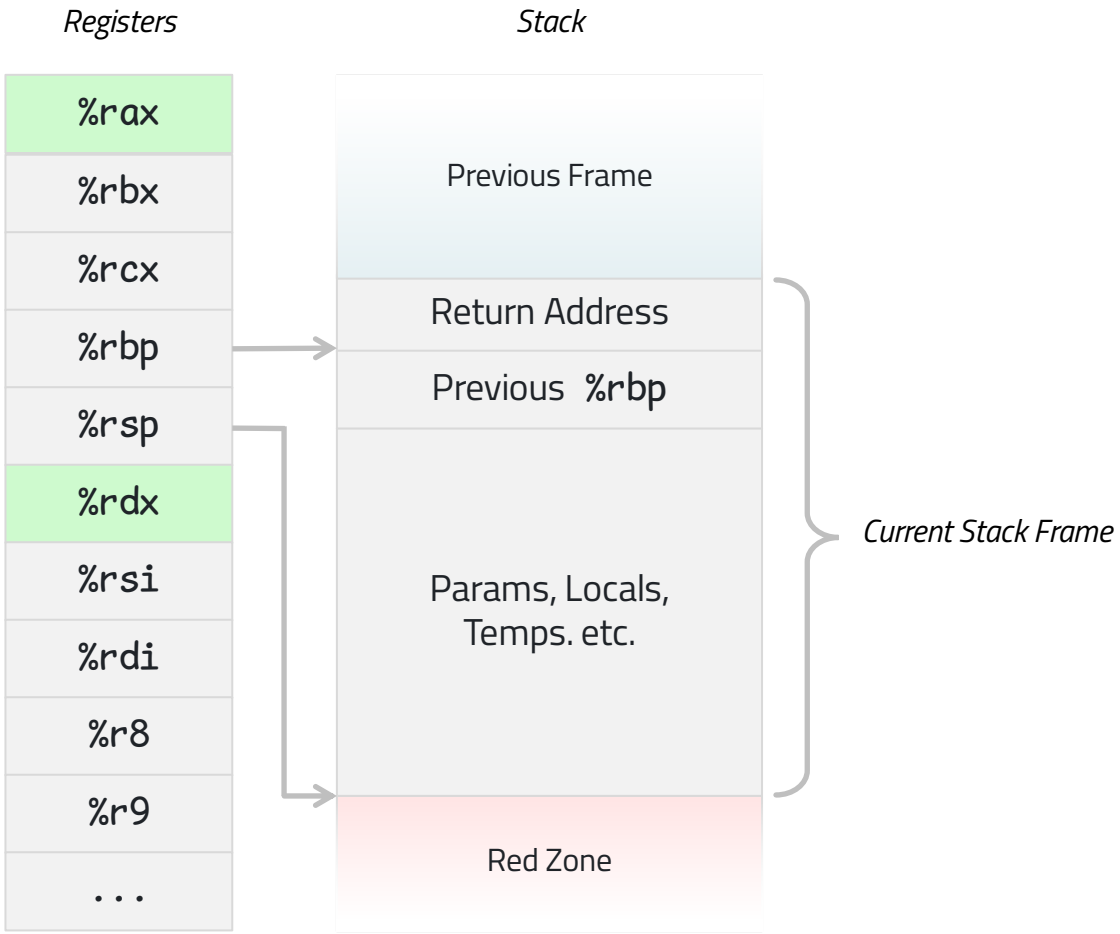


System V AMD64 ABI

Push Return Address & Base-Pointer on Stack

Parameters in `%rdi %rsi %rdx %rcx %r8 %r9*`

Platform/C ABI



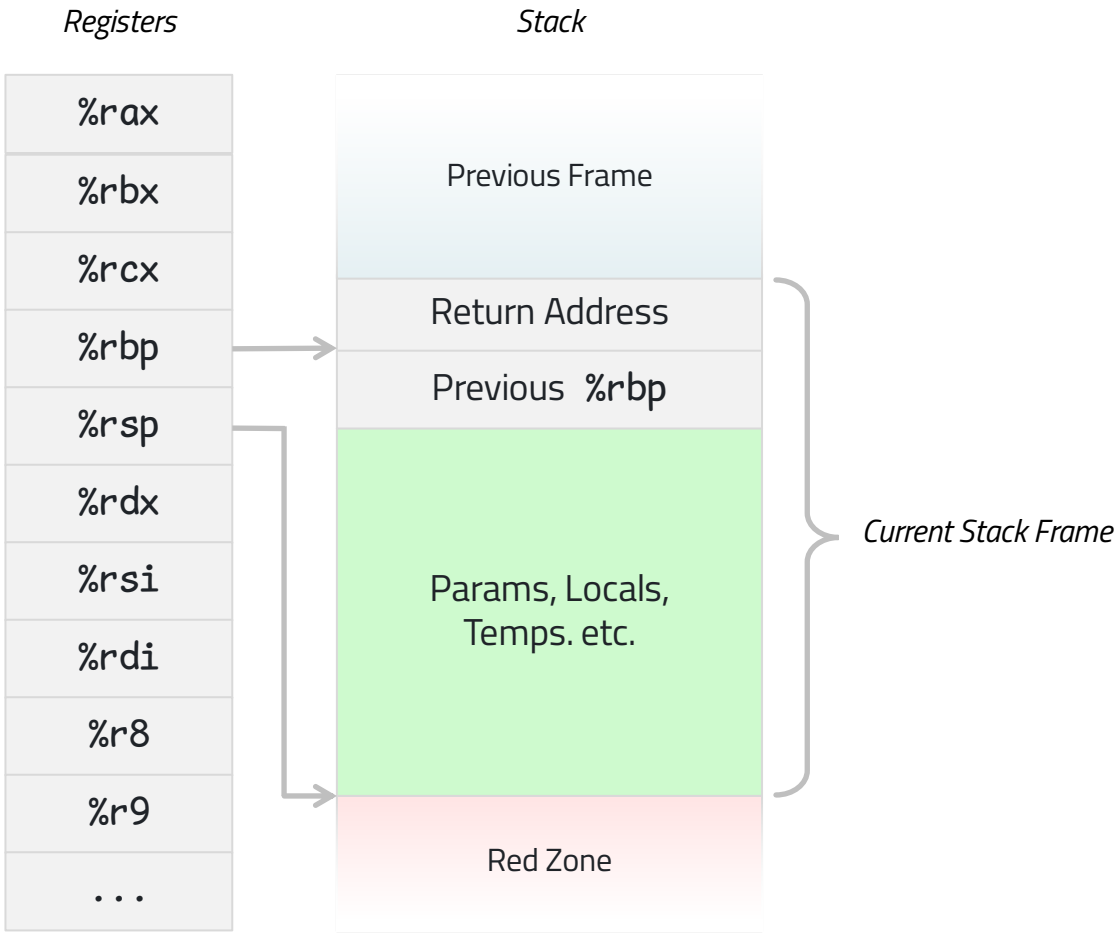
System V AMD64 ABI

Push Return Address & Base-Pointer on Stack

Parameters in `%rdi %rsi %rdx %rcx %r8 %r9`*

Return Values in `%rax %rdx`**

Platform/C ABI



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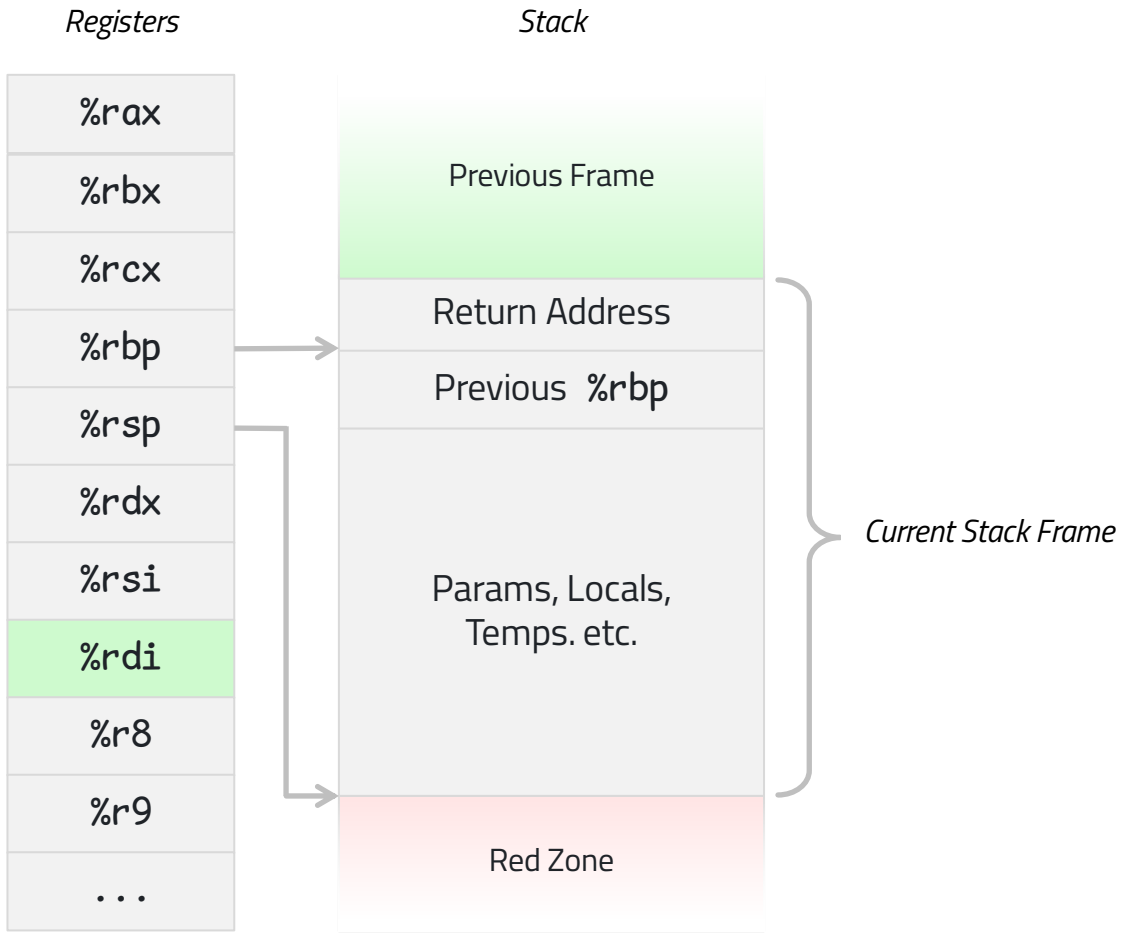
Platform/C ABI



System V AMD64 ABI

Push Return Address & Base-Pointer on Stack

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**Large return values & non-trivial types by ref.

Platform/C ABI

C++ ABI: Non-trivial

Platform/C ABI

C++ ABI: Non-trivial

Non-trivial *for the purposes of calls**

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**This is different from* `std::is_trivial`*,
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Platform/C ABI

C++ ABI: Non-trivial

Non-trivial *for the purposes of calls**

Non-trivial copy-constructor, move-constructor, or destructor

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Platform/C ABI

C++ ABI: Non-trivial

Non-trivial *for the purposes of calls**

Non-trivial copy-constructor, move-constructor, or destructor

Or all copy and move constructors are deleted

**This is different from `std::is_trivial`, which is deprecated in C++26 (P3247).*

Platform/C ABI

```
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03
04
05 #ifndef _MSC_VER
06 #  define __stdcall __attribute__((stdcall))
07 #endif
08
09 extern "C" void __stdcall baz();
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```

C++ ABI: Calling Convention

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No Calling Convention in C++ Standard

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Implementation defined keywords/attributes

`__stdcall`

`__attribute__((stdcall))`

Platform/C ABI

```
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02
03 extern "C" void foo();
04 void foo();
05
06 namespace bar {
07     extern "C" void foo();
08     void foo();
09 }
10
11 extern "C" foo(std::string str);
12 extern "C" bar(int &num);
13
14
```

C++ ABI: Language Linkage

Platform/C ABI

```
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04 void foo();
05
06 namespace bar {
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C++ ABI: Language Linkage

`extern "C"` is a language linkage specification

Platform/C ABI

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C++ ABI: Language Linkage

`extern "C"` is a language linkage specification

Names refer to the same entity

Platform/C ABI

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C++ ABI: Language Linkage

`extern "C"` is a language linkage specification

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No effect on calling convention

C++ language linkage is the default

Calling Convention

Platform/C ABI

Calling Convention

Platforms usually have a default

Platform/C ABI

Calling Convention

Platforms usually have a default

Default is usually denoted *C* or `cdecl`

Platform/C ABI

Calling Convention

Platforms usually have a default

Default is usually denoted *C* or `cdecl`

Windows x86 has `stdcall`, `fastcall`, `thiscall`

Platform/C ABI: Type Layout

Platform/C ABI

Type Layout

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Type Layout

Few guarantees in the C Standard

Platform/C ABI

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A `char` is 1 byte (`CHAR_BIT` bits) with weakest (usually 1) alignment

Platform/C ABI

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`struct` members are laid out in declaration order

Platform/C ABI

Type Layout

Few guarantees in the C Standard

A `char` is 1 byte (`CHAR_BIT` bits) with weakest (usually 1) alignment

`struct` members are laid out in declaration order

`structs` can have padding in the middle or at the end

Platform/C ABI

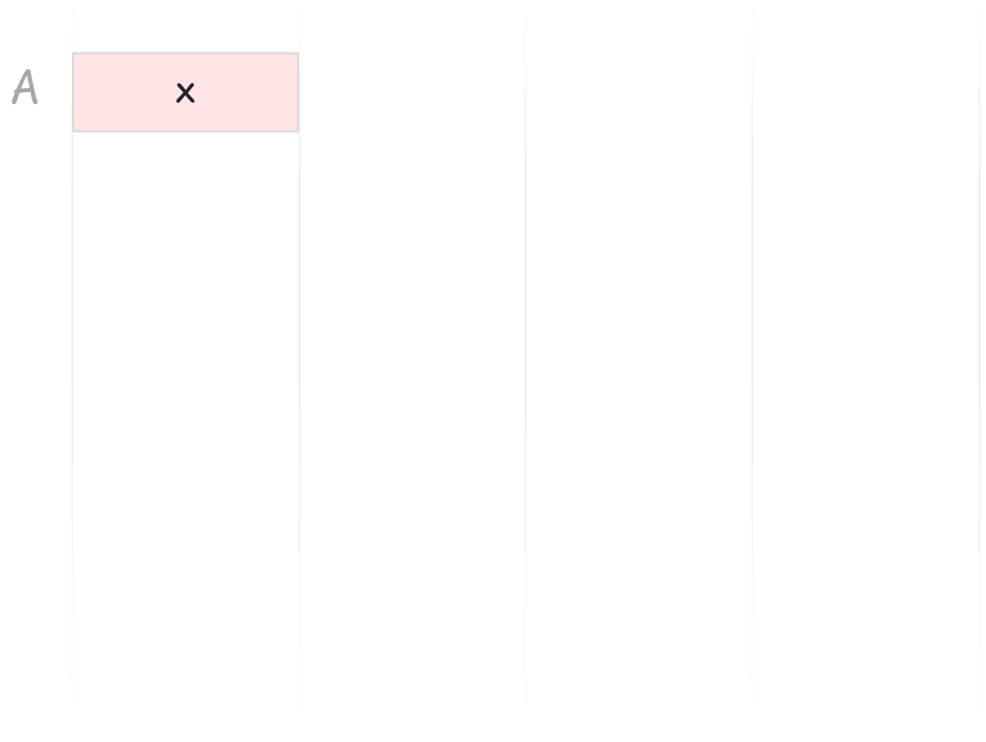
```
01
02
03
04 struct A { char x; };
05
06
07 struct B { char x; int y; };
08
09
10 struct C { char x; int y; char z; };
11
12
13
14
```

Type Layout

Platform/C ABI

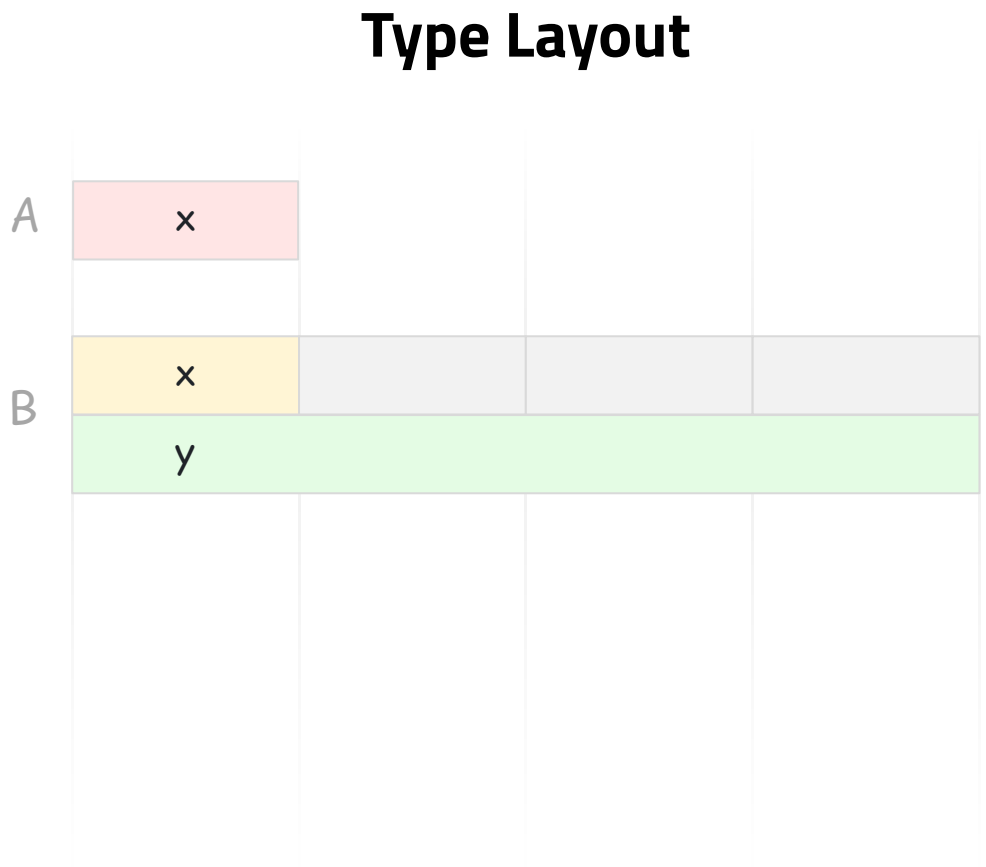
```
01
02
03
04 struct A { char x; };
05
06
07 struct B { char x; int y; };
08
09
10 struct C { char x; int y; char z; };
11
12
13
14
```

Type Layout



Platform/C ABI

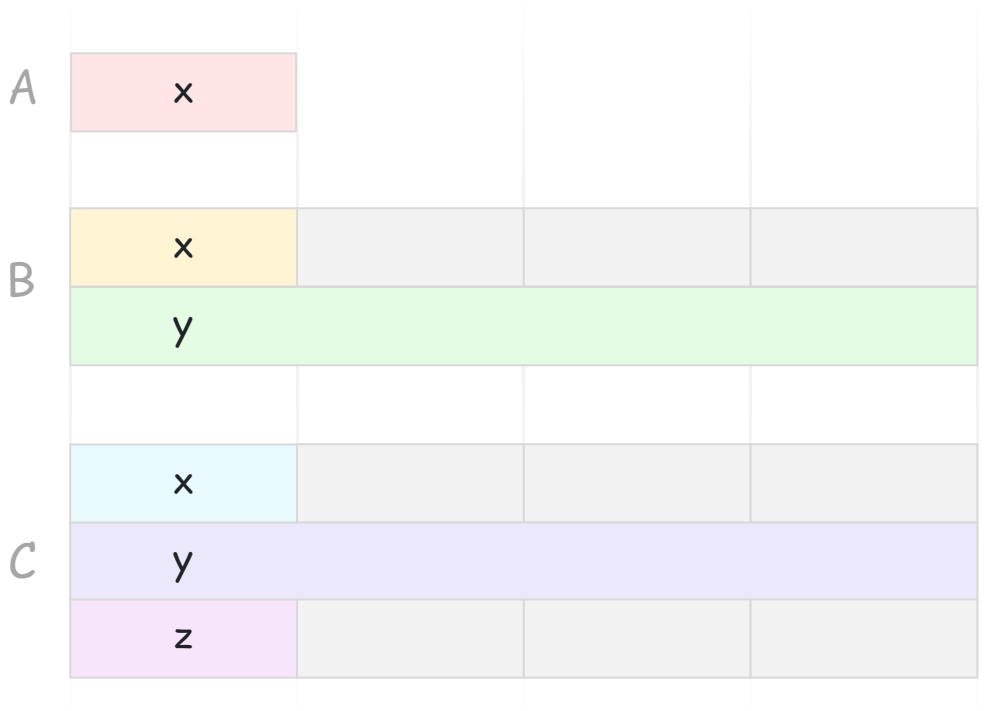
```
01
02
03
04 struct A { char x; };
05
06
07 struct B { char x; int y; };
08
09
10 struct C { char x; int y; char z; };
11
12
13
14
```



Platform/C ABI

```
01
02
03
04 struct A { char x; };
05
06
07 struct B { char x; int y; };
08
09
10 struct C { char x; int y; char z; };
11
12
13
14
```

Type Layout



Platform/C ABI

```
01
02
03
04 struct A { char x; };
05
06
07 struct B { char x; int y; };
08
09
10 struct C { char x; int y; char z; };
11
12
13
14
```

Type Layout

Platform/C ABI

```
01
02
03
04 struct A { char x; };
05 static_assert(sizeof(struct A) == 1);
06
07 struct B { char x; int y; };
08 static_assert(sizeof(struct B) == 8);
09
10 struct C { char x; int y; char z; };
11 static_assert(sizeof(struct C) == 12);
12
13
14
```

Type Layout

Use `static_assert` to guarantee type layout

Platform/C ABI

```
01
02
03
04
05 #include <stddef.h>
06
07 struct B { char x; int y; };
08 static_assert(offsetof(struct B, y) == 4);
09
10
11
12
13
14
```

Type Layout

Use `static_assert` to guarantee type layout

Use `offsetof` for member offsets

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);
```

C++ Standard-Layout Types

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);
```

C++ Standard-Layout Types

Standard-layout classes are useful for communication with code written in other programming languages. – *[class.prop]p6*

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);
```

C++ Standard-Layout Types

Standard-layout classes are useful for communication with code written in other programming languages. – *[class.prop]p6*

All NSDMs are also standard-layout

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);

class B: public A { int m; };
static_assert(std::is_standard_layout_v<B> == false);
```

C++ Standard-Layout Types

Standard-layout classes are useful for communication with code written in other programming languages. – *[class.prop]p6*

All NSDMs are also standard-layout

All NSDMs are in the same base class

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);

class B: public A { int m; };
static_assert(std::is_standard_layout_v<B> == false);

class C { int m; public: int n; };
static_assert(std::is_standard_layout_v<C> == false);
```

C++ Standard-Layout Types

Standard-layout classes are useful for communication with code written in other programming languages. – *[class.prop]p6*

All NSDMs are also standard-layout

All NSDMs are in the same base class

All NSDMs have the same access control*

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);

class B: public A { int m; };
static_assert(std::is_standard_layout_v<B> == false);

class C { int m; public: int n; };
static_assert(std::is_standard_layout_v<C> == false);
```

C++ Standard-Layout Types

Standard-layout classes are useful for communication with code written in other programming languages. – *[class.prop]p6*

All NSDMs are also standard-layout

All NSDMs are in the same base class

All NSDMs have the same access control*

**Re-ordering based on access control is removed in C++23 (P1847), but this requirement remains for standard-layout…*

Platform/C ABI

```cpp
#include <type_traits>

struct A { int m; };
static_assert(std::is_standard_layout_v<A> == true);

class B: public A { int m; };
static_assert(std::is_standard_layout_v<B> == false);

class C { int m; public: int n; };
static_assert(std::is_standard_layout_v<C> == false);

struct D { virtual void foo(); };
static_assert(std::is_standard_layout_v<D> == false);

```

C++ Standard-Layout Types

Standard-layout classes are useful for communication with code written in other programming languages. – [class.prop]p6

All NSDMs are also standard-layout

All NSDMs are in the same base class

All NSDMs have the same access control*

No virtual functions or virtual base classes

**Re-ordering based on access control is removed in C++23 (P1847), but this requirement remains for standard-layout...*

Building Bridges

Building Bridges

Can we do better than a C API?

Building Bridges

Can we do better than a C API?

Need to define APIs in terms of C

Building Bridges

Can we do better than a C API?

Need to define APIs in terms of C

Remove higher-level abstractions

Building Bridges

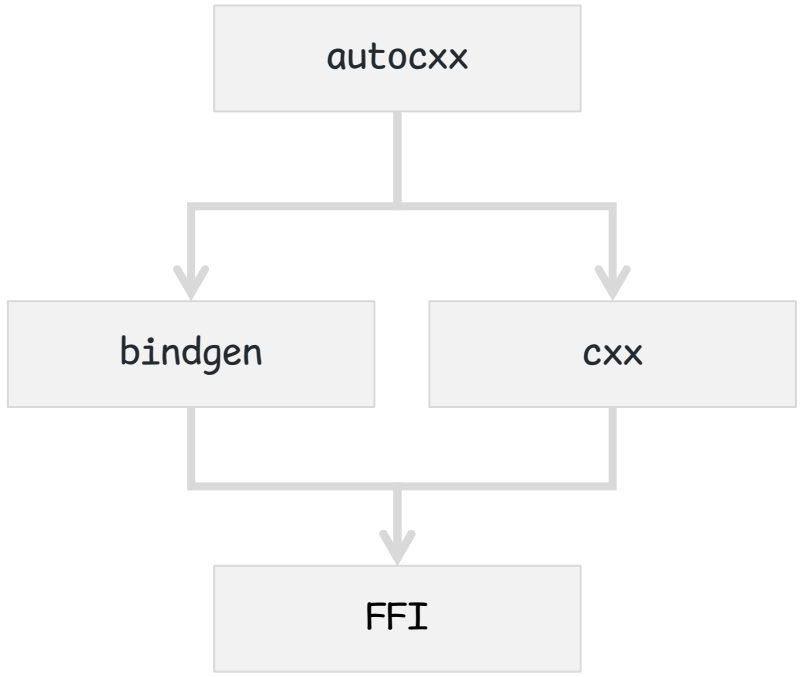
Can we do better than a C API?

Need to define APIs in terms of C

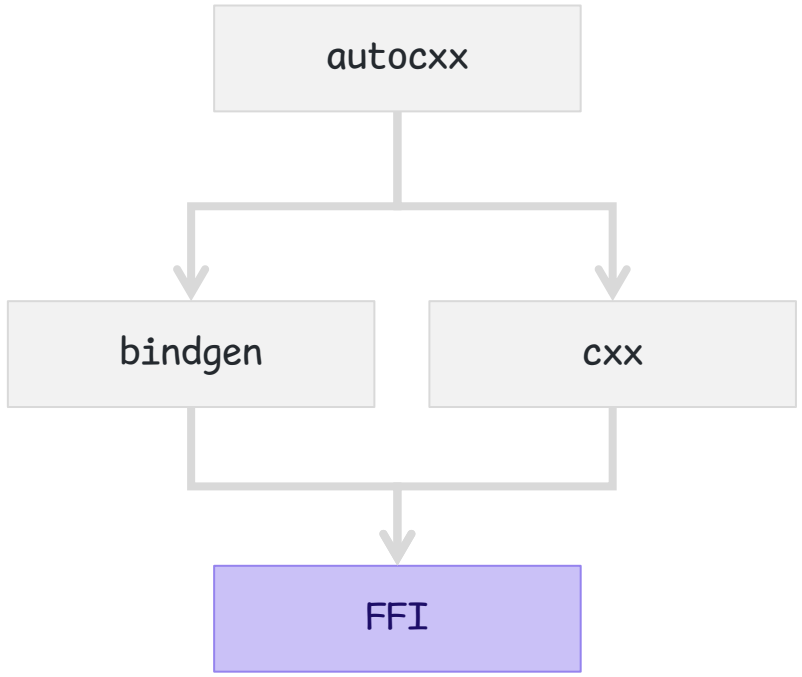
Remove higher-level abstractions

Case Study: Rust/C++

Rust/C++



Rust/C++ Ecosystem



Built-in C-like FFI

Rust/C++

```rust
use std::os::raw::*;

#[repr(C)]
struct Point {
    x: c_int,
    y: c_int,
}

unsafe extern "C" {
    fn dist(first: Point, second: Point) -> c_float;
}
```

Rust FFI

Rust/C++

```rust
use std::os::raw::*;

#[repr(C)]
struct Point {
    x: c_int,
    y: c_int,
}

unsafe extern "C" {
    fn dist(first: Point, second: Point) -> c_float;
}
```

Rust FFI

Basic C types

Rust/C++

```rust
use std::os::raw::*;

#[repr(C)]
struct Point {
    x: c_int,
    y: c_int,
}

unsafe extern "C" {
    fn dist(first: Point, second: Point) -> c_float;
}
```

Rust FFI

Basic C types

C-like structure types

Rust/C++

```
01 use std::os::raw::*;
02
03 #[repr(C)]
04 struct Point {
05     x: c_int,
06     y: c_int,
07 }
08
09 unsafe extern "C" {
10     fn dist(first: Point, second: Point) -> c_float;
11 }
12
13
14
```

Rust FFI

Basic C types

C-like structure types

C-like functions decls.

Rust/C++

```
01 int *foo() {
02     return nullptr;
03 }
```

```
04 unsafe extern "C" {
05     fn foo() -> Option<&i32>;
06 }
07
08 unsafe fn bar() {
09     if let Some(it) = foo() {
10         println!("{it}");
11     }
12 }
13
```

Rust FFI

Rust/C++

```
01 int *foo() {
02     return nullptr;
03 }
```

```
04 unsafe extern "C" {
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11     }
12 }
13
```

Rust FFI

Nullable Pointer Optimization

Rust/C++

```cpp
int *foo() {
    return nullptr;
}
```

```rust
unsafe extern "C" {
    fn foo() -> Option<&i32>;
}

unsafe fn bar() {
    if let Some(it) = foo() {
        println!("{it}");
    }
}

```

Rust FFI

Nullable Pointer Optimization

`Option::None` has same repr. as `nullptr`

Rust/C++

```cpp
int *foo() {
    return nullptr;
}
```

```rust
unsafe extern "C" {
    fn foo() -> Option<&i32>;
}

unsafe fn bar() {
    if let Some(it) = foo() {
        println!("{it}");
    }
}

```

Rust FFI

Nullable Pointer Optimization

`Option::None` has same repr. as `nullptr`

Idiomatic handling in Rust

C++ ABI

```cpp
void foo() try {
    bar();
} catch (const std:: runtime_error& e) {
    std::println("{}", e.what());
}
```

```rust
#[no_mangle]
pub extern "C-unwind" fn bar() {
    let n = Box::new(42);
    unsafe { baz(); }
}
```

```cpp
void baz() {
    throw std::runtime_error("Hello from Rust!");
}
```

Rust FFI: Unwind ABIs

C++ ABI

```
01 void foo() try {
02     bar();
03 } catch (const std:: runtime_error& e) {
04     std::println("{}", e.what());
05 }
```

```
06 #[no_mangle]
07 pub extern "C-unwind" fn bar() {
08     let n = Box::new(42);
09     unsafe { baz(); }
10 }
```

```
11 void baz() {
12     throw std::runtime_error("Hello from Rust!");
13 }
```

Rust FFI

Rust has `"-unwind"` ABIs

C++ ABI

```cpp
void foo() try {
    bar();
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pub extern "C-unwind" fn bar() {
    let n = Box::new(42);
    unsafe { baz(); }
}
```

```cpp
void baz() {
    throw std::runtime_error("Hello from Rust!");
}
```

Rust FFI

Rust has "-unwind" ABIs

C++ exceptions can passthrough Rust

C++ ABI

```
01 void foo() try {
02     bar();
03 } catch (const std:: runtime_error& e) {
04     std::println("{}", e.what());
05 }
```

```
06 #[no_mangle]
07 pub extern "C-unwind" fn bar() {
08     let n = Box::new(42);
09     unsafe { baz(); }
10 }
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```
11 void baz() {
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Rust FFI

Rust has `"-unwind"` ABIs

C++ exceptions can passthrough Rust

Correct cleanup in Rust

C++ ABI

```cpp
01 void foo() try {
02     bar();
03 } catch (const std:: runtime_error& e) {
04     std::println("{}", e.what());
05 }
```

```rust
06 #[no_mangle]
07 pub extern "C-unwind" fn bar() {
08     let n = Box::new(42);
09     unsafe { baz(); }
10 }
```

```cpp
11 void baz() {
12     throw std::runtime_error("Hello from Rust!");
13 }
```

Rust FFI

Rust has `"-unwind"` ABIs

C++ exceptions can passthrough Rust

Correct cleanup in Rust

Cannot catch foreign exceptions

C++ ABI

```cpp
void foo() try {
    bar();
} catch (const std:: runtime_error& e) {
    std::println("{}", e.what());
}
```

```rust
#[no_mangle]
pub extern "C-unwind" fn bar() {
    let n = Box::new(42);
    unsafe { baz(); }
}
```

```cpp
void baz() {
    throw std::runtime_error("Hello from Rust!");
}
```

Exception ABI

C++ ABI

```cpp
void foo() try {
    bar();
} catch (const std:: runtime_error& e) {
    std::println("{}", e.what());
}
```

```rust
#[no_mangle]
pub extern "C-unwind" fn bar() {
    let n = Box::new(42);
    unsafe { baz(); }
}
```

```cpp
void baz() {
    throw std::runtime_error("Hello from Rust!");
}
```

Exception ABI

Unwind Tables

C++ ABI

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void foo() try {
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Exception ABI

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    let n = Box::new(42);
    unsafe { baz(); }
}
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```cpp
void baz() {
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}
```

Exception ABI

Unwind Tables

Base Exception ABI

C++ ABI

```cpp
void foo() try {
    bar();
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```

```rust
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void baz() {
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Exception ABI

Unwind Tables

Base Exception ABI

Unwinds the stack using unwind tables: libunwind

C++ ABI

```cpp
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Exception ABI

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    let n = Box::new(42);
    unsafe { baz(); }
}
```

```cpp
void baz() {
    throw std::runtime_error("Hello from Rust!");
}
```


Exception ABI

Unwind Tables

Base Exception ABI

Unwinds the stack using unwind tables: libunwind

C++ ABI

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    bar();
} catch (const std:: runtime_error& e) {
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```

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    let n = Box::new(42);
    unsafe { baz(); }
}
```

```cpp
void baz() {
    throw std::runtime_error("Hello from Rust!");
}
```


Exception ABI

Unwind Tables

Base Exception ABI

Unwinds the stack using unwind tables: libunwind

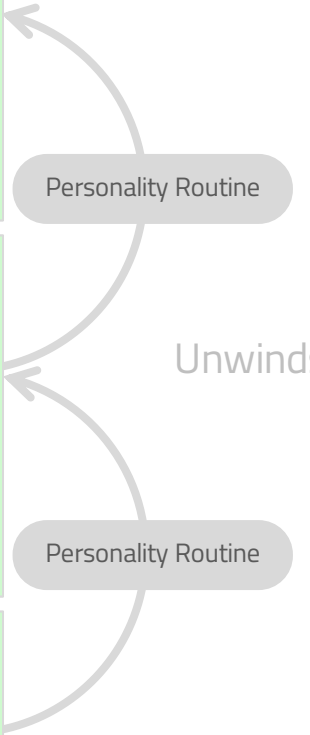
Language Exception ABI

C++ ABI

```
01 void foo() try {
02     bar();
03 } catch (const std:: runtime_error& e) {
04     std::println("{}", e.what());
05 }
```

```
06 #[no_mangle]
07 pub extern "C-unwind" fn bar() {
08     let n = Box::new(42);
09     unsafe { baz(); }
10 }
```

```
11 void baz() {
12     throw std::runtime_error("Hello from Rust!");
13 }
```



Exception ABI

Unwind Tables

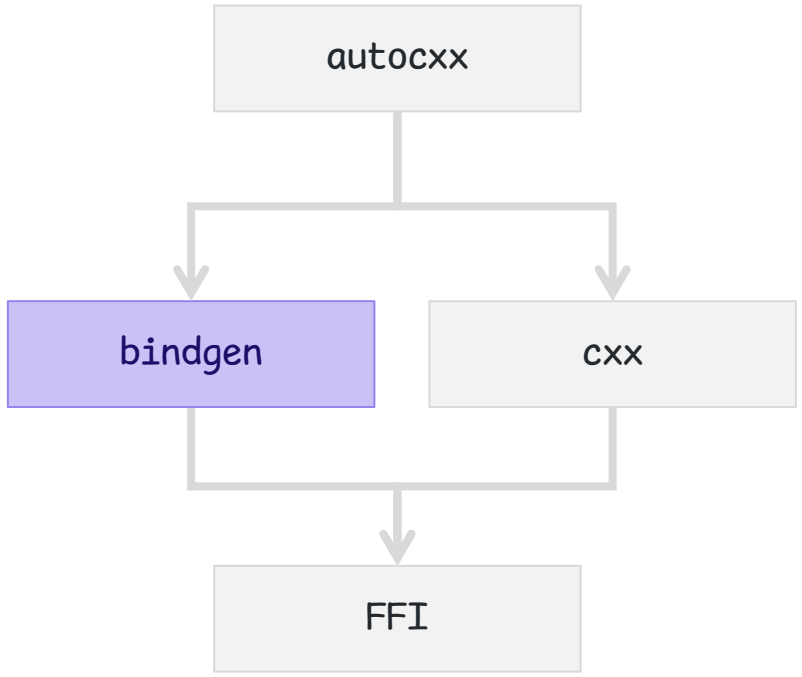
Base Exception ABI

Unwinds the stack using unwind tables: libunwind

Language Exception ABI

Personality routine

Rust/C++: bindgen



Automated binding generator

Rust/C++

```cpp
struct Point {
    int x;
    int y;
};

```

```rust

#[repr(C)]
#[derive(Debug, Copy, Clone)]
pub struct Point {
    pub x: c_int,
    pub y: c_int,
}

```

bindgen

Rust/C++

```
01 struct Point {
02     int x;
03     int y;
04 };
05
```

```
06
07 #[repr(C)]
08 #[derive(Debug, Copy, Clone)]
09 pub struct Point {
10     pub x: c_int,
11     pub y: c_int,
12 }
13
```

bindgen

Built with libclang

Rust/C++

```
01 struct Point {
02     int x;
03     int y;
04 };
05
```

```
06
07 #[repr(C)]
08 #[derive(Debug, Copy, Clone)]
09 pub struct Point {
10     pub x: c_int,
11     pub y: c_int,
12 }
13
```

bindgen

Built with libclang

Auto generates C/C++-Rust bindings

Rust/C++

```
01 struct Point {
02     int x;
03     int y;
04 };
05
```

```
06
07 #[repr(C)]
08 #[derive(Debug, Copy, Clone)]
09 pub struct Point {
10     pub x: c_int,
11     pub y: c_int,
12 }
13
```

bindgen

Built with libclang

Auto generates C/C++-Rust bindings

Command line tool or library for build integration

Rust/C++

```
01 struct Point {
02     int x;
03     int y;
04 };
05
```

```
06
07 #[repr(C)]
08 #[derive(Debug, Copy, Clone)]
09 pub struct Point {
10     pub x: c_int,
11     pub y: c_int,
12 }
13
```

bindgen

Built with libclang

Auto generates C/C++-Rust bindings

Command line tool or library for build integration

```
$ bindgen foo.hpp > out.rs
```

Rust/C++

```
01
02
03 const _: () = {
04     ["Size of Point"]
--         [::std::mem::size_of::<Point>() - 8usize];
05     ["Alignment of Point"]
--         [::std::mem::align_of::<Point>() - 4usize];
06     ["Offset of field: Point::x"]
--         [::std::mem::offset_of!(Point, x) - 0usize];
07     ["Offset of field: Point::y"]
--          [::std::mem::offset_of!(Point, y) - 4usize];
08 };
09
10
```

bindgen

Rust/C++

```
01
02
03 const _: () = {
04     ["Size of Point"]
--         [::std::mem::size_of::<Point>() - 8usize];
05     ["Alignment of Point"]
--         [::std::mem::align_of::<Point>() - 4usize];
06     ["Offset of field: Point::x"]
--         [::std::mem::offset_of!(Point, x) - 0usize];
07     ["Offset of field: Point::y"]
--          [::std::mem::offset_of!(Point, y) - 4usize];
08 };
09
10
```

bindgen

Static assertions for size and offset

Rust/C++

```c
int foo(char x);
int foo(char x, int y);
```

```rust


unsafe extern "C" {
    #[link_name = "_Z3fooc"]
    pub fn foo(x: c_char) -> c_int;

    #[link_name = "_Z3fooci"]
    pub fn foo1(x: c_char, y: c_int) -> c_int;
}


```

bindgen: Function Overloading

Rust/C++

```
01 int foo(char x);
02 int foo(char x, int y);
```

```
03
04
05 unsafe extern "C" {
06     #[link_name = "_Z3fooc"]
07     pub fn foo(x: c_char) -> c_int;
08
09     #[link_name = "_Z3fooci"]
10     pub fn foo1(x: c_char, y: c_int) -> c_int;
11 }
12
13
```

bindgen: Function Overloading

Auto-generates mangled names

Rust/C++

```
01 int foo(char x);
02 int foo(char x, int y);
```

```
03
04
05 unsafe extern "C" {
06     #[link_name = "_Z3fooc"]
07     pub fn foo(x: c_char) -> c_int;
08
09     #[link_name = "_Z3fooci"]
10     pub fn foo1(x: c_char, y: c_int) -> c_int;
11 }
12
13
```

bindgen: Function Overloading

Note `foo1`: No overloading in Rust

Rust/C++

```cpp
template<typename T>
struct S {
    T value;
};
void foo(S<int> s);
```

```rust
#[repr(C)]
pub struct S<T> {
    pub value: T,
}
unsafe extern "C" {
   #[link_name = "_Z3foo1SIiE"]
    pub fn foo(s: S<c_int>);
}
```

bindgen: Templates

Rust/C++

```
01 template<typename T>
02 struct S {
03     T value;
04 };
05 void foo(S<int> s);
```

```
06 #[repr(C)]
07 pub struct S<T> {
08     pub value: T,
09 }
10 unsafe extern "C" {
11    #[link_name = "_Z3foo1SIiE"]
12     pub fn foo(s: S<c_int>);
13 }
```

bindgen: Templates

Simple Templates use Rust Generics

Rust/C++

```
01 template<typename T>
02 struct S {
03     T value;
04 };
05 void foo(S<int> s);
```

```
06 #[repr(C)]
07 pub struct S<T> {
08     pub value: T,
09 }
10 unsafe extern "C" {
11     #[link_name = "_Z3foo1SIiE"]
12     pub fn foo(s: S<c_int>);
13 }
```

bindgen: Templates

Simple Templates use Rust Generics

Correct Usage as Parameter

Rust/C++

```
01 template<typename T>
02 struct S {
03     T value;
04 };
05 void foo(S<int> s);
```

```
06 #[repr(C)]
07 pub struct S<T> {
08     pub value: T,
09 }
10 unsafe extern "C" {
11    #[link_name = "_Z3foo1SIiE"]
12     pub fn foo(s: S<c_int>);
13 }
```

bindgen: Templates

Simple Templates use Rust Generics

Rust/C++

```
01 template<typename T>
02 struct S {
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04 };
05 void foo(S<int> s);
```

```
06 #[repr(C)]
07 pub struct S<T> {
08     pub value: T,
09 }
10 unsafe extern "C" {
11    #[link_name = "_Z3foo1SIiE"]
12     pub fn foo(s: S<c_int>);
13 }
```

bindgen: Templates

Simple Templates use Rust Generics

No method generation

Rust/C++

```
01 template<typename T>
02 struct S {
03     T value;
04 };
05 void foo(S<int> s);
```

```
06 #[repr(C)]
07 pub struct S<T> {
08     pub value: T,
09 }
10 unsafe extern "C" {
11    #[link_name = "_Z3foo1SIiE"]
12     pub fn foo(s: S<c_int>);
13 }
```

bindgen: Templates

Simple Templates use Rust Generics

No method generation

No static assertions generated

C++ ABI

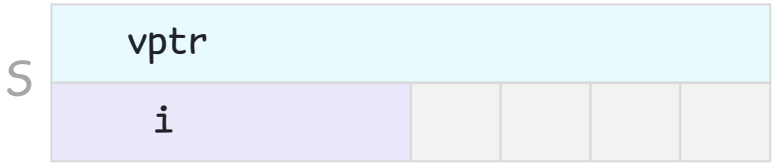
Polymorphic Types

```
01 struct S {
02     int i;
03     virtual void foo();
04 };
05
06 static_assert(sizeof(S) == 16);
```

C++ ABI

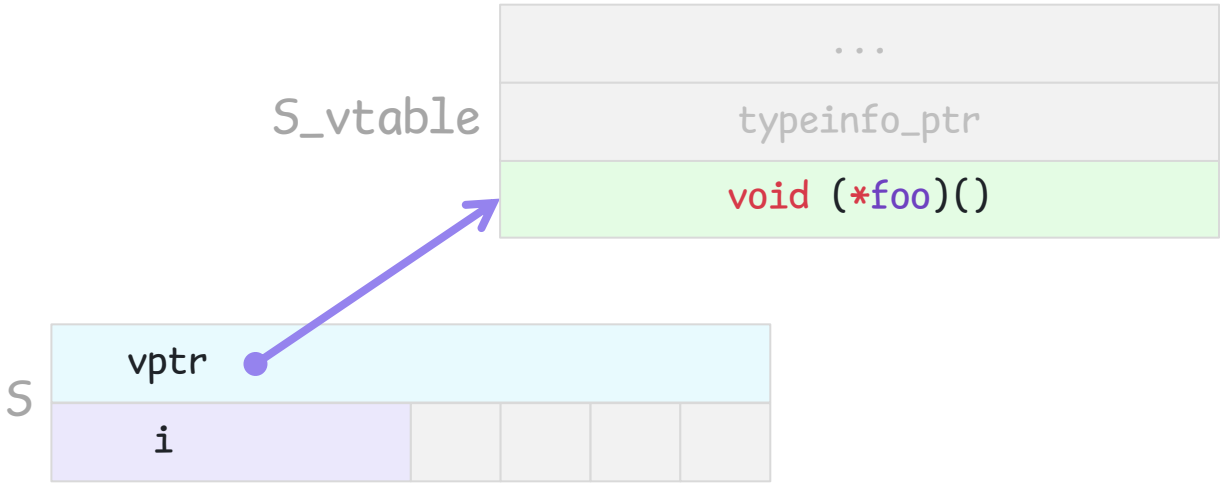
Polymorphic Types

Vptr inserted into layout




```
01 struct S {
02     int i;
03     virtual void foo();
04 };
05
06 static_assert(sizeof(S) == 16);
```

C++ ABI



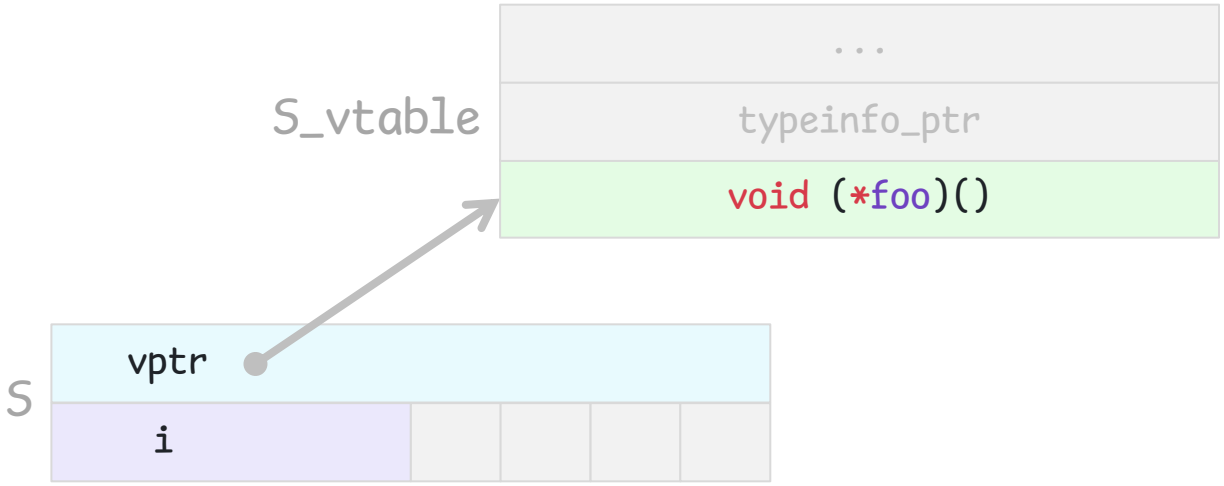
Polymorphic Types

vptr inserted into layout

vtable contains method overrides, RTTI, & more

```
01 struct S {
02     int i;
03     virtual void foo();
04 };
05
06 static_assert(sizeof(S) == 16);
```

C++ ABI




```
01 struct S {
02     int i;
03     virtual void foo();
04 };
05
06 static_assert(sizeof(S) == 16);
```

Polymorphic Types

vptr inserted into layout

vtable contains method overrides, RTTI, & more

vtable layout & behavior is complicated

Rust/C++

```
01
02
03 struct Base {
04     int i;
05     virtual void foo();
06 };
07
08 struct Derived : Base {
09     int j;
10     void foo() override;
11 };
12
13
14
```

bindgen: Polymorphic Types

Rust/C++

```
01 #[repr(C)]
02 pub struct Base__bindgen_vtable(c_void);
03
04 #[repr(C)]
05 pub struct Base {
06     pub vtable_: *const Base__bindgen_vtable,
07     pub i: c_int,
08 }
09
10 #[repr(C)]
11 pub struct Derived {
12     pub _base: Base,
13     pub j: c_int,
14 }
```

bindgen: Polymorphic Types

Rust/C++

```rust
#[repr(C)]
pub struct Base__bindgen_vtable(c_void);

#[repr(C)]
pub struct Base {
    pub vtable_: *const Base__bindgen_vtable,
    pub i: c_int,
}

#[repr(C)]
pub struct Derived {
    pub _base: Base,
    pub j: c_int,
}
```

bindgen: Polymorphic Types

Base has a vptr

Rust/C++

```
01
02
03
04 unsafe extern "C" {
05     #[link_name = "_ZN4Base3fooEv"]
06     pub fn Base_foo(this: *mut c_void);
07
08     #[link_name = "_ZN7Derived3fooEv"]
09     pub fn Derived_foo(this: *mut c_void);
10 }
11
12
13
14
```

bindgen: Polymorphic Types

Rust/C++

```
01
02
03
04 unsafe extern "C" {
05     #[link_name = "_ZN4Base3fooEv"]
06     pub fn Base_foo(this: *mut c_void);
07
08     #[link_name = "_ZN7Derived3fooEv"]
09     pub fn Derived_foo(this: *mut c_void);
10 }
11
12
13
14
```

bindgen: Polymorphic Types

Pure FFI functions; no methods

```
01
02
03
04 unsafe extern "C" {
05     #[link_name = "_ZN4Base3fooEv"]
06     pub fn Base_foo(this: *mut c_void);
07
08     #[link_name = "_ZN7Derived3fooEv"]
09     pub fn Derived_foo(this: *mut c_void);
10 }
11
12
13
14
```

bindgen: Polymorphic Types

Raw void pointers

Rust/C++

```
01
02
03
04
05 fn main() {
06     let mut d = get_derived();
07     unsafe {
08         Derived_foo(&mut d as *mut _ as *mut c_void);
09     }
10 }
11
12
13
14
```

bindgen: Polymorphic Types

Rust/C++

```
01
02
03
04
05 fn main() {
06     let mut d = get_derived();
07     unsafe {
08         Derived_foo(&mut d as *mut _ as *mut c_void);
09     }
10 }
11
12
13
14
```

bindgen: Polymorphic Types

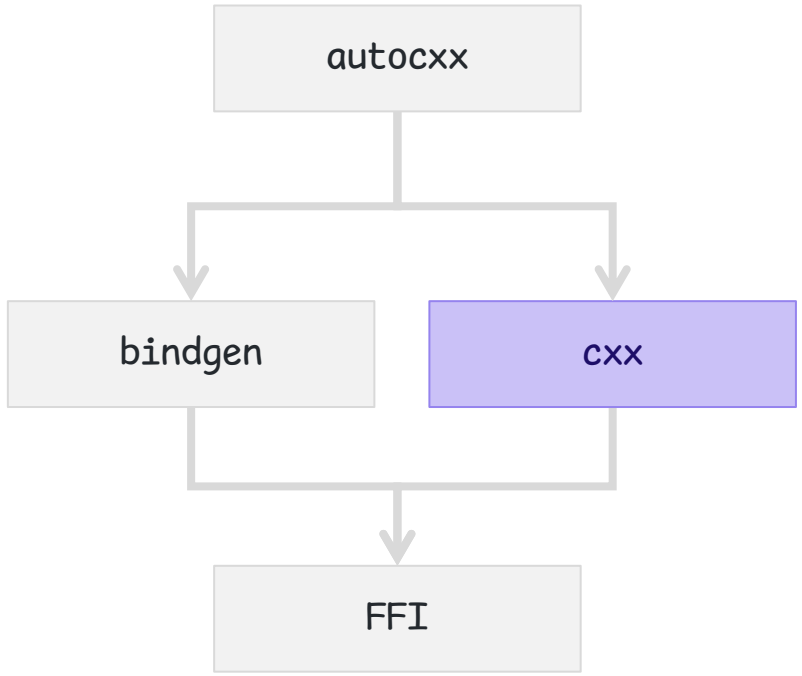
Unsafe… and a bit messy 🙈

```
01
02
03
04
05 fn main() {
06     let mut d = get_derived();
07     unsafe {
08         Derived_foo(&mut d as *mut _ as *mut c_void);
09     }
10 }
11
12
13
14
```

bindgen: Polymorphic Types

bindgen only tries to get the layout correct

Rust/C++: cxx



Automated bindings + bridged types

Rust/C++

cxx

cxx

Bindings for types like `std::string` and `std::vector`

cxx

Bindings for types like `std::string` and `std::vector`

Special consideration given to ownership

Rust/C++

cxx

Bindings for types like `std::string` and `std::vector`

Special consideration given to ownership

Patterns for error handling

Rust/C++

```
01
02
03
04 #[cxx::bridge]
05 mod ffi {
06     unsafe extern "C++" {
07         include!("foo.hpp");
08         type Foo;
09         fn new_foo() -> UniquePtr<Foo>;
10     }
11 }
12
13
14
```

cxx

Rust/C++

```
01
02
03
04 #[cxx::bridge]
05 mod ffi {
06     unsafe extern "C++" {
07         include!("foo.hpp");
08         type Foo;
09         fn new_foo() -> UniquePtr<Foo>;
10     }
11 }
12
13
14
```

cxx

Include C/C++ files

Rust/C++

```
01
02
03
04 #[cxx::bridge]
05 mod ffi {
06     unsafe extern "C++" {
07         include!("foo.hpp");
08         type Foo;
09         fn new_foo() -> UniquePtr<Foo>;
10     }
11 }
12
13
14
```

cxx

Declare types & functions

Rust/C++

```rust

fn foo(s: String) {}

fn main() {
    let s = "Hello, Meeting C++".to_string();
    foo(s); // Move
    foo(s); // Error: use of moved value: `s`
}


```

Move Semantics

Rust/C++

```
01
02
03
04 fn foo(s: String) {}
05
06 fn main() {
07     let s = "Hello, Meeting C++".to_string();
08     foo(s); // Move
09     foo(s); // Error: use of moved value: `s`
10 }
11
12
13
14
```

Move Semantics

Rust has destructive moves

Rust/C++

```rust

fn foo(s: String) {}

fn main() {
    let s = "Hello, Meeting C++".to_string();
    foo(s); // Move
    foo(s); // Error: use of moved value: `s`
}


```

Move Semantics

No destructor call for **s**

Rust/C++

```
01
02
03
04 void foo(std::string s) {}
05
06 int main() {
07     auto s = std::string("Hello, Meeting C++");
08     foo(std::move(s)); // Move
09     foo(s);            // Ok
10 } // `s.~S()`
11
12
13
14
```

Move Semantics

Rust/C++

```
01
02
03
04 void foo(std::string s) {}
05
06 int main() {
07     auto s = std::string("Hello, Meeting C++");
08     foo(std::move(s)); // Move
09     foo(s);            // Ok
10 } // `s.~S()`
11
12
13
14
```

Move Semantics

C++ leaves s in a valid state

Rust/C++

```
01
02
03
04 void foo(std::string s) {}
05
06 int main() {
07     auto s = std::string("Hello, Meeting C++");
08     foo(std::move(s)); // Move
09     foo(s);            // Ok
10 } // `s.~S()`
11
12
13
14
```

Move Semantics

Destructor is still run

cxx: Types

cxx: Types

Shared

cxx: Types

Shared **Opaque**

cxx: Types

Shared **Opaque** **Extern**

cxx: Types

Shared	Opaque	Extern
Visible to both languages		
Passed by value		
Trivial types		

Rust/C++

cxx: Types

Shared	Opaque	Extern
Visible to both languages	Visible to one language	
Passed by value	Handled behind indirection	
Trivial types	Non-trivial types	

cxx: Types

Shared	Opaque	Extern
Visible to both languages	Visible to one language	Defined outside of cxx
Passed by value	Handled behind indirection	Opaque or Trivial
Trivial types	Non-trivial types	

cxx: Types

Shared	Opaque	Extern
Visible to both languages	Visible to one language	Defined outside of cxx
Passed by value	**Handled behind indirection**	Opaque or Trivial
Trivial types	Non-trivial types	

Rust/C++

```
01 struct S {
02     ~S();
03 };
04 std::unique_ptr<S> make();
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn make() -> UniquePtr<S>;
11     }
12 }
13
```

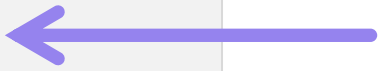
cxx: Opaque C++ Types

Rust/C++

```
01 struct S {
02     ~S();
03 };
04 std::unique_ptr<S> make();
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn make() -> UniquePtr<S>;
11     }
12 }
13
```

cxx: Opaque C++ Types



Handled behind an indirection

Rust/C++

```
01 struct S {
02     ~S();
03     int foo() const;
04 };
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn foo(self: &S);
11     }
12 }
13
```

cxx: Opaque C++ Types

Declare methods as expected, but…

Rust/C++

```
01 struct S {
02     ~S();
03     void bar();
04 };
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn bar(self: Pin<&mut S>);
11     }
12 }
13
```

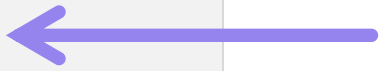
cxx: Opaque C++ Types

Rust/C++

```
01 struct S {
02     ~S();
03     void bar();
04 };
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn bar(self: Pin<&mut S>);
11     }
12 }
13
```

cxx: Opaque C++ Types



Non-const methods require `Pin`

Rust/C++

```
01 struct S {
02     ~S();
03     void bar();
04 };
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn bar(self: Pin<&mut S>);
11     }
12 }
13
```

cxx: Opaque C++ Types

`&mut T` can be used to swap memory

Rust/C++

```
01 struct S {
02     ~S();
03     void bar();
04 };
```

```
05 #[cxx::bridge]
06 mod ffi {
07     unsafe extern "C++" {
08         include!("foo.hpp");
09         type S;
10         fn bar(self: Pin<&mut S>);
11     }
12 }
13
```

cxx: Opaque C++ Types

`&mut T` can be used to swap memory

```
01 use std::mem::{swap, take, replace};
```

```
01 pub const fn swap<T>(x: &mut T, y: &mut T);
```

cxx: Types

Shared	Opaque	Extern
Visible to both languages	Visible to one language	Defined outside of cxx
Passed by value	Handled behind indirection	**Opaque or Trivial**
Trivial types	Non-trivial types	

Rust/C++

```
struct S {
    ~S();
};
```

```
struct S(i32);
unsafe impl ExternType for S {
    type Id = cxx::type_id!("S");
    type Kind = cxx::kind::Trivial;
}
#[cxx::bridge]
mod ffi {
    unsafe extern "C++" {
        include!("foo.hpp");
        type S = super::S;
    }
}
```

cxx: Trivial Extern C++ Types

Rust/C++

```
01 struct S {
02     ~S();
03 };
```

```
04 struct S(i32);
05 unsafe impl ExternType for S {
06     type Id = cxx::type_id!("S");
07     type Kind = cxx::kind::Trivial;
08 }
09 #[cxx::bridge]
10 mod ffi {
11     unsafe extern "C++" {
12         include!("foo.hpp");
13         type S = super::S;
14     }
15 }
```

cxx: Trivial Extern C++ Types

Existing (bindgen or hand-written) bindings

Rust/C++

```
01 struct S {
02     ~S();
03 };
```

```
04 struct S(i32);
05 unsafe impl ExternType for S {
06     type Id = cxx::type_id!("S");
07     type Kind = cxx::kind::Trivial;
08 }
09 #[cxx::bridge]
10 mod ffi {
11     unsafe extern "C++" {
12         include!("foo.hpp");
13         type S = super::S;
14     }
15 }
```

cxx: Trivial Extern C++ Types

Existing (bindgen or hand-written) bindings

`Trivial` = subject to Rust move semantics*

Rust/C++

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01 struct S {
02     ~S();
03 };
```

```
04 struct S(i32);
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09 #[cxx::bridge]
10 mod ffi {
11     unsafe extern "C++" {
12         include!("foo.hpp");
13         type S = super::S;
14     }
15 }
```

cxx: Trivial Extern C++ Types

Existing (bindgen or hand-written) bindings

`Trivial` = subject to Rust move semantics*

*C++26 introduces `std::is_trivially_relocatable` (P2786)

Rust/C++

```rust
fn foo() -> Result<(), String> {
    Err("Rust Error".to_string())
}

#[cxx::bridge]
mod ffi {
    extern "Rust" {
        fn foo() -> Result<()>;
    }
    unsafe extern "C++" {
        fn bar() -> Result<()>;
    }
}

```

cxx: Error Handling

Rust/C++

```rust
fn foo() -> Result<(), String> {
    Err("Rust Error".to_string())
}

#[cxx::bridge]
mod ffi {
    extern "Rust" {
        fn foo() -> Result<()>;
    }
    unsafe extern "C++" {
        fn bar() -> Result<()>;
    }
}

```

cxx: Error Handling

C++ exceptions to Rust `Result<T, E>`

Rust/C++

```rust
fn foo() -> Result<(), String> {
    Err("Rust Error".to_string())
}

#[cxx::bridge]
mod ffi {
    extern "Rust" {
        fn foo() -> Result<()>;
    }
    unsafe extern "C++" {
        fn bar() -> Result<()>;
    }
}

```

cxx: Error Handling

C++ exceptions to Rust `Result<T, E>`

Converted at the boundary

Rust/C++

```
01 namespace rust {
02 namespace behavior {
03
04 template <typename Try, typename Fail>
05 static void trycatch(Try &&func, Fail &&fail) noexcept
06 try {
07     func();
08 } catch (const std::exception &e) {
09     fail(e.what());
10 }
11
12 } // namespace behavior
13 } // namespace rust
14
```

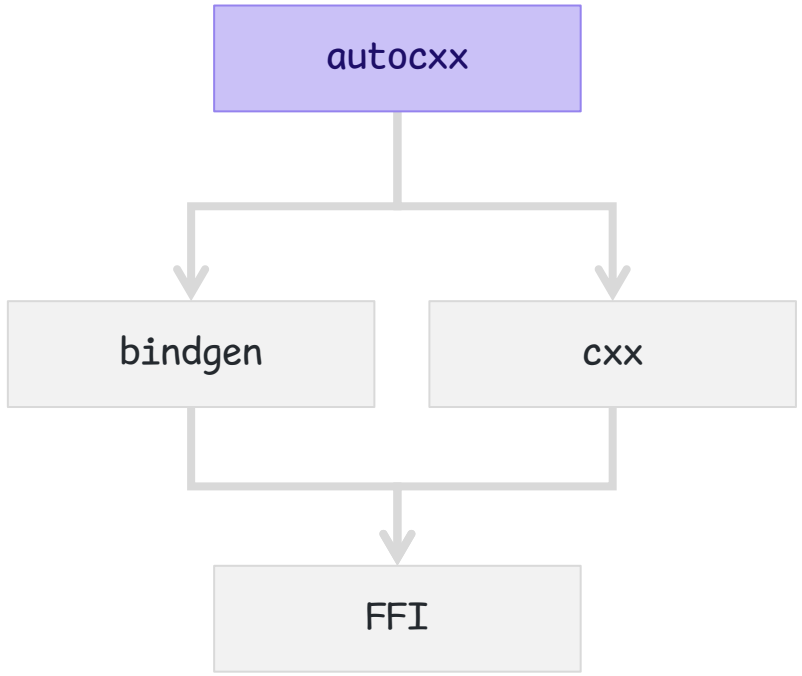
cxx: Error Handling

C++ exceptions to Rust `Result<T, E>`

Converted at the boundary

Custom conversion function

Rust/C++: autocxx



Glues bindgen and cxx together

Rust/C++

```rust
include_cpp! {
    #include "foo.hpp"
    safety!(unsafe)
    generate!("Foo")
    generate!("Bar")
}
fn main() {
    let foo = ffi::Foo::new(10.into());
    println!("{}", foo.val);

    let mut bar = ffi::Bar::new(20.into())
        .within_unique_ptr();
    println!("{}", bar.pin_mut().val());
}
```

autocxx

Rust/C++

```
01 include_cpp! {
02     #include "foo.hpp"
03     safety!(unsafe)
04     generate!("Foo")
05     generate!("Bar")
06 }
07 fn main() {
08     let foo = ffi::Foo::new(10.into());
09     println!("{}", foo.val);
10
11     let mut bar = ffi::Bar::new(20.into())
12         .within_unique_ptr();
13     println!("{}", bar.pin_mut().val());
14 }
```

autocxx

Glues bindgen and cxx together

Rust/C++

```
01 include_cpp! {
02     #include "foo.hpp"
03     safety!(unsafe)
04     generate!("Foo")
05     generate!("Bar")
06 }
07 fn main() {
08     let foo = ffi::Foo::new(10.into());
09     println!("{}", foo.val);
10
11     let mut bar = ffi::Bar::new(20.into())
12         .within_unique_ptr();
13     println!("{}", bar.pin_mut().val());
14 }
```

autocxx

Glues bindgen and cxx together

Provides a fluent bridge

Rust/C++

```
01 include_cpp! {
02     #include "foo.hpp"
03     safety!(unsafe)
04     generate!("Foo")
05     generate!("Bar")
06 }
07 fn main() {
08     let foo = ffi::Foo::new(10.into());
09     println!("{}", foo.val);
10
11     let mut bar = ffi::Bar::new(20.into())
12         .within_unique_ptr();
13     println!("{}", bar.pin_mut().val());
14 }
```

autocxx

Glues bindgen and cxx together

Provides a fluent bridge

Trivial types are simple values

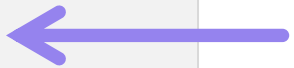
Rust/C++

```
01 include_cpp! {
02     #include "foo.hpp"
03     safety!(unsafe)
04     generate!("Foo")
05     generate!("Bar")
06 }
07 fn main() {
08     let foo = ffi::Foo::new(10.into());
09     println!("{}", foo.val);
10
11     let mut bar = ffi::Bar::new(20.into())
12         .within_unique_ptr();
13     println!("{}", bar.pin_mut().val());
14 }
```

autocxx

Glues bindgen and cxx together

Provides a fluent bridge



Non-trivial types behind an indirection + `Pin`

Building Bridges

Building Bridges

Summary

Use C as a foundation

Building Bridges

Summary

Use C as a foundation

Static assert type layout

Building Bridges

Summary

Use C as a foundation

Static assert type layout

Use code generation to overcome differences

Building Bridges

Summary

Use C as a foundation

Static assert type layout

Use code generation to overcome differences

Handle exceptions at the boundary

Qt Quality Assurance

Danke schön!
Fragen?