A Freestanding Rust Binary

Feb 10, 2018

The first step in creating our own operating system kernel is to create a Rust executable that does not link the standard library. This makes it possible to run Rust code on the bare metal without an underlying operating system.

This blog is openly developed on GitHub. If you have any problems or questions, please open an issue there. You can also leave comments at the bottom. The complete source code for this post can be found in the `post-01` branch.

Introduction

To write an operating system kernel, we need code that does not depend on any operating system features. This means that we can't use threads, files, heap memory, the network, random numbers, standard output, or any other features requiring OS abstractions or specific hardware. Which makes sense, since we're trying to write our own OS and our own drivers.

This means that we can't use most of the Rust standard library, but there are a lot of Rust features that we *can* use. For example, we can use iterators, closures, pattern matching, option and result, string formatting, and of course the ownership system. These features make it possible to write a kernel in a very expressive, high level way without worrying about undefined behavior or memory safety.

In order to create an OS kernel in Rust, we need to create an executable that can be run without an underlying operating system. Such an executable is often called a "freestanding" or "bare-metal" executable.

This post describes the necessary steps to create a freestanding Rust binary and explains why the steps are needed. If you're just interested in a minimal example, you can **jump to the summary**.

Disabling the Standard Library

By default, all Rust crates link the standard library, which depends on the operating system for features such as threads, files, or networking. It also depends on the C standard library `libc`, which closely interacts with OS services. Since our plan is to write an operating system, we can't use any OS-dependent libraries. So we have to disable the automatic inclusion of the standard library through the `no_std` attribute.

We start by creating a new cargo application project. The easiest way to do this is through the command line:

```
cargo new blog_os --bin --edition 2018
```

I named the project `blog_os`, but of course you can choose your own name. The `--bin` flag specifies that we want to create an executable binary (in contrast to a library) and the `--edition 2018` flag specifies that we want to use the 2018 edition of Rust for our crate. When we run the command, cargo creates the following directory structure for us:

Other Lang
- Chinese (s
- Chinese (t
- French
- Japanese
- Persian
- Russian
- Korean
- Arabic

```
blog_os
├── Cargo.toml
└── src
    └── main.rs
```

The `Cargo.toml` contains the crate configuration, for example the crate name, the author, the semantic version number, and dependencies. The `src/main.rs` file contains the root module of our crate and our `main` function. You can compile your crate through `cargo build` and then run the compiled `blog_os` binary in the `target/debug` subfolder.

The `no_std` Attribute

Right now our crate implicitly links the standard library. Let's try to disable this by adding the `no_std` attribute:

```
// main.rs

#![no_std]

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

When we try to build it now (by running `cargo build`), the following error occurs:

```
error: cannot find macro `println!` in this scope
 --> src/main.rs:4:5
  |
4 |     println!("Hello, world!");
  |     ^^^^^^^
```

The reason for this error is that the `println` macro is part of the standard library, which we no longer include. So we can no longer print things. This makes sense, since `println` writes to standard output, which is a special file descriptor provided by the operating system.

So let's remove the printing and try again with an empty main function:

```
// main.rs

#![no_std]

fn main() {}
```

```
> cargo build
error: `#[panic_handler]` function required, but not found
error: language item required, but not found: `eh_personality`
```

Now the compiler is missing a `#[panic_handler]` function and a *language item*.

Panic Implementation

The `panic_handler` attribute defines the function that the compiler should invoke when a panic occurs. The standard library provides its own panic handler function, but in a `no_std`

environment we need to define it ourselves:

```
// in main.rs

use core::panic::PanicInfo;

/// This function is called on panic.
#[panic_handler]
fn panic(_info: &PanicInfo) -> ! {
    loop {}
}
```

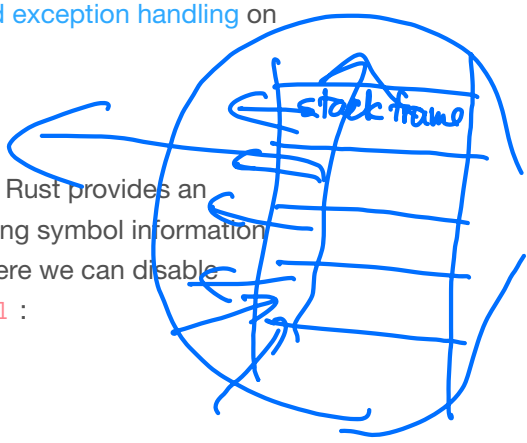
The `PanicInfo` parameter contains the file and line where the panic happened and the optional panic message. The function should never return, so it is marked as a diverging function by returning the "never" type `!`. There is not much we can do in this function for now, so we just loop indefinitely.

The `eh_personality` Language Item

Language items are special functions and types that are required internally by the compiler. For example, the `Copy` trait is a language item that tells the compiler which types have *copy semantics*. When we look at the implementation, we see it has the special `#[lang = "copy"]` attribute that defines it as a language item.

While providing custom implementations of language items is possible, it should only be done as a last resort. The reason is that language items are highly unstable implementation details and not even type checked (so the compiler doesn't even check if a function has the right argument types). Fortunately, there is a more stable way to fix the above language item error.

The `eh_personality` language item marks a function that is used for implementing stack unwinding. By default, Rust uses unwinding to run the destructors of all live stack variables in case of a panic. This ensures that all used memory is freed and allows the parent thread to catch the panic and continue execution. Unwinding, however, is a complicated process and requires some OS-specific libraries (e.g. libunwind on Linux or structured exception handling on Windows), so we don't want to use it for our operating system.



Disabling Unwinding

There are other use cases as well for which unwinding is undesirable, so Rust provides an option to abort on panic instead. This disables the generation of unwinding symbol information and thus considerably reduces binary size. There are multiple places where we can disable unwinding. The easiest way is to add the following lines to our `Cargo.toml`:

```
[profile.dev]
panic = "abort"

[profile.release]
panic = "abort"
```

This sets the panic strategy to `abort` for both the `dev` profile (used for `cargo build`) and the `release` profile (used for `cargo build --release`). Now the `eh_personality` language item should no longer be required.

Now we fixed both of the above errors. However, if we try to compile it now, another error

occurs:

```
> cargo build
error: requires `start` lang_item
```

Our program is missing the `start` language item, which defines the entry point.

The start attribute

One might think that the `main` function is the first function called when you run a program. However, most languages have a runtime system, which is responsible for things such as garbage collection (e.g. in Java) or software threads (e.g. goroutines in Go). This runtime needs to be called before `main`, since it needs to initialize itself.

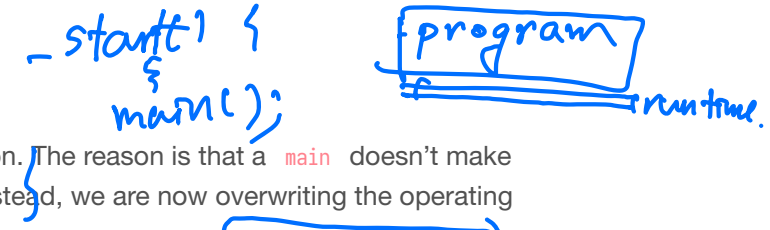
In a typical Rust binary that links the standard library, execution starts in a C runtime library called `crt0` ("C runtime zero"), which sets up the environment for a C application. This includes creating a stack and placing the arguments in the right registers. The C runtime then invokes the entry point of the Rust runtime, which is marked by the `start` language item. Rust only has a very minimal runtime, which takes care of some small things such as setting up stack overflow guards or printing a backtrace on panic. The runtime then finally calls the `main` function.

Our freestanding executable does not have access to the Rust runtime and `crt0`, so we need to define our own entry point. Implementing the `start` language item wouldn't help, since it would still require `crt0`. Instead, we need to overwrite the `crt0` entry point directly.

Overwriting the Entry Point

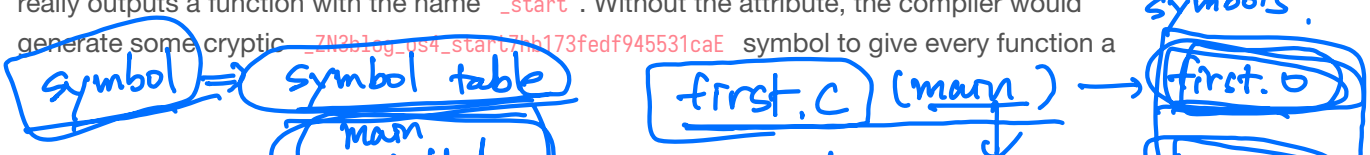
To tell the Rust compiler that we don't want to use the normal entry point chain, we add the `#![no_main]` attribute.

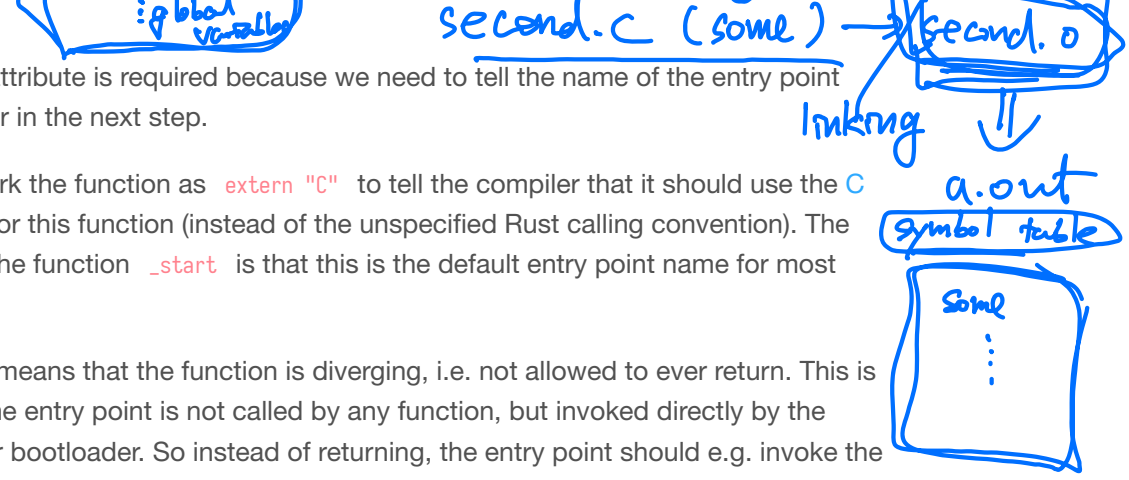
```
#![no_std]
#![no_main]

use core::panic::PanicInfo;

/// This function is called on panic.
#[panic_handler]
fn panic(_info: &PanicInfo) -> ! {
    loop {}
}
```



You might notice that we removed the `main` function. The reason is that a `main` doesn't make sense without an underlying runtime that calls it. Instead, we are now overwriting the operating system entry point with our own `_start` function:

By using the `#[no_mangle]` attribute, we disable name mangling to ensure that the Rust compiler really outputs a function with the name `_start`. Without the attribute, the compiler would generate some cryptic `_ZN3blog_os4_start7hb173fedf945531caE` symbol to give every function a





unique name. The attribute is required because we need to tell the name of the entry point function to the linker in the next step.

We also have to mark the function as `extern "C"` to tell the compiler that it should use the C calling convention for this function (instead of the unspecified Rust calling convention). The reason for naming the function `_start` is that this is the default entry point name for most systems.

The `!` return type means that the function is diverging, i.e. not allowed to ever return. This is required because the entry point is not called by any function, but invoked directly by the operating system or bootloader. So instead of returning, the entry point should e.g. invoke the `exit` system call of the operating system. In our case, shutting down the machine could be a reasonable action, since there's nothing left to do if a freestanding binary returns. For now, we fulfill the requirement by looping endlessly.

When we run `cargo build` now, we get an ugly *linker* error.

Linker Errors

The linker is a program that combines the generated code into an executable. Since the executable format differs between Linux, Windows, and macOS, each system has its own linker that throws a different error. The fundamental cause of the errors is the same: the default configuration of the linker assumes that our program depends on the C runtime, which it does not.

To solve the errors, we need to tell the linker that it should not include the C runtime. We can do this either by passing a certain set of arguments to the linker or by building for a bare metal target.

Building for a Bare Metal Target

By default Rust tries to build an executable that is able to run in your current system environment. For example, if you're using Windows on `x86_64`, Rust tries to build an `.exe` Windows executable that uses `x86_64` instructions. This environment is called your "host" system.

To describe different environments, Rust uses a string called *target triple*. You can see the target triple for your host system by running `rustc --version --verbose`:

```
rustc 1.35.0-nightly (474e7a648 2019-04-07)
binary: rustc
commit-hash: 474e7a6486758ea6fc761893b1a49cd9076fb0ab
commit-date: 2019-04-07
host: x86_64-unknown-linux-gnu
release: 1.35.0-nightly
LLVM version: 8.0
```

The above output is from a `x86_64` Linux system. We see that the `host` triple is `x86_64-unknown-linux-gnu`, which includes the CPU architecture (`x86_64`), the vendor (`unknown`), the operating system (`linux`), and the ABI (`gnu`).

By compiling for our host triple, the Rust compiler and the linker assume that there is an underlying operating system such as Linux or Windows that uses the C runtime by default, which causes the linker errors. So, to avoid the linker errors, we can compile for a different

environment with no underlying operating system.

An example of such a bare metal environment is the `thumbv7em-none-eabihf` target triple, which describes an embedded ARM system. The details are not important, all that matters is that the target triple has no underlying operating system, which is indicated by the `none` in the target triple. To be able to compile for this target, we need to add it in rustup:

```
rustup target add thumbv7em-none-eabihf
```

This downloads a copy of the standard (and core) library for the system. Now we can build our freestanding executable for this target:

```
cargo build --target thumbv7em-none-eabihf
```

By passing a `--target` argument we cross compile our executable for a bare metal target system. Since the target system has no operating system, the linker does not try to link the C runtime and our build succeeds without any linker errors.

This is the approach that we will use for building our OS kernel. Instead of `thumbv7em-none-eabihf`, we will use a custom target that describes a `x86_64` bare metal environment. The details will be explained in the next post.

Linker Arguments

Instead of compiling for a bare metal system, it is also possible to resolve the linker errors by passing a certain set of arguments to the linker. This isn't the approach that we will use for our kernel, therefore this section is optional and only provided for completeness. Click on *"Linker Arguments"* below to show the optional content.

▶ Linker Arguments

Summary

A minimal freestanding Rust binary looks like this:

`src/main.rs`:

```
#![no_std] // don't link the Rust standard library
#![no_main] // disable all Rust-level entry points

use core::panic::PanicInfo;

#[no_mangle] // don't mangle the name of this function
pub extern "C" fn _start() -> ! {
    // this function is the entry point, since the linker looks for a function
    // named `_start` by default
    loop {}
}

/// This function is called on panic.
#[panic_handler]
fn panic(_info: &PanicInfo) -> ! {
    loop {}
}
```

`Cargo.toml` :

```
[package]
name = "crate_name"
version = "0.1.0"
authors = ["Author Name <author@example.com>"]

# the profile used for `cargo build`
[profile.dev]
panic = "abort" # disable stack unwinding on panic

# the profile used for `cargo build --release`
[profile.release]
panic = "abort" # disable stack unwinding on panic
```

To build this binary, we need to compile for a bare metal target such as `thumbv7em-none-eabihf` :

```
cargo build --target thumbv7em-none-eabihf
```

Alternatively, we can compile it for the host system by passing additional linker arguments:

```
# Linux
cargo rustc -- -C link-arg=-nostartfiles
# Windows
cargo rustc -- -C link-args="/ENTRY:_start /SUBSYSTEM:console"
# macOS
cargo rustc -- -C link-args="-e __start -static -nostartfiles"
```

Note that this is just a minimal example of a freestanding Rust binary. This binary expects various things, for example, that a stack is initialized when the `_start` function is called. **So for any real use of such a binary, more steps are required**.

What's next?

The next post explains the steps needed for turning our freestanding binary into a minimal operating system kernel. This includes creating a custom target, combining our executable with a bootloader, and learning how to print something to the screen.

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A Minimal Rust Kernel »

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