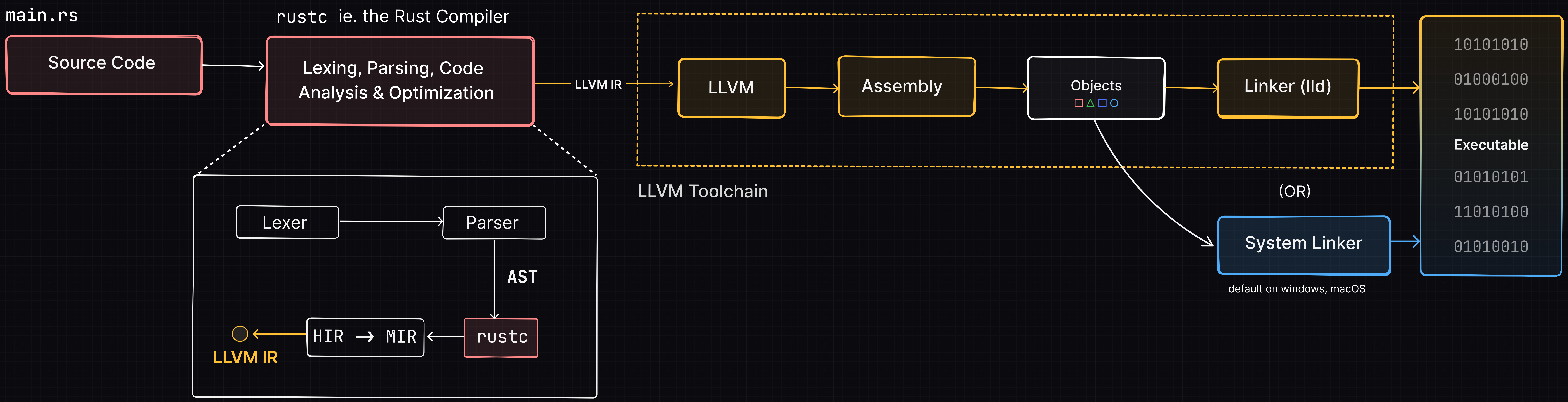
# Rust Unlinked

## Compiler, Symbols, Linkers & Static Libraries



`main.rs`

Source Code

`rustc` ie. the Rust Compiler

Lexing, Parsing, Code Analysis & Optimization

Lexer

Parser

AST

`rustc`

HIR → MIR

LLVM IR

LLVM IR

LLVM

Assembly

Objects

□△□○

Linker (lld)

LLVM Toolchain

(OR)

System Linker

default on windows, macOS

10101010

01000100

10101010

Executable

01010101

11010100

01010010

**Shriram Balaji, Microsoft**

CONF42 • RUSTLANG 2024

# ABOUT ME

- Working on **M365 Core** at Microsoft
- Tinkering with Rust since 2020
- Lately, I've been into reading about databases, systems programming languages, and distributed systems
- **@shrirambalaji** everywhere

## AGENDA

- Understanding Linking
- Rust Compilation - A High Level Overview
- What’s in an Object File? Can we link them?
- **ELF** - The Executable and Linkable Format
- Symbols, Symbol Tables and how to visualize them?
- `staticlib` to the rescue
- Cargo Build Script for linking object files

# Understanding Linking

**Linking** involves combining object files into an executable or shared library. It’s like putting together puzzle pieces to create a working program.

→ `.exe`

**Linking** involves combining object files into an executable or shared library. It’s like putting together puzzle pieces to create a working program.

→ `./program`

**Linking** does the magic of **Symbol Resolution**, where the linker matches variable and function names (ie. symbols) to their specific memory addresses, making sure everything fits together.

→ `./program`

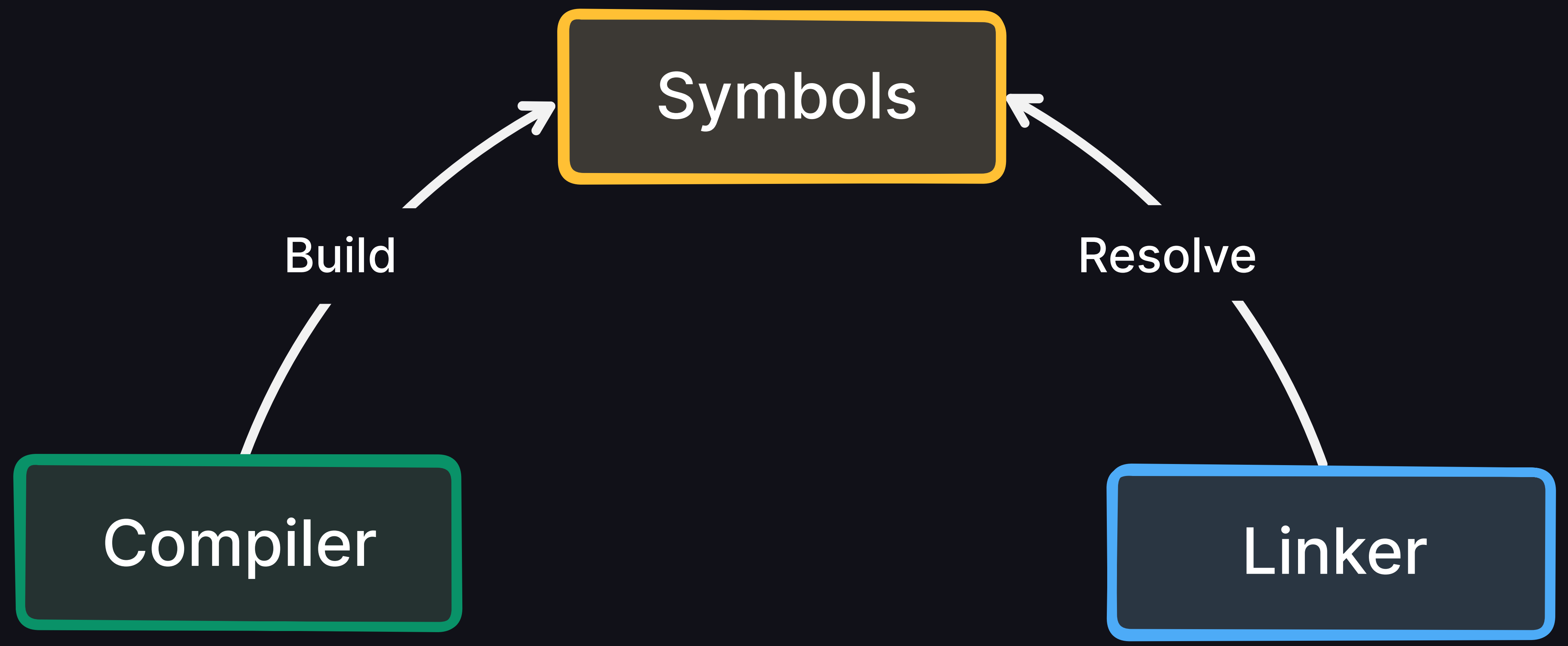
# Why is understanding Linking necessary?

Linking time is often a big part of compilation time.

In large Rust projects, roughly *half* of the time could be spent in the linker.

# Phases of Compilation

- a compiler compiles source files into object files (`.o files`)
- then, a linker takes all object files and combines them into a single executable or shared library file.



# Rust 🤝 Static Linking

## STATIC LINKING

All the necessary dependencies are compiled and linked in the final executable binary **statically**. This enables easier distribution, but the tradeoff being bigger executables.

## DYNAMIC LINKING

**Dynamic linking** allows a program to load external libraries / shared libraries into memory and use their functionalities at runtime, rather than at compile time.

It is **crucial** to understand a little about the stages of rust compilation, *before* we get to linking.

**Disclaimer**: I’m not a `rustc` compiler dev, rather just someone curious about it 😄

# Rust Compilation - High Level Overview

Simplified

# Rust Compilation - High Level Overview

*presented linearly for clarity

# Rust Compilation - High Level Overview

*actual implementation is query based

# Rust Compilation - High Level Overview

# Lexing and Parsing

Source Code

main.rs

```rust
fn main() {
  println!("Hello, world!");
}
```

# Lexing and Parsing

`rustc` ie. the Rust Compiler

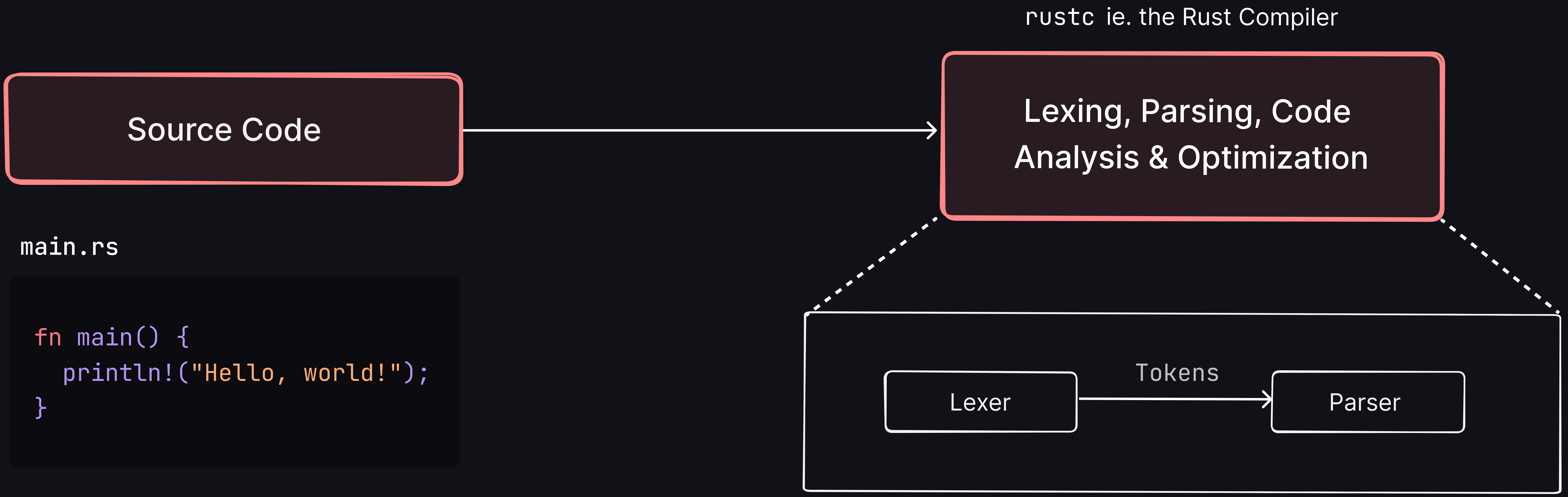
Source Code

Lexing, Parsing, Code Analysis & Optimization

`main.rs`

```rust
fn main() {
  println!("Hello, world!");
}
```

# Lexing and Parsing



`rustc` ie. the Rust Compiler

Source Code

Lexing, Parsing, Code Analysis & Optimization

Lexer

Tokens

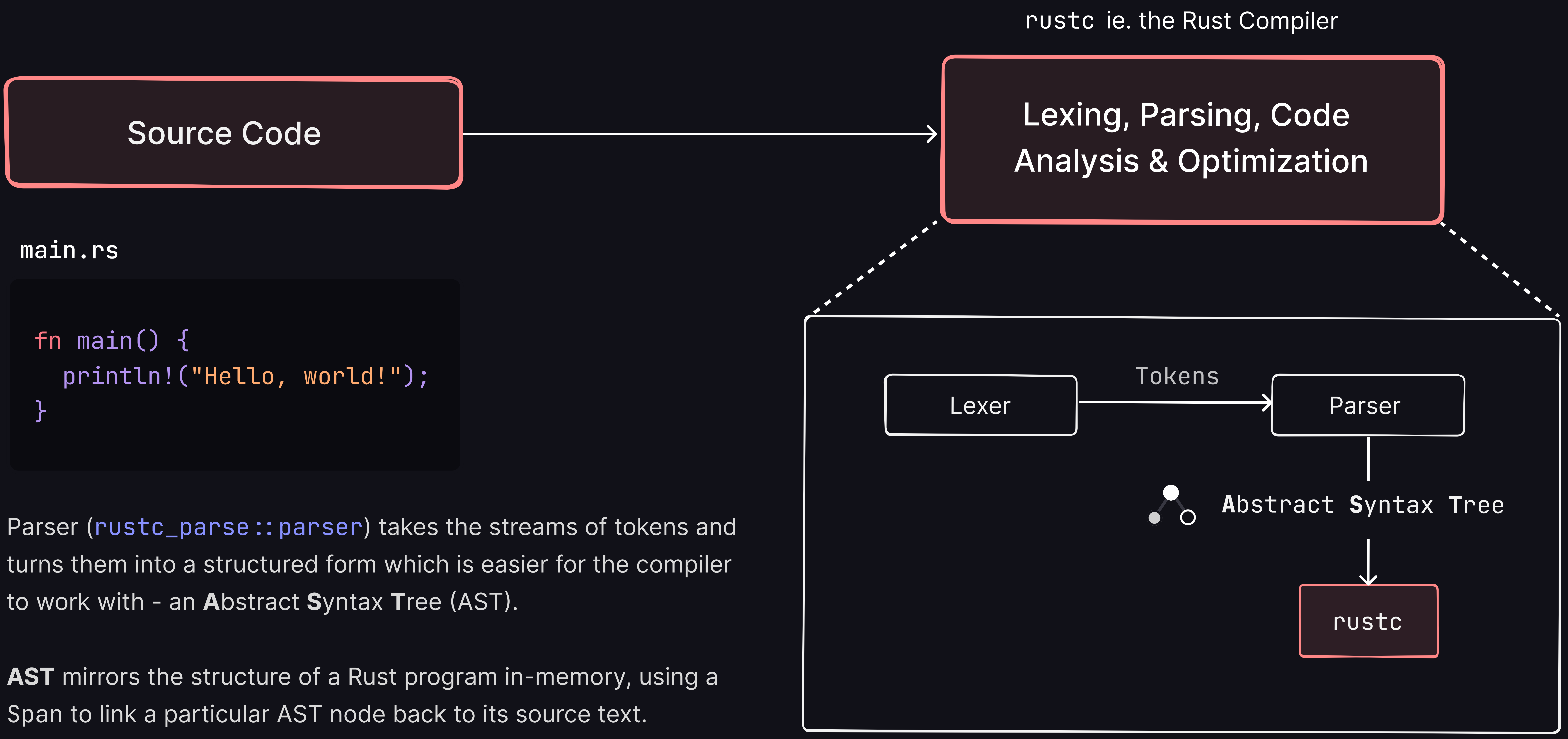
Parser

`main.rs`

```rust
fn main() {
  println!("Hello, world!");
}
```

`rustc_lexer` + `rustc_parse::lexer` converts source code `&str` into parse-able token types for the

# Lexing and Parsing



Source Code

`rustc` ie. the Rust Compiler

Lexing, Parsing, Code Analysis & Optimization

Lexer

Tokens

Parser

Abstract Syntax Tree

rustc

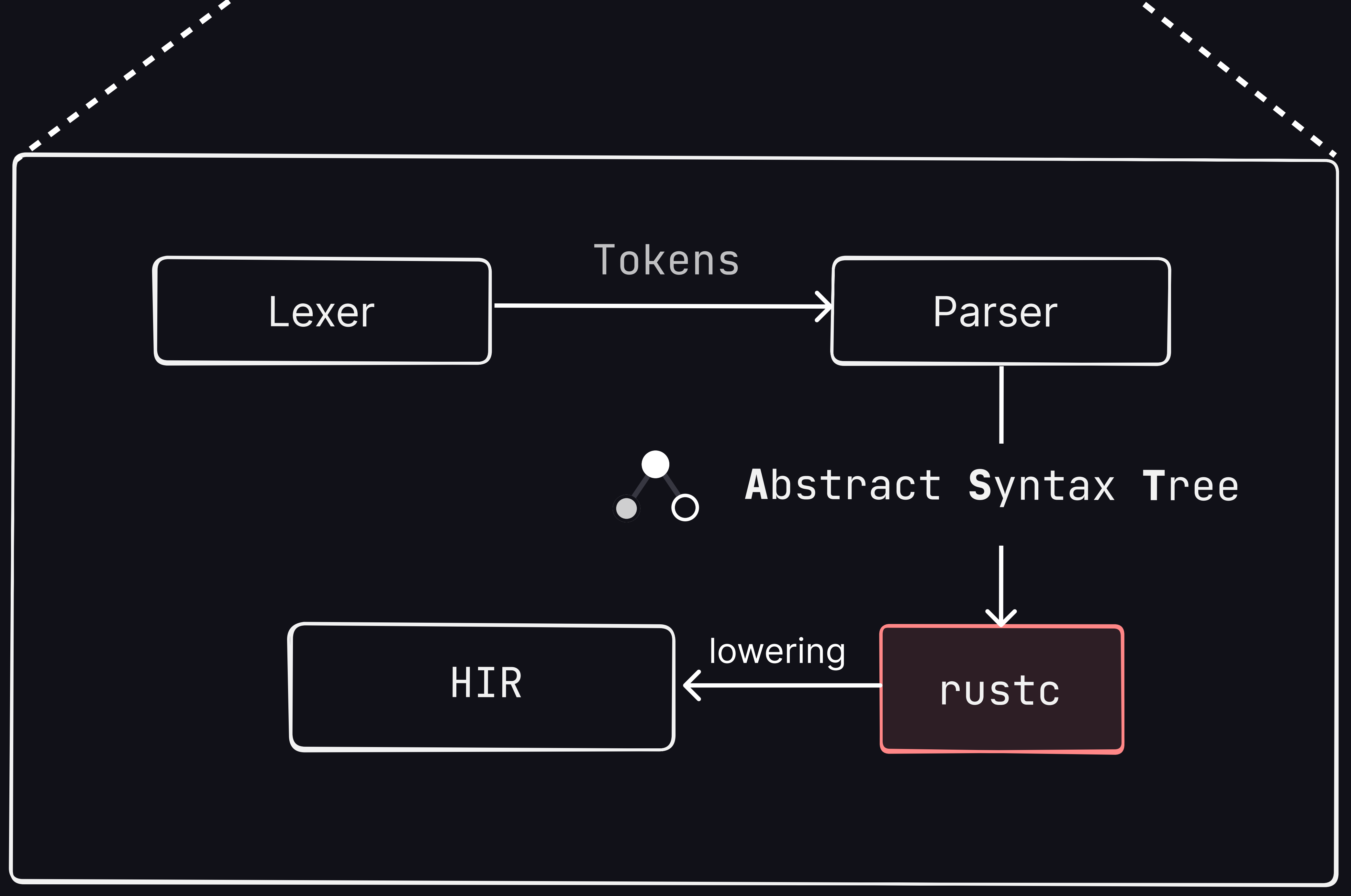
main.rs

```rust
fn main() {
  println!("Hello, world!");
}
```

Parser (`rustc_parse::parser`) takes the streams of tokens and turns them into a structured form which is easier for the compiler to work with - an **A**bstract **S**yntax **T**ree (AST).

**AST** mirrors the structure of a Rust program in-memory, using a Span to link a particular AST node back to its source text.

# Code Analysis & Optimization



`main.rs`

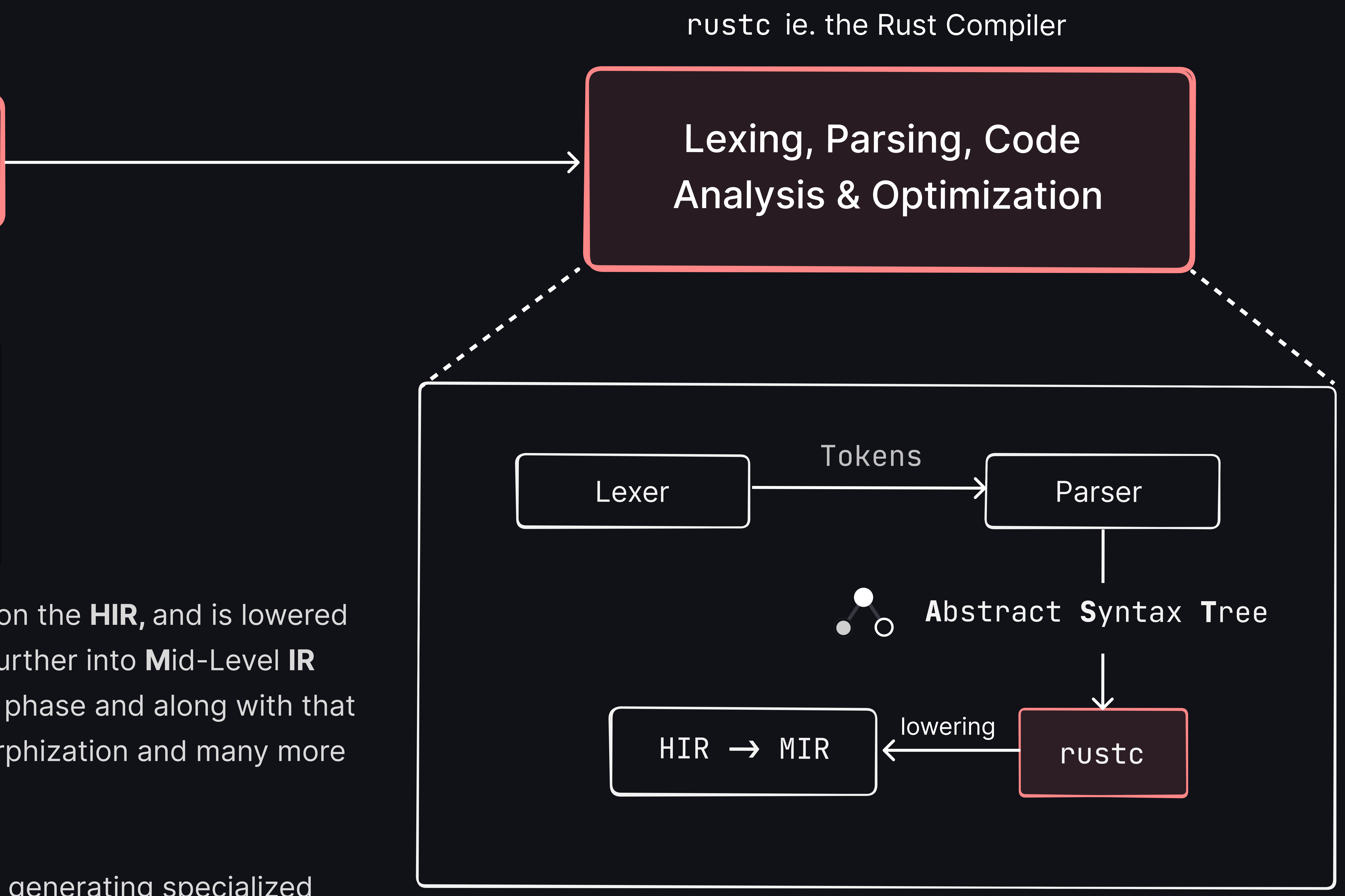
```rust
fn main() {
  println!("Hello, world!");
}
```

AST is further lowered into a **H**igh Level **I**ntermediate **R**epresentation (**HIR**). During lowering - `rustc` expands macros, de-sugars syntax (for eg. `if let → match`), performs name resolution to resolve import and macro names. then, it does:

- Type inference → automatically deducing the types of variables and expressions
- Trait Solving → Finding the correct implementation of a trait for a type

# Code Analysis & Optimization

Source Code



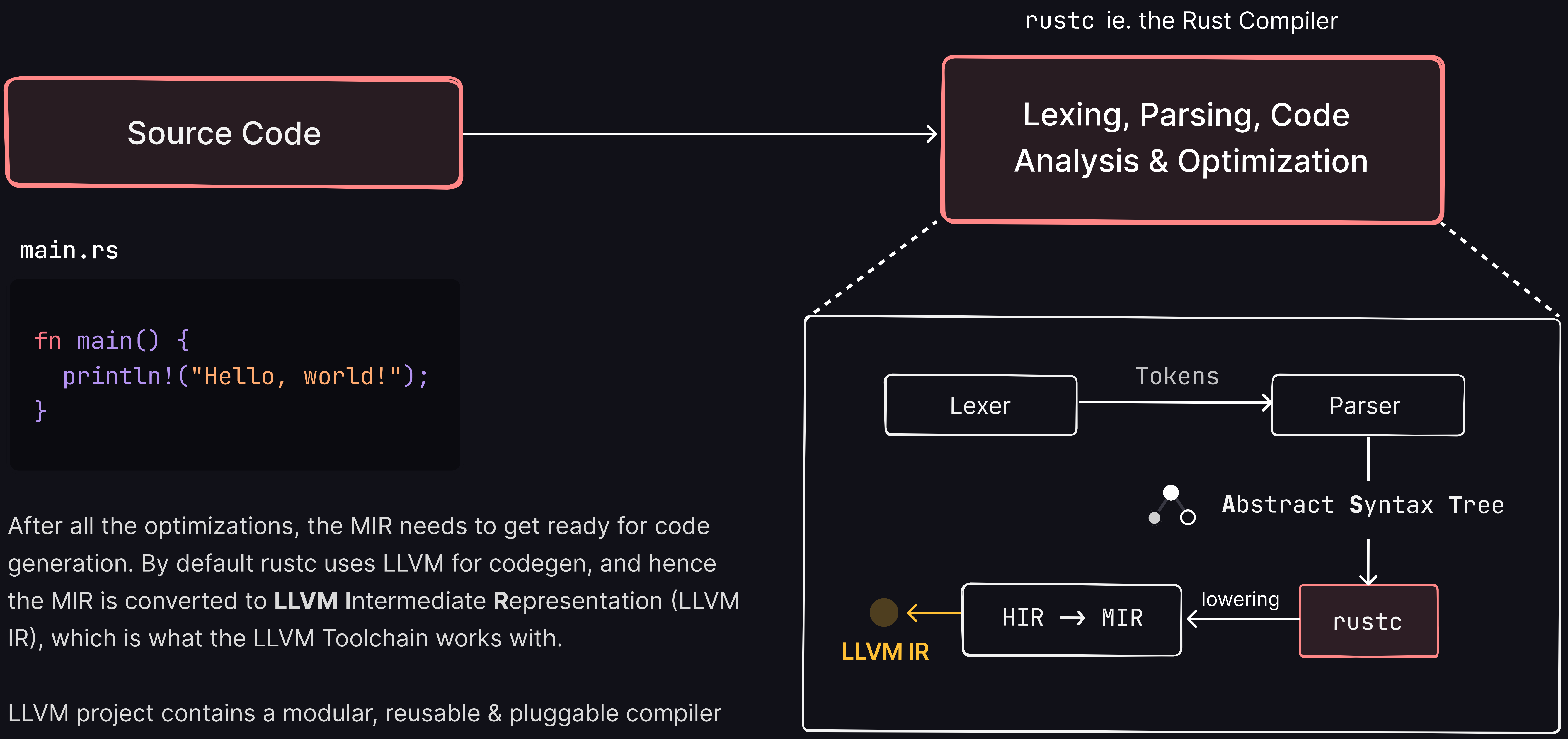
`main.rs`

```rust
fn main() {
  println!("Hello, world!");
}
```

The Compiler then runs **Type Checking** on the **HIR,** and is lowered into a **T**yped **HIR** (**THIR**) and then even further into **M**id-Level **IR** (**MIR**). Borrow Checking happens in this phase and along with that `rustc` does operator lowering, monomorphization and many more optimizations *after* borrow checking.

**Monomorphization** is the fancy term for generating specialized code for each type that a generic function is called with.

# Preparing for Code Generation



`rustc` ie. the Rust Compiler

Source Code

Lexing, Parsing, Code Analysis & Optimization

`main.rs`

```rust
fn main() {
  println!("Hello, world!");
}
```

After all the optimizations, the MIR needs to get ready for code generation. By default rustc uses LLVM for codegen, and hence the MIR is converted to **LLVM I**ntermediate **R**epresentation (LLVM IR), which is what the LLVM Toolchain works with.

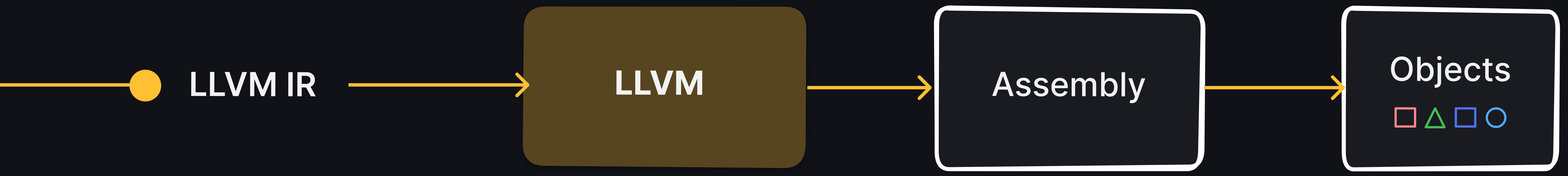
LLVM project contains a modular, reusable & pluggable compiler backend used by many compiler projects, including the clang C compiler and rustc.

# Code Generation & Building the executable

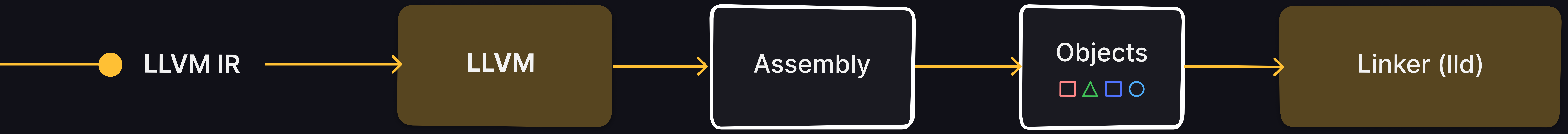
LLVM IR

LLVM

# Code Generation & Building the executable



# Code Generation & Building the executable

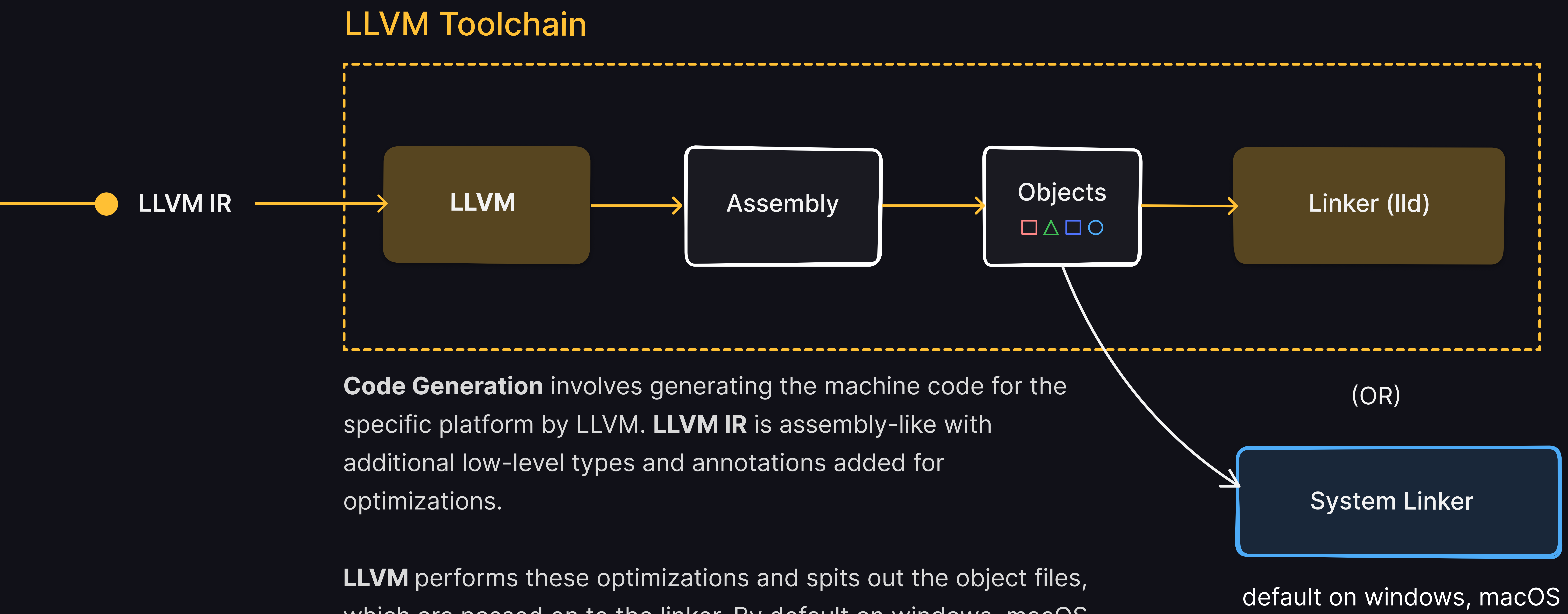


LLVM IR → LLVM → Assembly → Objects □△□○ → Linker (lld)

**Code Generation** involves generating the machine code for the specific platform by LLVM. **LLVM IR** is assembly-like with additional low-level types and annotations added for optimizations.

**LLVM** performs these optimizations and spits out the object files, which are passed on to the linker.

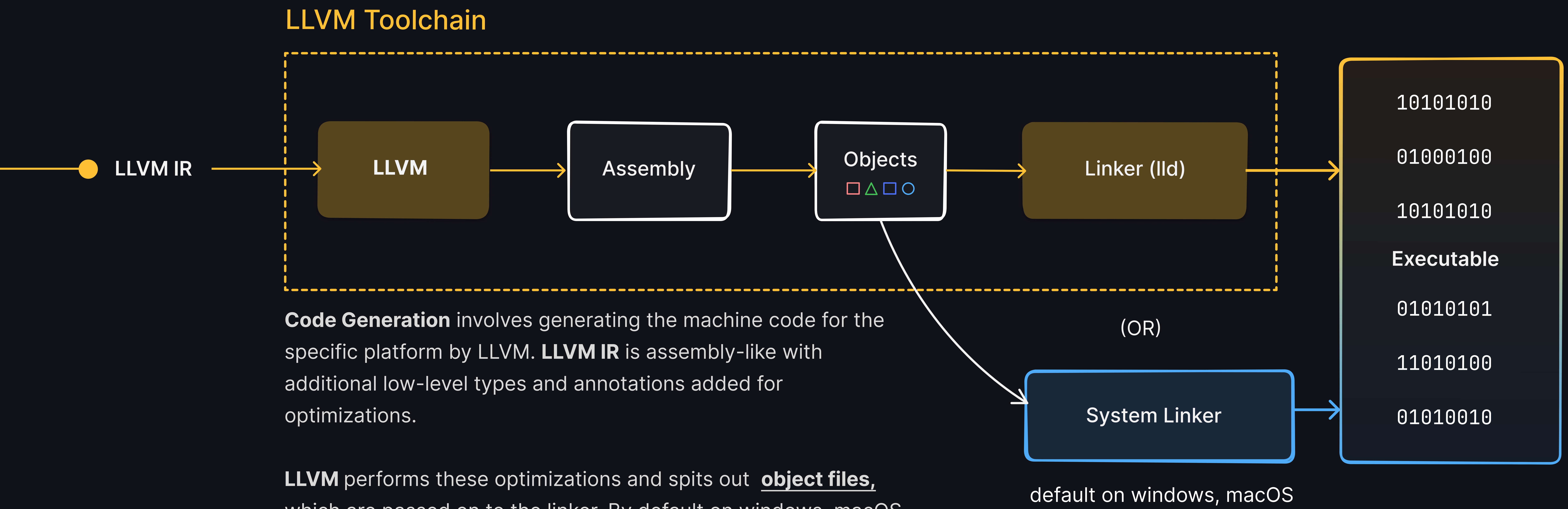
# Code Generation & Building the executable



**Code Generation** involves generating the machine code for the specific platform by LLVM. **LLVM IR** is assembly-like with additional low-level types and annotations added for optimizations.

**LLVM** performs these optimizations and spits out the object files, which are passed on to the linker. By default on windows, macOS they are passed to system's linker. On linux, as of May 2024 it's passed onto rust-lld in nightly builds.

# Code Generation & Building the executable



**Code Generation** involves generating the machine code for the specific platform by LLVM. **LLVM IR** is assembly-like with additional low-level types and annotations added for optimizations.

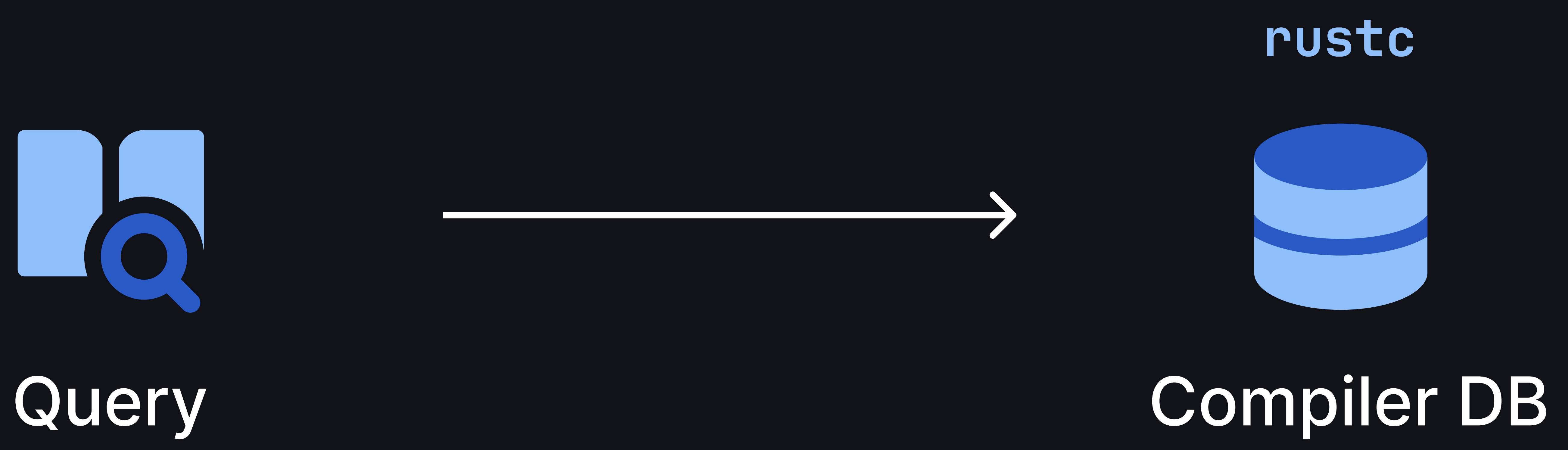
**LLVM** performs these optimizations and spits out **object files,** which are passed on to the linker. By default on windows, macOS they are passed to system's linker. On linux, as of **May 2024** it's passed onto rust-lld in nightly builds. The linker then links together the object files to return an executable.

# What does query based compilation look like in `rustc`?

# Demand Driven Compilation with Queries

Query

# Demand Driven Compilation with Queries



Query → `rustc` Compiler DB

compiler's knowledge about a crate → "database"

# Demand Driven Compilation with Queries

`name`
`key`
`result type`
`query modifiers`
`provider function`

Query

`rustc`

Compiler DB

# Every Step from earlier is modeled as a “Query”

# Let’s look at a query from the “Trait Solving” Step

# Demand Driven Compilation with Queries

```
/// Given a crate and a trait, look up all impls of that trait in the crate.
/// Return `(impl_id, self_ty)`.
query implementations_of_trait(key: (CrateNum, DefId)) -> &'tcx [(DefId, Option<SimplifiedType>)] {
    desc { "looking up implementations of a trait in a crate" }
    separate_provide_extern
}
```

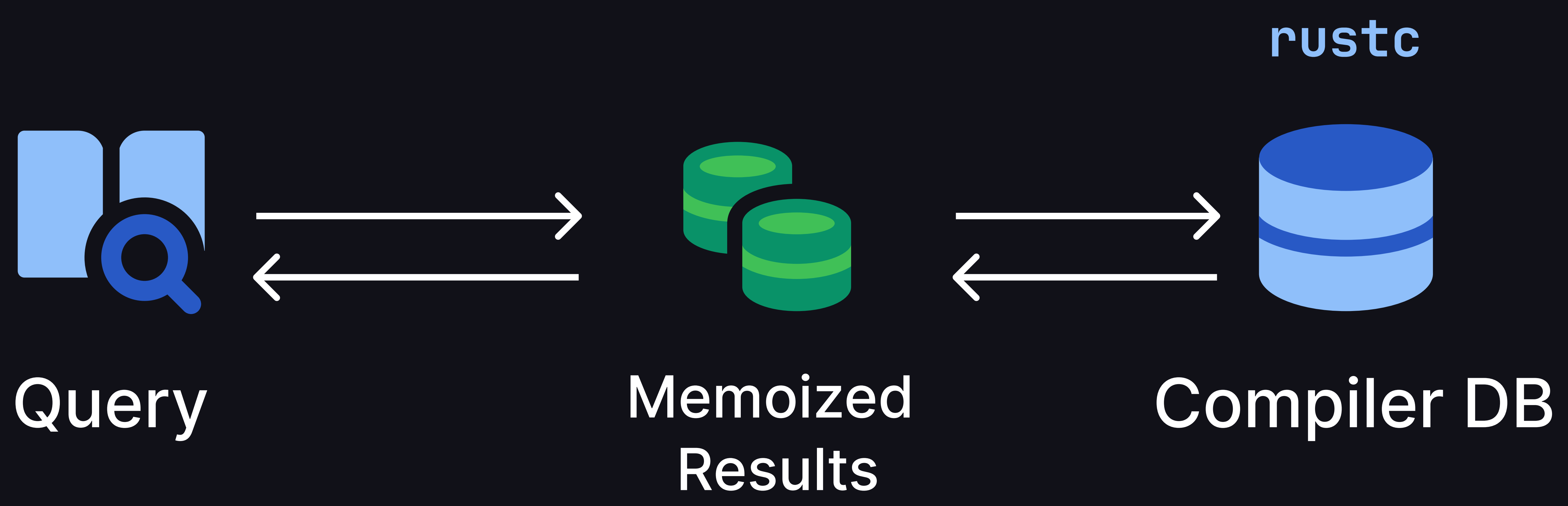
**source**: compiler/rustc_middle/src/query/mod.rs

# Demand Driven Compilation with Queries

```
/// Given a crate and a trait, look up all impls of that trait in the crate.
/// Return `(impl_id, self_ty)`.
query implementations_of_trait(key: (CrateNum, DefId)) -> &'tcx [ ... ]
----- ------------------------      ---------------       ------  ----

▲              ▲                          ▲                 ▲      ▲
|              |                          |                 |      |
|              |                          |                 |  query modifiers
|              |                          |                 |
|              |                          |            result type
|              |                    query key type
|         query name
|
keyword
```

**source**: compiler/rustc_middle/src/query/mod.rs

# Demand Driven Compilation with Queries



`rustc`

Query

Memoized Results

Compiler DB

*Memoization enables incremental compilation, and faster builds

# Enough about Compilation, Back to Linking ⛓️

You may have looked at `.o` files in the past and wondered . . .

# What’s in these `.o` files?

“An **object file** contains machine code or bytecode, as well as other data and metadata, generated by a compiler or assembler from source code during the compilation or assembly process. The machine code that is generated is known as object code.”

source: Wikipedia

If it's just machine code, can we link them ourselves?

Let’s understand with an example

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

importing a `Global` variable from foo.rs in bar.rs and update it’s value to 20.

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

The `#![no_main]` attribute tells the compiler that there is no main function, and effectively not to throw a compiler error when it doesn’t find one.

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

The `#[no_mangle]` attribute disables **mangling**. When Rust code is compiled, identifiers are “mangled” ie. transformed into a different name.

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

for eg. `Global` variable gets mangled to `__ZN11foo6Global17ha2a12041c4e557c5E`. This is done to avoid naming conflicts when linking with other libraries.

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

however, we disable it with `#[no_mangle]` so that the symbol name is preserved, and can be easily linked by name.

## BAR.RS

```
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

The `extern "C"` block tells the compiler that `Global` is defined elsewhere in a foreign library.

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

`extern "C"` doesn't mean we are inter-operating with C, but rather using the platform's C ABI (**A**pplication **B**inary **I**nterface).

## FOO.RS

```
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

```
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

`bar.rs` assumes that a variable declaration for `Global`, is present in a foreign library.

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

This block is `unsafe` because we are updating a global static mutable.

## BAR.RS

```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

## FOO.RS

```rust
#![no_main]

#[no_mangle]
pub static mut Global: i32 = 5;

#[no_mangle]
pub fn foo() {
    unsafe {
        Global = 10;
    }
}
```

## BAR.RS

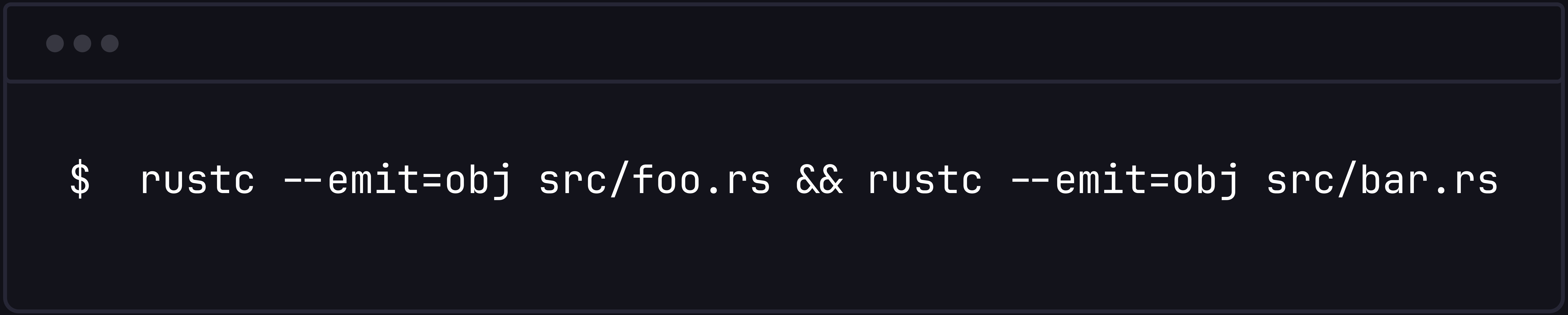
```rust
#![no_main]

extern "C" {
    static mut Global: i32;
}

#[no_mangle]
pub extern "C" fn bar() {
    unsafe {
        Global = 20;
    }
}
```

This block is `unsafe` because Rust cannot guarantee safety in FFI calls. We are trying to mutate a global static variable imported from a library, which cannot be memory-safe.

Let’s compile and get those object files!

But, wait since we want to try manually linking - let’s **not** use `cargo` for now

# Compiling & Emitting Object Files

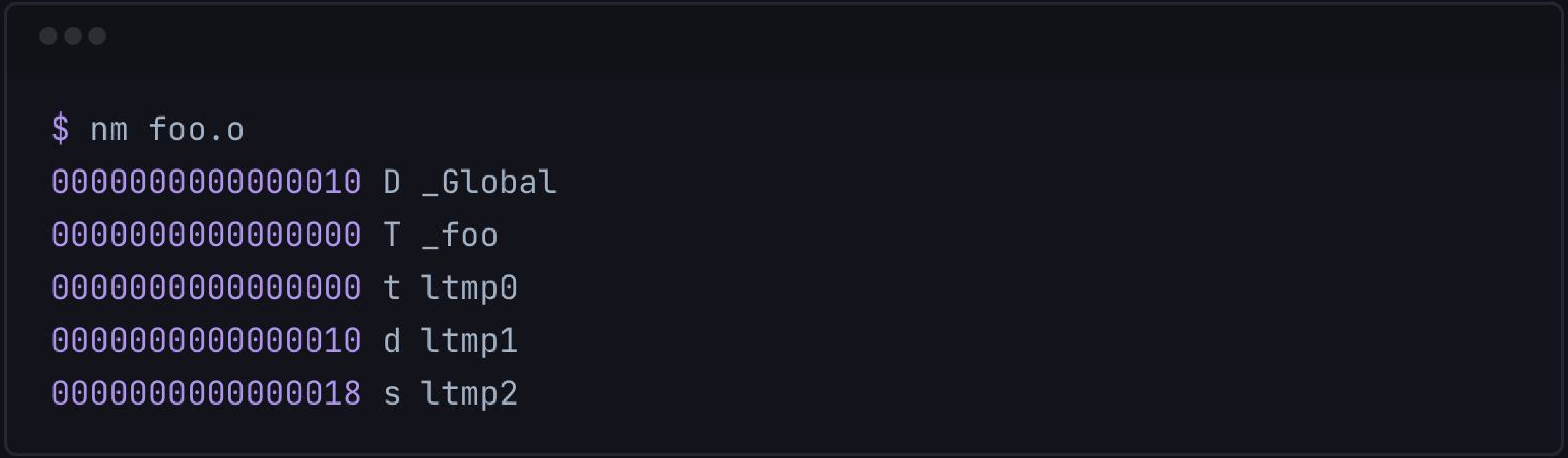


```
$  rustc --emit=obj src/foo.rs && rustc --emit=obj src/bar.rs
```

A **symbol** in a symbol table refers to an identifier, such as a variable name or function name, that is stored in a data structure called a **symbol table**.

**Symbols** are stored in sections of the object file in a specific format - **ELF** (**E**xecutable and **L**inkable **F**ormat) on Unix-like systems. On macOS, it’s Mach-O (Mach Object) but similar to ELF. On Windows, it’s the COFF (**C**ommon **O**bject **F**ile **F**ormat)

# Visualizing Symbols - `nm`



```
$ nm foo.o
0000000000000010 D _Global
0000000000000000 T _foo
0000000000000000 t ltmp0
0000000000000010 d ltmp1
0000000000000018 s ltmp2
```

The output of `nm` is in the following format:

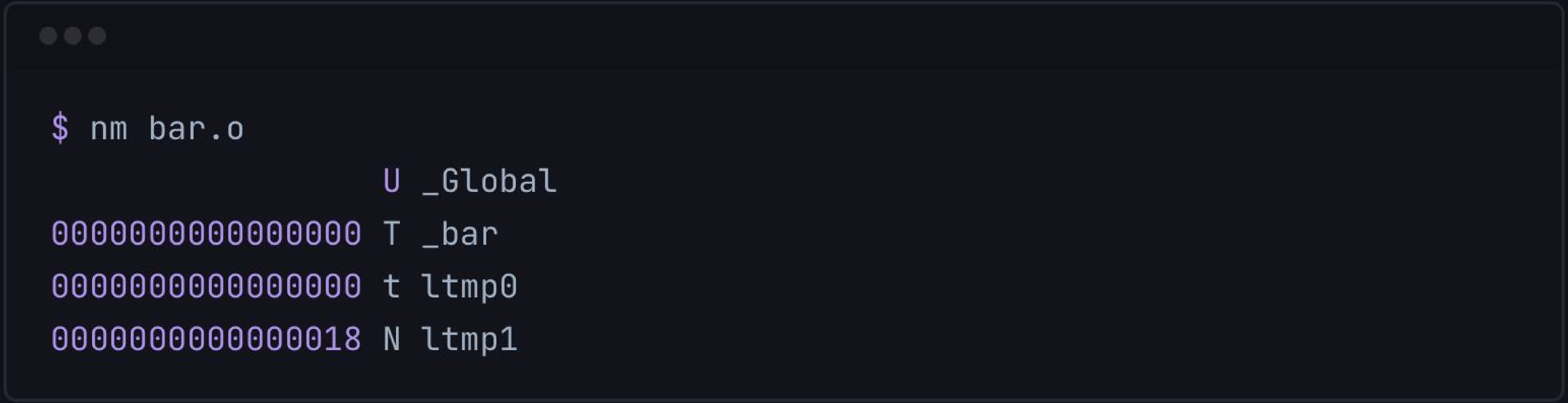
- `D` - Global Data section symbol
- `T` - Global Text symbol
- `d` - Local symbol in the data section
- `s` - Unitialized Local symbol for small objects

If you haven't noticed, lowercase denotes local symbols, and uppercase denotes global symbols.

The `ltmp` symbols are temporary symbols generated by the compiler during compilation.

# Visualizing Symbols - `nm`

Let's take a look at the symbol table for `bar.o` as well:



```
$ nm bar.o
                 U _Global
0000000000000000 T _bar
0000000000000000 t ltmp0
0000000000000018 N ltmp1
```

wherein `U` denotes an Undefined symbol. Remember, the Undefined pseudo section I was mentioning, that's where the `Global` symbol exists. This is because there's an *undefined* symbol reference to the `Global` variable, which will be resolved only during the linking phase.

# Inside **ELF** - **E**xecutable & **L**inkable **F**ormat

| | | |
|---|---|---|
| ELF Header | metadata of .o file | |
| .text | assembly language code | |
| .rodata | readonly variables | |
| .data | read/write/global variables | |
| .bss | block starting symbol (ie. values that start with 0)<br>shortcut that is used to save space instead of allocating zeroes in .o file | |
| .symtab | symbol table | |
| .rel.text | relocation entry for text section | missing symbols fixed later by linker |
| .rel.data | relocation entry for data section | |
| .debug | stack local variables, debugger info | required for debugging |
| .line | maps asm code to line number in source | |
| .strtab | maps symtab entries to source var names | |

Let’s try manually linking!

Lets make a `main.rs` that calls the `foo` and `bar` functions.

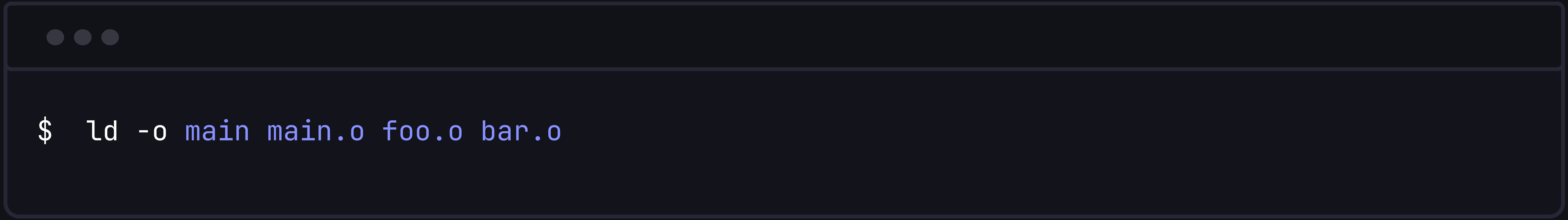
main.rs

```rust
extern "C" {
    fn foo();
    fn bar();
    static mut Global: i32;
}

fn main() {
    unsafe {
        foo();
        bar();
        println!("Global: {}", Global);
    }
}
```

Let's compile the `main.rs` file and emit an object file like before:

```
$ rustc --emit=obj -o main.o main.rs
```

# Manually Linking using `ld`



```
$  ld -o main main.o foo.o bar.o
```

# Manually Linking using `ld`

```
$  ld -o main main.o foo.o bar.o
Undefined symbols for architecture arm64:
  "__Unwind_Resume", referenced from:
      __ZN4core3ops8function6FnOnce9call_once17hf02687347fd78dc0E in main.o
  "__ZN3std2io5stdio6_print17h27e3b43a8b5f8b6aE", referenced from:
      __ZN4main4main17h49930d4df5c05f23E in main.o
  "__ZN3std2rt19lang_start_internal17h47d7f1f6477d860bE", referenced from:
      __ZN3std2rt10lang_start17h43f0cdc6e9029b25E in main.o

"__ZN4core3fmt3num3imp52_$LT$impl$u20$core..fmt..Display$u20$for$u20$i32$GT$3fmt17h810eb3
12f616c580E", referenced from:
      __ZN4main4main17h49930d4df5c05f23E in main.o
  "_rust_eh_personality", referenced from:
      /Users/shrirambalaji/Repositories/learning-linkers/main.o
  "dyld_stub_binder", referenced from:
      <initial-undefines>
ld: symbol(s) not found for architecture arm64
```

`std::core` *crate needs to be linked*

# `staticlib` to the rescue

Instead of us trying to link the `core` crate and bring in `std` dependencies ourselves, we can create a static library from the `foo.rs` and `bar.rs` files, and then link them manually:

```
$ mkdir -p target/out
$ rustc --crate-type=staticlib -o target/out/libfoo.a foo.rs
$ rustc --crate-type=staticlib -o target/out/libbar.a bar.rs
```

The output is a `.a file`, which is a static library / archive in *nix systems.

and it contains the .o files we saw previously.

# `staticlib` to the rescue

We can use the `ar` command to list the contents of the archive.

```
$ ar -t target/out/libfoo.a | grep foo
foo.foo.730f9a7e513a85b2-cgu.0.rcgu.o
foo.10ftosr6tvdwscdu.rcgu.o
```

Interestingly the `.a` file contains the `.o` files we saw earlier, but with a different name, specifically with `*.rcgu.o` suffix. The `rcgu` stands for “Rust Codegen Unit” and is a unit of code that the compiler generates during Code Generation phase.

# `staticlib` to the rescue

If we extract the `.o` file and look, we can see the same symbols we saw earlier.

```
$ ar -x target/out/libfoo.a foo.foo.730f9a7e513a85b2-cgu.0.rcgu.o
$ nm foo.foo.730f9a7e513a85b2-cgu.0.rcgu.o
0000000000000010 D _Global
0000000000000000 T _foo
0000000000000000 t ltmp0
0000000000000010 d ltmp1
0000000000000018 s ltmp2
```

# Doing things the rust way - `cargo’s` back!

Until now, we ignored poor cargo and were relying on rustc. Ideally, we should leverage cargo as its meant to be

# `Cargo` build script

We can add a build script in a `build.rs` that goes in the project's root. This will link the static libraries from the previous step together.

build.rs

```rust
fn main() {
    println!("cargo:rustc-link-search=native=target/out");
    println!("cargo:rustc-link-lib=static=foo");
    println!("cargo:rustc-link-lib=static=bar");
}
```

- `cargo:rustc-link-search=native=target/out` instruction tells the compiler to search for the static libraries in the `target/out` directory
- `cargo:rustc-link-lib=static=foo` and `cargo:rustc-link-lib=static=bar` tells the compiler to link the `foo` and `bar` static libraries. As an alternative to the linking these in the build script, we can also use the `#[link](https://doc.rust-lang.org/reference/items/external-blocks.html#the-link-attribute)` attribute directly in `main.rs`

# Bonus: What does the LLVM IR look like?

LINKS

# References

- Blog
- Slides
- Code Snippets on Github
- CS 361 Systems Programming by Chris Kanich
- High Level Compiler Architecture - Rustc Guide
- Rust Borrow Checker -  Nell Shamrell-Harrington
- Linkage - Rust Reference
- Visualizing Rust Compilation
- Freestanding Rust Binary - Philipp Oppermann
- Matt Godbolt - The Bits between the Bits

# Thank You

@shrirambalaji