

All-in-one Rust Embedded Programming for STM32F4 series

In this book, we will cover all the pieces of knowledge we need to know for using **Rust** to do embedded programming.

And we pick the **ARM-based MCU STM32F4** series chips as our target to run all the demos.

All commands below are running on **macOS**. I will provide the link to **Windows** and **Linux** as well.

1.1 What is **MCU**, **Soc** and **SBC**?

- **MCU** stands for **Microcontroller Unit**.
- **Soc** stands for **System-on-chip**.
- **SBC** stands for **Single Board Computer**.

Summaries, **MCU** and **Soc** sound like the same thing which is an all-in-one chip. It includes all the hardware components below inside the single-chip:

- CPU (even FPU)
- RAM (Random Access Memory)
- ROM (Read-only Memory)
- Flash (as the hard drive to store your program)
- Any related I/O

It's basically a very small computer on an **IC** (integrated circuit) or microchip. Compare to **SBC**, it got a few different below:

- **MCU** usually with limited hardware power resources which suit for non-heavy computation solution.
- **MCU** can deal with fast power on and off at any given time and won't hurt your program which **SBC** can't do like that (as it got **os** on it).

- MCU doesn't have OS at all, your program will be the **only** one program running there with full control and real-time responsiveness.

1.2 What is STM32 ?

STM32 is a family of 32-bit MCU by STMicroelectronics. The STM32 chips are grouped into related series that are based around the same 32-bit ARM processor core, such as:

- Cortex-M33F
- Cortex-M7F
- Cortex-M4F
- Cortex-M3
- Cortex-M0+
- Cortex-M0

The F means with FPU (Floating Point Unit).

Internally, each MCU consists of the processor core, static RAM, flash memory, debugging interface, and various peripherals.

The company behind the Arm trademark (Arm Holdings) doesn't actually manufacture chips for purchase. Instead, their primary business model is to just design parts of chips. They will then license those designs to manufacturers, who will in turn implement the designs (perhaps with some of their own tweaks) in the form of physical hardware that can then be sold.

2. About the hardware

2.1 STM32F407G-DISC1 dev board for running on the emulator

- STM32F407G-DISC1 (replaces STM32F4DISCOVERY) dev board which with the STM32F407VG high performance MCU. Here is the [user manual](#).
- About the onboard STM32F407VG MCU:

- High-performance foundation line, ARM **Cortex-M4** core with **DSP** and **FPU**, 1 Mbyte Flash, 168 MHz CPU, ART Accelerator, Ethernet, FSMC
- More hardware details at [here](#), [datasheet](#) and [reference manual](#).

2.2 WeAct Black Pill for running on the hardware

- **WeAct Black Pill** board which with the `STM32F411CEU6` high performance `MCU`.
- About the onboard `STM32F411CEU6` MCU:
 - High-performance foundation line, ARM **Cortex-M4** core with **DSP**, **FPU** and **MPU**, 512 Kbytes Flash, 100 MHz CPU.
 - [Aliexpress link](#)
 - [TaoBao link](#)
 - [STM32-base.org link](#)
 - [Official GitHub with detail info and diagram](#)

3. Setup Environment

Before writing rust code and test it on emulator or the real hardware, we need to install some tools below:

For **Windows** and **Linux**, plz go to [here](#).

3.1 Install tooling

- `rust` and related binaries

```
# Install latest rustup
curl --proto '=https' --tlsv1.2 -sSf https://sh.rustup.rs | sh

# `cargo-generate` used to generate the rust embedded project from
template
cargo install cargo-generate

# `cargo-binutils` is a collection of cargo subcommand LLVM tools.
Like:
# `rust-objdump`,
# `rust-readobj`,
# `rust-ld`,
# `rust-lld`,
# `rust-lld`,
# `rust-nm`,
# `rust-size`,
# etc.

cargo install cargo-binutils

rustup component add llvm-tools-preview

# We need this for hot-load
cargo install cargo-watch

# Add cross-compilation target
rustup target add thumbv7em-none-eabi
rustup target add thumbv7em-none-eabihf
```

- QEMU ARM emulator and STM32F4 support

```
brew install qemu
```

QEMU is a generic and open source machine emulator. By default, it doesn't support STM32F4, below are the steps how to make that happen:

```
# Detail is here: https://xpack.github.io/qemu-arm/install/
cd ~/Downloads/
curl -LJO "https://github.com/xpack-dev-tools/qemu-arm-
xpack/releases/download/v2.8.0-9/xpack-qemu-arm-2.8.0-9-darwin-
x64.tar.gz"
mkdir -p ~/Library/xPacks/qemu-arm/2.8.0-9
cd ~/Library/xPacks/qemu-arm/2.8.0-9
tar xvf ~/Downloads/xpack-qemu-arm-2.8.0-9-darwin-x64.tar.gz
mv xpack-qemu-arm-2.8.0-9/* ./
rm -rf xpack-qemu-arm-2.8.0-9/
chmod -R -w ./

# Add `/Users/wison/Library/xPacks/qemu-arm/2.8.0-9/bin` to your
`$PATH`
# After that, test it:
qemu-system-gnuarmeclipse --version

# List all support machine and we should be able to see `STM32F4XXX`:
qemu-system-gnuarmeclipse -machine help
```

- ARM version `GDB` and `OpenOCD` for remote debugging

`GDB` isn't able to communicate directly with the ST-Link debugging hardware on your STM32F3DISCOVERY development board. It needs a translator and the Open On-Chip Debugger, `OpenOCD`, is that translator. `OpenOCD` is a program that runs on your laptop/PC and translates between GDB's TCP/IP based remote debug protocol and ST-Link's USB based protocol.

`OpenOCD` also performs other important work as part of its translation for the debugging of the ARM Cortex-M based microcontroller on your STM32F3DISCOVERY development board:

It knows how to interact with the memory mapped registers used by the ARM CoreSight debug peripheral. It is these CoreSight registers that allow for:
Breakpoint/Watchpoint manipulation
Reading and writing of the CPU registers
Detecting when the CPU has been halted for a debug event
Continuing CPU execution after a debug event has been encountered etc. It also knows how to erase and write to the microcontroller's FLASH

```
brew install armmbed/formulae/arm-none-eabi-gcc  
brew install openocd
```

After that, you will find the `OpenOCD` interface configuration and target configuration at here:

```
/usr/local/Cellar/open-  
ocd/{VERSION_NUMBER}/share/openocd/scripts/interface/stlink-v2-1.cfg  
/usr/local/Cellar/open-  
ocd/{VERSION_NUMBER}/share/openocd/scripts/target/stm32f4x.cfg
```

- **ST-LINK** to use burn your program into `STM32F4` hardware

```
brew install stlink
```

[More detail here](#)

3.2 Create a `demo` project from exists template

```
cargo generate --git https://github.com/rust-embedded/cortex-m-quickstart  
✖ Project Name: demo
```

3.3 Run hello example in `QEMU` and set a breakpoint in `ARM GDB`

- Add the below settings to `.cargo/config`

```
[target.thumbv7em-none-eabi]
# Settings below will make `cargo run` execute programs on QEMU
# Normal version
# runner = "qemu-system-gnuarmeclipse -cpu cortex-m4 -mcu STM32F407VG
-machine STM32F4-Discovery -nographic -semihosting-config
enable=on,target=native -kernel" # Normal version (show dev board UI)
# Normal version (with dev board UI)
# runner = "qemu-system-gnuarmeclipse -cpu cortex-m4 -mcu STM32F407VG
-machine STM32F4-Discovery -semihosting-config
enable=on,target=native -kernel"

# Debug version, QEMU will wait for the GDB connection from TCP port
3333 and halt the machine.
# runner = "qemu-system-gnuarmeclipse -gdb tcp::3333 -S -cpu cortex-
m4 -mcu STM32F407VG -machine STM32F4-Discovery -nographic -
semihosting-config enable=on,target=native -kernel"
# Debug version (with dev board UI), QEMU will wait for the GDB
connection from TCP port 3333 and halt the machine.
runner = "qemu-system-gnuarmeclipse -gdb tcp::3333 -S -cpu cortex-m4
-mcu STM32F407VG -machine STM32F4-Discovery -semihosting-config
enable=on,target=native -kernel"
```

[build]

```
# As we use STM32F4DISCOVERY, then pick the `Cortex-M4F`
# target = "thumbv7em-none-eabihf" # Cortex-M4F and Cortex-M7F (with
FPU)

# But if running in QEMU, then we can't use the FPU version, as QEMU
doesn't support!!!
target = "thumbv7em-none-eabi" # Cortex-M4 and Cortex-M7 (no FPU)
```

- Run `qemu` in debug mode with `cargo run --example hello`
- Now we're able to run arm version `GDB` and connect to debug TCP port:

```
arm-none-eabi-gdb \
-q target/thumbv7em-none-eabi/debug/examples/hello \
-ex "target remote:3333"

# List the `main` fn then we can set breakpoint to the line number we
want:
(gdb) list main
(gdb) break 13
Breakpoint 1 at 0x484: file examples/hello.rs, line 13.

(gdb) step
#gdb) print &x
#gdb) next
#gdb) continue
#gdb) stop
(gdb) quit
```

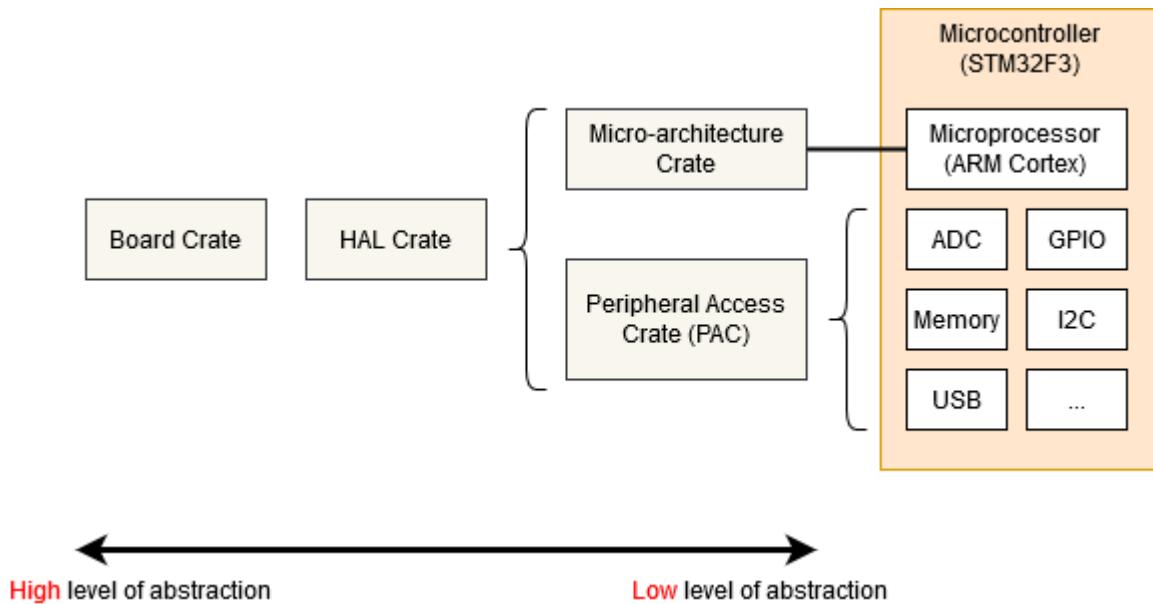
3.4 Run hello example in hardware

- First, make sure you go through this [step](#) to make sure all hardware connections already work.
- We use `--target` in `cargo` command, then we don't need to modify `.cargo/config` again

```
cargo run --target thumbv7em-none-eabihf --example hello
```

- For debugging, plz follow steps [here](#)

4. Write the first example



In `Rust` world, you got several options to start your project, it totally depends on your situation, below are the tips:

- **Micro-architecture Crate**

This sort of crate handles any useful routines common to the processor core your microcontroller is using, as well as any peripherals that are common to all micro-controllers that use that particular type of processor core. For example the `cortex-m` crate gives you functions to enable and disable interrupts, which are the same for all `Cortex-M` based micro-controllers. It also gives you access to the 'SysTick' peripheral included with all `Cortex-M` based micro-controllers.

- **Peripheral Access Crate (PAC)**

This sort of crate is a thin wrapper over the various memory-wrapper registers defined for your particular part-number of micro-controller you are using. For example, `stm32f4` for the **ST-Micro STM32F40x series**. Here, you'll be interacting with the registers directly, following each peripheral's operating instructions given in your micro-controller's Technical Reference Manual.

- **HAL (Hardware Abstraction Layer) Crate**

These crates offer a more user-friendly API for your particular processor, often by implementing some common traits defined in `embedded-hal`. For example, `stm32f4xx-hal` crate might offer a Serial struct, with a constructor that takes an appropriate set of GPIO pins and a baud rate, and offers some sort of

write_byte function for sending data. See the chapter on Portability for more information on embedded-hal.

- **Board Crate**

These crates go one step further than a HAL Crate by pre-configuring various peripherals and GPIO pins to suit the specific developer kit or board you are using, such as [stm32f3-discovery](#) for the **STM32F3DISCOVERY** board.

Let's try that one-by-one:

4.1 The basic example

- Make sure your `Cargo.toml` has the settings below:

The `[features]` config tells the compiler to know that which feature rely on the particular optional dependencies.

```
[features]
default = []
enable-debug = ["cortex-m-semihosting"]
enable-pac = ["stm32f4"]
enable-hal = ["stm32f4xx-hal"]

[dependencies]
cortex-m = "0.6.0"
cortex-m-rt = "0.6.10"

panic-semihosting = { version = "0.5.3", features = ['exit'] }

cortex-m-semihosting = { version = "0.3.3", optional = true }

stm32f4 = { version = "0.11.0", features = ["stm32f407", "rt"], optional = true }

stm32f4xx-hal = { version = "0.8.3", features = ['stm32f407'], optional = true }
```

- Make sure your `.cargo/config` has the settings below:

```
[target.thumbv7em-none-eabi]
runner = "qemu-system-gnuarmeclipse -cpu cortex-m4 -mcu STM32F407VG -
machine STM32F4-Discovery -nographic -semihosting-config
enable=on,target=native -kernel"
```

- Create `demo/src/bin/basic.rs` with the following code:

```
#![allow(warnings)]
// This attribute means the program won't use `std` crate which
assumes
// an underlying OS. The program will use `core` crate, a subset of
`std`
// that can run on bare metal systems.
#![no_std]
// This attribute means the program won't use the standard `main`
interface.
#![no_main]

use cortex_m::peripheral::Peripherals;
use cortex_m_rt::entry;

// `cortex_m_semihosting` gives us the ability to print the debug
info
// into the host console. But keep in mind that, each write operation
// is super slow which takes several milliseconds depends on the
// hardware!!! That's why we make it as an option feature.
#[cfg(feature = "enable-debug")]
use cortex_m_semihosting::{dbg, hprintln};

// `panic_semihosting` will call `debug::EXIT_FAILURE` after logging
the
// panic message.
use panic_semihosting as _;

// We will use the `entry` attribute from the `cortex_m_rt` crate to
define
// the entry point. The entry point function must have signature
`fn() -> !;`
// which means can't return, as the program never terminates.
#[entry]
fn main() -> ! {
    // `hprintln` returns `Result<(), ()>`
    #[cfg(feature = "enable-debug")]
    let _ = hprintln!("Basic STM32F4 demo is running >>>>");
}
```

```
// Get the singleton `Peripherals` instance. This method can only
// successfully called **once()**, that's why return an `Option`.
let peripherals = Peripherals::take().unwrap();

// You can't do this, as `cortex_m::Peripherals` cannot be
// formatted
// using `{:?}` because it doesn't implement `core::fmt::Debug`.
// dbg!(peripherals);

let x = 10;
#[cfg(feature = "enable-debug")]
{
    hprintln!("x is {}", x);
    dbg!(x);
}

// This will panic!!!
assert_eq!(x, 8);

loop {
    // Your program loop code here
}
}
```

- How to run

```
cargo watch -c --exec 'run --bin basic --features "enable-debug"'
```

Every time you save `demo/src/bin/basic.rs`, `cargo run --bin basic` will run again.

```
(qemu) System timer demo is running >>>>
x is 10
[examples/basic.rs:35] x = 10
panicked at 'assertion failed: `!(left == right)`
left: `10`,
right: `8`, examples/basic.rs:36:5
[Finished running. Exit status: 1]
```

4.2 The GPIO LED blinking example

In this example, we will use `HAL` crate rather than using `PAC` which provides a better high-level abstraction API for coding. The `HAL` crate is `stm32f4xx-hal`, also make sure enable the `stm32f407` feature, as that's the `MCU` we use.

- Make sure your `.cargo/config` has the settings below:

We need to use the `runner` config without `-nographic`, then `QEMU` will open a dev board GUI, so we can see the blinking LED.

```
[target.thumbv7em-none-eabi]
runner = "qemu-system-gnueclipse -cpu cortex-m4 -mcu STM32F407VG -
machine STM32F4-Discovery -semihosting-config enable=on,target=native
-kernel"
```

- Create `demo/src/bin/gpio_led.rs` with the following code:

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

use cortex_m_rt::entry;

#[cfg(feature = "enable-debug")]
use cortex_m_semihosting::hprintln;

use panic_semihosting as _;

#[cfg(feature = "enable-hal")]
use crate::hal::{prelude::*, stm32};

// This is very important!!!
#[cfg(feature = "enable-hal")]
use stm32f4xx_hal as hal;

// Import from `stm32f4xx_hal`
#[cfg(feature = "enable-hal")]
use hal::{
    delay::Delay,
    gpio::{
        gpiod::{Parts, PD12, PD13, PD14, PD15},
        Output, PushPull,
    },
    rcc::Rcc, // Constrained RCC peripheral
};

#[entry]
fn main() -> ! {
    #[cfg(feature = "enable-debug")]
    let _ = hprintln!("STM32F4 GPIO Led demo is running >>>>");

    let stm32407_peripherals = stm32::Peripherals::take().unwrap();
    let cortex_m_peripherals =
        cortex_m::peripheral::Peripherals::take().unwrap();
}
```

```
// Set up the LEDs. Below LED info copied from STM32F4Discovery
user manual:
//
// • User LD3: orange LED is a user LED connected to the I/O PD13
of the STM32F407VGT6.
//
// • User LD4: green LED is a user LED connected to the I/O PD12
of the STM32F407VGT6.
//
// • User LD5: red LED is a user LED connected to the I/O PD14 of
the STM32F407VGT6.
//
// • User LD6: blue LED is a user LED connected to the I/O PD15
of the STM32F407VGT6.
//
// All those LED pins group into the port `D` which defined here:
// https://docs.rs/stm32f4xx-
hal/0.8.3/stm32f4xx_hal/stm32/struct.GPIO.html#method.split
//
// `GPIOD.split()` return a `Parts` struct instance which include
all pins with the default
// <MODE<type state>> which is `Input<Floating>`:
// https://docs.rs/stm32f4xx-
hal/0.8.3/stm32f4xx_hal/gpio/gpiod/struct.Parts.html
let gpiod: Parts = stm32407_peripherals.GPIOD.split();

// Take all those LED pins and convert into `Output` mode with
`PushPull` type state
let mut green_led: PD12<Output<PushPull>> =
gpiod.pd12.into_push_pull_output();
let mut orange_led: PD13<Output<PushPull>> =
gpiod.pd13.into_push_pull_output();
let mut red_led: PD14<Output<PushPull>> =
gpiod.pd14.into_push_pull_output();
let mut blue_led: PD15<Output<PushPull>> =
gpiod.pd15.into_push_pull_output();

// Set up the system clock. We want to run at 16Mhz for this one.
let constrained_rcc_peripheral: Rcc =
stm32407_peripherals.RCC.constrain();
```

```

let clocks =
constrained_rcc_peripheral.cfgr.sysclk(16.mhz()).freeze();

// Create a delay abstraction based on SysTick
let mut delay = Delay::new(cortex_m_peripherals.SYST, clocks);

// I don't know how the `sysclk` works and how to set the correct
`Mhz`, but for now,
// the `expected_delay_time_in_ms` needs to cut half for getting
the correct delay time.
let expected_delay_time_in_ms = 1000u32;
let delay_time_in_ms = (expected_delay_time_in_ms / 2) as u32;

loop {
    // On for 1s
    green_led.set_high().unwrap();
    orange_led.set_high().unwrap();
    red_led.set_high().unwrap();
    blue_led.set_high().unwrap();

    delay.delay_ms(delay_time_in_ms);

    // off for 1s
    green_led.set_low().unwrap();
    orange_led.set_low().unwrap();
    red_led.set_low().unwrap();
    blue_led.set_low().unwrap();

    delay.delay_ms(delay_time_in_ms);
}
}

```

- How to run

```
cargo watch -c --exec 'run --bin gpio_led --features "enable-debug
enable-hal"'
```

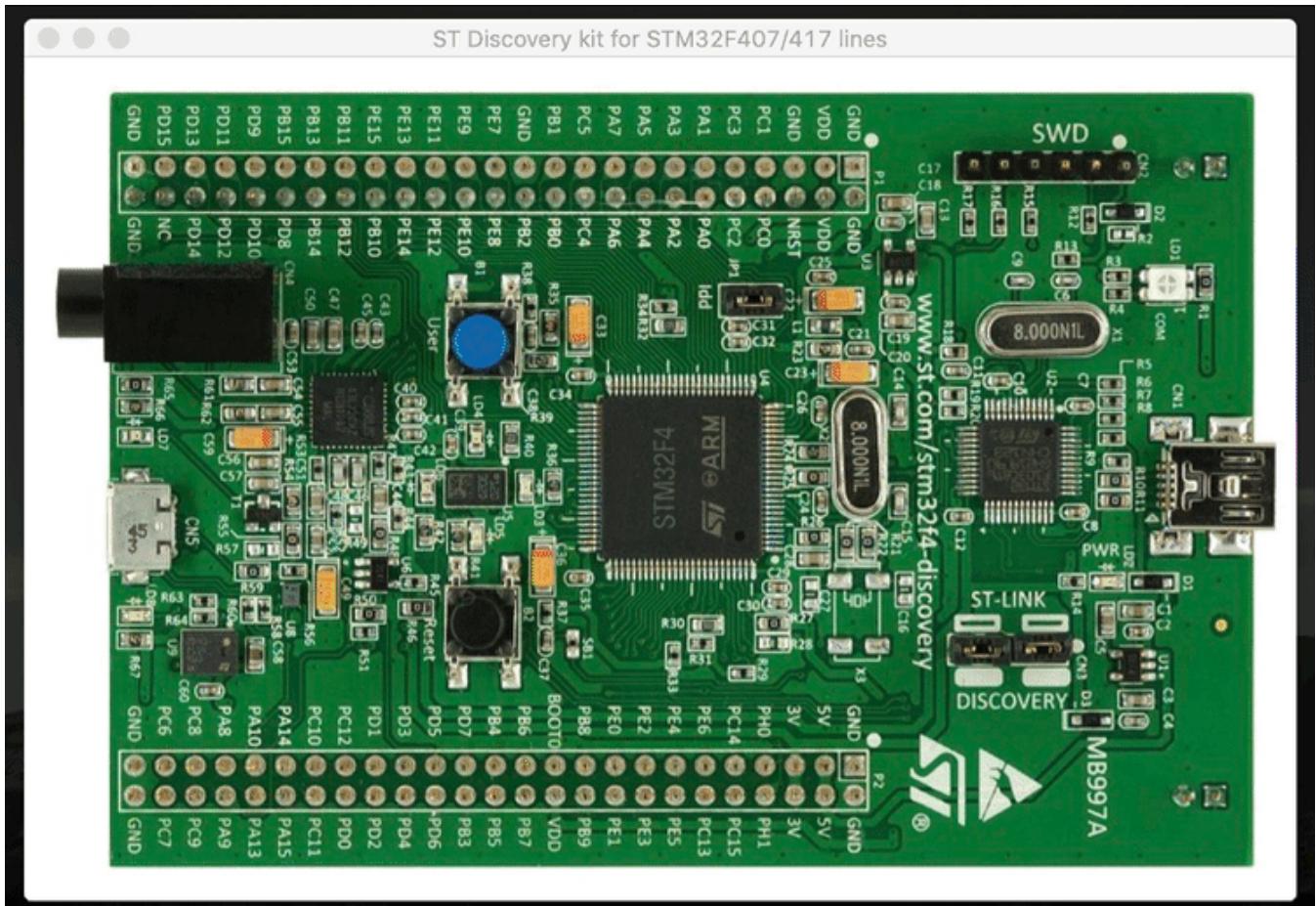
Every time you save `demo/src/bin/gpio_led.rs`, `cargo run --bin gpio_led` will run again.

And you should be able to see the console log like below:

```
cargo watch -c --exec 'run --example gpio_led'
[Running 'cargo run --example gpio_led']
    Finished dev [unoptimized + debuginfo] target(s) in 0.02s
      Running `qemu-system-gnueclipse -cpu cortex-m4 -mcu STM32F407VG -machine STM32
F4-Discovery -semihosting-config enable=on,target=native -kernel target/thumbv7em-none
-eabi/debug/examples/gpio_led`  

STM32F4 GPIO Led demo is running >>>>
[led:green on]
[led:orange on]
[led:red on]
[led:blue on]
[led:green off]
[led:orange off]
[led:red off]
[led:blue off]
```

Also, see the blinking LED in dev board UI:



4.3 How to quit cargo run qemu

The previous example shows us how to run `cargo watch` and `qemu` together like below:

```
cargo watch -c --exec 'run --bin gpio_led --features "enable-debug enable-hal"'
```

But how can you stop and quit that process?

- If `qemu` is running without `-nographic` option, that's easy, just quit the `qemu` UI will quit the `qemu` process.
- If `qemu` is running with `-nographic` option, then you need to follow the steps below:
 - Type `Enter` go into `qemu` CLI, and you can see the `(qemu)` prompt there.
 - Type `quit` and enter, you **CANNOT SEE** what you're typing in, but it just works.
 - Type `Control + C` to end the `cargo run` process.

A screenshot of a terminal window. The text inside the window is:
J

(qemu)
[Finished running. Exit status: 0]
^C◀

The terminal window has a dark background with light-colored text. The '(qemu)' prompt is in orange. The '[Finished running. Exit status: 0]' message is also in orange. The '^C' and the arrow key are highlighted in yellow.

5. Something you need to know before we dive deep

If anyone of you is coming from high-level language programming with zero hardware programming background, then the chapter below is very important for you, as we will go through all the basic concepts and details about **hardware programming**.

5.1 About STM32F4 MCU registers

A register is a special region of memory that controls a **peripheral**. A **peripheral** is a piece of electronics that sits right next to the processor within the microcontroller package and provides the processor with extra functionality. After all, the processor, on its own, can only do math and logic. There are couples of supported peripherals inside the `STM32F4` `MCU`:

- GPIO
- I2C
- SPI
- USART
- RCC
-etc

Why we use `MCU`? The usual reason is that: Want to control the external peripherals (some kind of sensors, robot arms, motors, etc). So the question is How you can control the external peripherals? The answer is via the **peripheral register** inside the `MCU`. Each peripheral includes a couple of registers which call `RegisterBlock` in `stm32f` PAC (Peripheral Access Crate) or HAL (Hardware Abstraction Layer Crate) like below:

Struct `stm32f4::stm32f407::gpioa::RegisterBlock`

[-]

[+] Expand attributes

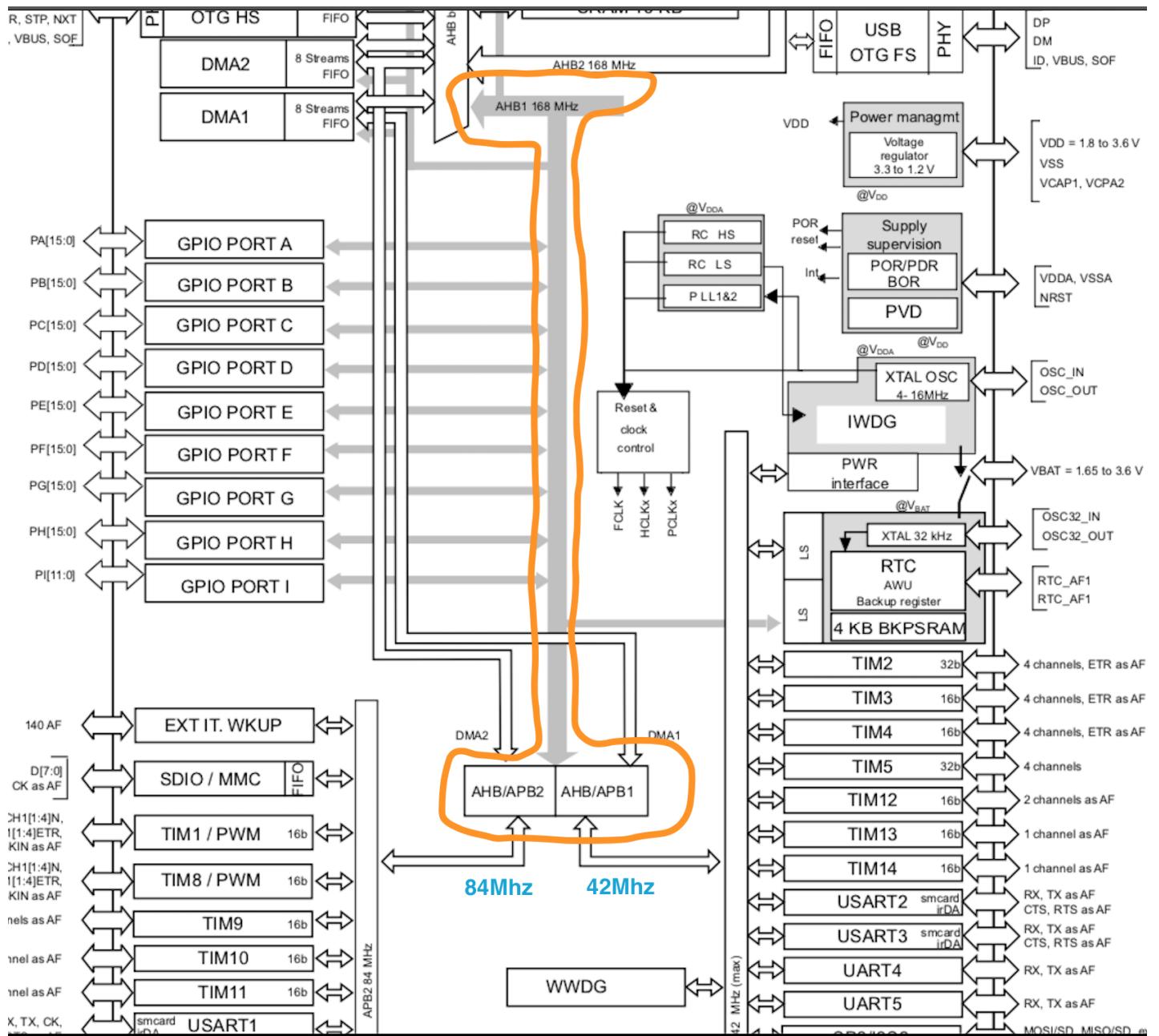
```
pub struct RegisterBlock {  
    pub moder: MODER,  
    pub otyper: OTYPER,  
    pub ospeedr: OSPEEDR,  
    pub pupdr: PUPDR,  
    pub idr: IDR,  
    pub odr: ODR,  
    pub bsrr: BSRR,  
    pub lckr: LCKR,  
    pub afrl: AFRL,  
    pub afrh: AFRH,  
}
```

[-] Register block

Fields

If you have no idea about what those registers for, just leave it at this moment, we will get into the detail later.

But before dive into the **GPIO** register, let's take a look at how those peripherals are connected. Below is the [STM32F4 block diagram](#) in [datasheet](#) (page 19):



As you can see, the orange highlighted part is the system bus, all supported peripherals connected onto it:

- **AHB1** can up to **168Mhz** (`STM32F407VG` for example)
- **AHB1** separated into 2 extra bus for connecting to different peripherals:
 - **AHB1/APB2** is high speed which can up to **84Mhz**
 - **AHB1/APB1** is low speed which can up to **42Mhz**

Ok, so we got enough basic knowledge for the peripheral registers, let's pick the **GPIO registers** as the experimental case and write some low-level code to control the **GPIO register** to turn-on and turn-off the onboard LEDs.

5.2 STM32F4 GPIO registers

This particular register controls **General Purpose Input/Output (GPIO)** pins (**GPIO** is a peripheral) and can be used to drive each of those pins **low** or **high**:

- **Low** means the particular pin is **0** voltage.
- **High** means the particular pin is **output** voltage. For example **5v** or **3.3v** which depends on your **MCU**.

Let's take a look at the **GPIO** registers in the [reference manual](#) page **267**:

Each **GPIO** port has ten registers:

- Four 32-bit configuration registers (**GPIOx_MODER**, **GPIOx_OTYPER**, **GPIOx_OSPEEDR** and **GPIOx_PUPDR**).
- Two 32-bit data registers (**GPIOx_IDR** and **GPIOx_ODR**).
- A 32-bit set/reset register (**GPIOx_BSRR**).
- A 32-bit locking register (**GPIOx_LCKR**).
- Two 32-bit alternate function selection register (**GPIOx_AFRH** and **GPIOx_AFRL**).

x means the port number, each **GPIO** port can handle 16 pins (pin0 ~ pin15). How many **GPIO** port (the **x** value) you have totally depended on the **MCU** itself. For **STM32F407VG** has **GPIOA ~ GPIOK** (11 ports).

It sounds crazy, but let's only focus on the registers below:

- **GPIOx_MODER**: Modify register, it's responsible for setting the GPIO pin to **output** or **input** mode.
- **GPIOx_OTYPER**: Output type register, it's responsible for setting the GPIO pin to specified type: **PushPull**, **OpenDrain**.
- **GPIOx_IDR**: Input data register, it's responsible for reading data from the GPIO pin.
- **GPIOx_ODR**: Output data register, it's responsible for writing data to the GPIO pin. *But we don't use it, we use **GPIOx_BSRR** instead, that's an atomic write operation.*
- **GPIOx_BSRR**: Bit set/reset register, use to write **High** or reset to **Low** to the GPIO pin.

5.3 How to control the GPIO register

Usually, we need a few steps to control the particular peripheral registers:

- Enable it
- Configure it
- Read data from or write data to it

All steps above need the register memory address and we can find it in the [reference manual](#).

In the next demo, we want to turn-on and turn-off the onboard LEDs. For the first step, we need to open [Discovery_kit_withSTM32F407VG MCU_user_manual.pdf](#) and jump to page 16, then we can see the info below:

- User LD3: orange LED is a user LED connected to the I/O PD13 of the STM32F407VGT6.
- User LD4: green LED is a user LED connected to the I/O PD12 of the STM32F407VGT6.
- User LD5: red LED is a user LED connected to the I/O PD14 of the STM32F407VGT6.
- User LD6: blue LED is a user LED connected to the I/O PD15 of the STM32F407VGT6.

So we know that all the LEDs are connected to the **GPIO** port **D** with the `pin 12 ~ pin 15`.

Let's walk through all those steps to reach our goal:

5.3.1 How to enable the **GPIO** port **D**

When you first turn on the `MCU`, everything turns off for power saving. We need to enable the **GPIOD**. And here are the tips:

- Search `gpiod` which stands for “gpiod enable” in the [reference manual](#), then we got this at page 243:

Bit 3 **GPIODEN**: IO port D clock enable

Set and cleared by software.

- 0: IO port D clock disabled
- 1: IO port D clock enabled

Then scroll up to the page 242:

Reset and clock control for STM32F405xx/07xx and STM32F415xx/17xx(RCC)

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7.3.10 RCC AHB1 peripheral clock enable register (**RCC_AHB1ENR**)

Address offset: 0x30

Reset value: 0x00010 0000

Access: no wait state, word, half-word and byte access.

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reser- ved	OTGH S ULPIE N	OTGH SEN	ETHM ACPTP EN	ETHM ACRXE N	ETHM ACTXE N	ETHM CEN		Reserved		DMA2E N	DMA1E N	CCMDAT ARAMEN	Res.	BKPSR AMEN	Reserved	
	rw	rw	rw	rw	rw	rw		rw	rw		rw			rw		
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Reserved		CRCE N	Reserved			GPIOE N	GPIOH EN	GPIOG EN	GPIOFE N	GPIOEEN	GPIOD EN	GPIOC EN	GPIO BEN	GPIO AEN		
			rw				rw	rw	rw	rw	rw	rw	rw	rw		

Bit 31 Reserved, must be kept at reset value.

also, we got the low power mode setting at page 250 as well:

Reset and clock control for STM32F405xx/07xx and STM32F415xx/17xx(RCC)

RM0090

7.3.15 RCC AHB1 peripheral clock enable in low power mode register **(RCC_AHB1LPENR)**

Address offset: 0x50

Reset value: 0x7E67 91FF

Access: no wait state, word, half-word and byte access.

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reser-ved	OTGHS ULPILPE N	OTGH S LPEN	ETHPT P LPEN	ETHRX LPEN	ETHTX LPEN	ETHMA C LPEN	Reserved	DMA2 LPEN	DMA1 LPEN	Reserved	Reserved	BKPSRA M LPEN	SRAM 2 LPEN	SRAM 1 LPEN		
	rw	rw	rw	rw	rw	rw		rw	rw			rw	rw	rw		
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
FLITF LPEN	Reserved	CRC LPEN	Reserved	Reserved	GPIOI LPEN	GPIOH LPEN	GPIOG LPEN	GPIOF LPEN	GPIOE LPEN	GPIOD LPEN	GPIOC LPEN	GPIOB LPEN	GPIOA LPEN			
rw		rw			rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Bit 31 Reserved, must be kept at reset value.

So what information we got here?

- **GPIOD** connects to **AHB1** bus
- There is an **RCC_AHB1ENR** register responsible for enabling the **GPIOD**
- We need to set the **RCC_AHB1ENR** register `bit3` to `1`, then **GPIOD** will be enabled.
- The **RCC_AHB1ENR** register memory address offset is **0x30**

We got a register address *offset*, then what is the address *base*? Keep searching `boundary address`, so we got it in page 65:

0x4002 3800 - 0x4002 3BFF	RCC	
0x4002 3000 - 0x4002 33FF	CRC	
0x4002 2800 - 0x4002 2BFF	GPIOK	
0x4002 2400 - 0x4002 27FF	GPIOJ	
0x4002 2000 - 0x4002 23FF	GPIOI	
0x4002 1C00 - 0x4002 1FFF	GPIOH	
0x4002 1800 - 0x4002 1BFF	GPIOG	
0x4002 1400 - 0x4002 17FF	GPIOF	
0x4002 1000 - 0x4002 13FF	GPIOE	
0x4002 0C00 - 0x4002 0FFF	GPIOD	
0x4002 0800 - 0x4002 0BFF	GPIOC	
0x4002 0400 - 0x4002 07FF	GPIOB	
0x4002 0000 - 0x4002 03FF	GPIOA	

That means the **RCC_AHB1ENR** register memory address will be **0x40023800 + 0x30** which is **0x40023830**.

RCC stand for Reset and Clock Control

There is an **RCC register map** table in [reference manual](#) page 265 as well.

- Then we're able to write `rust` code to enable the **GPIOD** like below:

```
const RCC_REGISTER: u32 = 0x40023800;
const RCC_AHB1ENR_REGISTER: u32 = RCC_REGISTER + 0x30; // page 242,
243
const RCC_AHB1LPENR_REGISTER: u32 = RCC_REGISTER + 0x50; // Low power
(sleep) mode, page 250, 252,
unsafe {
    // Enable `GPIOD` by setting the `bit3` to `1` for both
    registers.
    *(RCC_AHB1ENR_REGISTER as *mut u32) = 1 << 3;
    *(RCC_AHB1LPENR_REGISTER as *mut u32) = 1 << 3;
}
```

5.3.2 About the bitwise operation?

Just a quick tips if you don't know (or totally forgot what you learned from school), here is how you handle the bitwise operation:

```

1 fn main() {
2     let mut b1 = 0b000000111u8;
3     println!("b1(u8): {:08b}", b1);
4
5     // How to set the particular bit to `1`?
6     // For example, I want to set bit5 and bit6 to `1` and left
7     // the rest untouched.
8     b1 |= 1 << 5 | 1 << 6;
9     println!("b1(u8): {:08b} - set bit5 and bit6 = '1'", b1);
10
11    // How to set the particular bit to `0`?
12    // For example, I want to set bit0 and bit1 to `0` and left
13    // the rest untouched.
14    b1 &= !(1 << 0 | 1 << 1);
15    println!("b1(u8): {:08b} - set bit0 and bit1 = '0'", b1);
16
17    // How to set the particular bit to `0` and another bit to `1`?
18    // For example, I want to set bit5 to `0` and bit4 to `1` and left
19    // the rest untouched.
20    // b1 &= !(1 << 5);
21    // b1 |= 1 << 4;
22    b1 = b1 & !(1 << 5) | (1 << 4);
23    println!("b1(u8): {:08b} - set bit5 to '0' and bit4 to '1'", b1);
24 }
```

Finished dev [unoptimized + debuginfo] target(s) in 0.20s
 Running `target/debug/bitwise-operations`
 b1(u8): 00000111
 b1(u8): 01100111 - set bit5 and bit6 = '1'
 b1(u8): 01100100 - set bit0 and bit1 = '0'
 b1(u8): 01010100 - set bit5 to '0' and bit4 to '1'
 [Finished running. Exit status: 0]

5.3.3 How to configure the **GPIO** port **D** to output mode

Let's go to the [reference manual](#) page 281, then we will see the info below:

8.4 GPIO registers

This section gives a detailed description of the GPIO registers.

For a summary of register bits, register address offsets and reset values, refer to [Table 39](#).

The GPIO registers can be accessed by byte (8 bits), half-words (16 bits) or words (32 bits).

8.4.1 GPIO port mode register (GPIOx_MODER) ($x = A..I/J/K$)

Address offset: 0x00

Reset values:

- 0xA800 0000 for port A
- 0x0000 0280 for port B
- 0x0000 0000 for other ports

GPIOx pin 12 ~ pin 15

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
MODER15[1:0]	MODER14[1:0]	MODER13[1:0]	MODER12[1:0]	MODER11[1:0]	MODER10[1:0]	MODER9[1:0]	MODER8[1:0]								
0 rw	1 rw	0 rw	1 rw	0 rw	1 rw	0 rw	1 rw	rw	rw	rw	rw	rw	rw	rw	rw
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
MODER7[1:0]	MODER6[1:0]	MODER5[1:0]	MODER4[1:0]	MODER3[1:0]	MODER2[1:0]	MODER1[1:0]	MODER0[1:0]								
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Bits 2y:2y+1 **MODERy[1:0]**: Port x configuration bits ($y = 0..15$)

These bits are written by software to configure the I/O direction mode.

00: Input (reset state)

01: General purpose output mode

10: Alternate function mode

11: Analog mode

8.4.2 GPIO port output type register (GPIOx_OTYPER) ($x = A..I/J/K$)

Address offset: 0x04

Reset value: 0x0000 0000

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved															
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
OT15	OT14	OT13	OT12	OT11	OT10	OT9	OT8	OT7	OT6	OT5	OT4	OT3	OT2	OT1	OT0
0 rw	0 rw	0 rw	0 rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Bits 31:16 Reserved, must be kept at reset value.

Bits 15:0 **OTy**: Port x configuration bits ($y = 0..15$)

These bits are written by software to configure the output type of the I/O port.

0: Output push-pull (reset state)

1: Output open-drain

So what information we got here?

- **GPIOx_MODER** uses to configure the register mode, take a look at the blue highlighted part:

- MODER12 means **pin 12**, MODER13 means **pin 12**, ..., MODER15 means **pin 15**

- Each pin use 2 bits to set the register to the particular mode
 - For setting the **pin 12** to output mode, we need to set `01` to `bit25` and `bit24`
 - ...
 - For setting the **pin 15** to output mode, we need to set `01` to `bit31` and `bit30`
-
- **GPIOD_OTYPER** uses to configure the register output type, take a look at the orange highlighted part:
 - Each pin use 1 bit to set the register to the particular output mode
 - For setting the **pin 12** to `push-pull` mode, we need to set `0` to `bit12`
 - ...
 - For setting the **pin 15** to `push-pull` mode, we need to set `0` to `bit15`
 - Then we're able to write `rust` code to configure **GPIOD** work in **output** mode like below:

```
// `GPIOD` register mapping address, in `reference manual` page 65,
(`STM32F4xx register boundary addresses`).
const GPIOD_REGISTER: u32 = 0x40020c00;

// GPIO port mode register (GPIOx_MODER) address, `reference manual`
page 281.
const GPIOD_MODER: u32 = GPIOD_REGISTER + 0x00;
let gpiod_moder_mut_ptr: *mut u32 = GPIOD_MODER as *mut u32; // 
Mutable raw pointer
let gpiod_moder_ptr: *const u32 = GPIOD_MODER as *const u32; // 
Immutable raw pointer
unsafe {
    // Set `GPIOD` pin12 ~ pin15 to OUTPUT mode

    // Keep the prev value and add (`|`) new setting:
    // bit 25, 24 set to `01`
    // bit 27, 26 set to `01`
    // bit 29, 28 set to `01`
    // bit 31, 30 set to `01`
    *gpiod_moder_mut_ptr |= (1 << 24) | (1 << 26) | (1 << 28) | (1 <<
30);

    // Let's print the "GPIOD_MODER" register bit value (32bit, 4
bytes), and it should be:
    // 0b01010101000000000000000000000000
    //
    // From right to left is bit0 ~ bit31, only bit24, bit26, bit 28,
    bit30 set to `1`.
    #[cfg(feature = "enable-debug")]
    let _ = hprintln!("GPIOD_MODER: {:#034b}", *gpiod_moder_ptr);
}

// GPIO port output type register (GPIOx_OTYPER) address, `reference
manual` page 281.
// As the output type `push-pull` is `0`, then we don't need to set
```

```
`GPIOD_OTYPER` explicitly.  
// const GPIOD_OTYPER: u32 = GPIOD_REGISTER + 0x04;
```

5.3.4 How to set the GPIO port D (pin12 ~ pin15) to High or Low

Let's go to the [reference manual](#) page 284, then we will see the info below:

General-purpose I/Os (GPIO)

RM0090

8.4.7 GPIO port bit set/reset register (GPIOx_BSRR) (x = A..I/J/K)

Address offset: 0x18

Reset value: 0x0000 0000

Set `1` to `bsbitX + 16` to set `Low`

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
BR15	BR14	BR13	BR12	BR11	BR10	BR9	BR8	BR7	BR6	BR5	BR4	BR3	BR2	BR1	BR0
1 w	1 w	1 w	1 w	w	w	w	w	w	w	w	w	w	w	w	w
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
BS15	BS14	BS13	BS12	BS11	BS10	BS9	BS8	BS7	BS6	BS5	BS4	BS3	BS2	BS1	BS0
1 w	1 w	1 w	1 w	w	w	w	w	w	w	w	w	w	w	w	w

Bits 31:16 **BRy**: Port x reset bit y (y = 0..15)

These bits are write-only and can be accessed in word, half-word or byte mode. A read to these bits returns the value 0x0000.

0: No action on the corresponding ODRx bit

1: Resets the corresponding ODRx bit

Note: If both BSx and BRx are set, BSx has priority.

Bits 15:0 **BSy**: Port x set bit y (y = 0..15)

These bits are write-only and can be accessed in word, half-word or byte mode. A read to these bits returns the value 0x0000.

0: No action on the corresponding ODRx bit

1: Sets the corresponding ODRx bit

So what information we got here?

- **GPIOB_BSRR** uses to set the register value (High or Low)

- How to set High, take a look at the green highlighted part:

- `bit0` to `bit15` means **pin 0 to pin 15** and use to set **High**

- After setting to `1`, it will set the corresponding **GPIOD_ODR** register bit
 - Nothing will happen when setting the `0` to the specified bit
 - For setting the **pin 12** to `High`, we need to set `bit12` to `1`
 - ...
 - For setting the **pin 15** to `High`, we need to set `bit15` to `1`
- How to set `Low`, take a look at the red highlighted part:
- `bit16` to `bit31` means **pin 0** to **pin 15** and use to set `Low`
 - After setting to `1`, it will set the corresponding **GPIOD_ODR** register bit
 - Nothing will happen when setting the `0` to the specified bit
 - For setting the **pin 12** to `Low`, we need to set `bit(12 + 16)` to `1`
 - ...
 - For setting the **pin 15** to `Low`, we need to set `bit(15 + 16)` to `1`
- Then we're able to write `rust` code to set **pin 12~15** to `High` or `Low` like below:

```
// GPIO port bit set/reset register (GPIOx_BSRR) address, `reference
manual` page 284.

const GPIOD_BSRR: u32 = GPIOD_REGISTER + 0x18;
let gpiod_bsrr_mut_ptr = GPIOD_BSRR as *mut u32;

// Setup GPIOD.P12 ~ P15 to output mode with `

unsafe {
    // Set bit (pin) 12 ~ 15 to `1` to turn on 4 LEDs. As the
    "GPIOD_BSRR" does nothing when
    //
    // As the "GPIOD_BSRR" does nothing when setting bit to `0`, so
    actually, we even don't
    // need the |=` for keeping the previous value.
    *gpiod_bsrr_mut_ptr = (1 << 12) | (1 << 13) | (1 << 14) | (1 <<
15);
}

#[cfg(feature = "enable-debug")]
let _ = hprintln!("\\nDelay 1s.....\\n");

delay.delay_ms(delay_time_in_ms);

unsafe {
    // Set bit (pint) 12 + 16, 13 + 16 to `1` to turn off 2 LEDs. As
    the "GPIOD_BSRR" does nothing when
    //
    // As the "GPIOD_BSRR" does nothing when setting bit to `0`, so
    actually, we even don't
    // need the |=` for keeping the previous value.
    *gpiod_bsrr_mut_ptr = (1 << (12 + 16)) | (1 << (13 + 16));
}
```

5.4 Finally, Let's put all together: use raw GPIO register to control LED

- Make sure your `.cargo/config` has the settings below:

We need to use the `runner` config without `-nographic`, then `QEMU` will open a dev board GUI, so we can see the blinking LED.

```
[target.thumbv7em-none-eabi]
runner = "qemu-system-gnueclipse -cpu cortex-m4 -mcu STM32F407VG -
machine STM32F4-Discovery -semihosting-config enable=on,target=native
-kernel"
```

- Create `demo/src/bin/gpio_led_by_register.rs` with the following code:

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

use cortex_m::asm::delay;
use cortex_m_rt::entry;

#[cfg(feature = "enable-debug")]
use cortex_m_semihosting::hprintln;

use panic_semihosting as _;

// As we don't use `PAC` and `HAL` in this example, and we didn't
// touch the `Clock` and
// `Interrupt` yet. That's why we use a dumb version `delay` at this
moment. It's not
// accuracy, that's fine, as that's not the point we focus on at this
moment.

fn dumb_delay(millisecond: u32) {
    delay(100_000 * millisecond);
}

#[entry]
fn main() -> ! {
    #[cfg(feature = "enable-debug")]
    let _ = hprintln!("STM32F4 GPIO Register Led demo is running
>>>>");

    // Below is the very important step:
    //
    // When you first turn on the `MCU`, everything turns off for
power saving. We need to enable
    // the `GPIOD` port. Info in `reference manual` (page 265, RCC
register map).
    //
    // RCC (Reset and Clock Control)
    const RCC_REGISTER: u32 = 0x4002_3800;
    const RCC_AHB1ENR_REGISTER: u32 = RCC_REGISTER + 0x30; // page
```

242, 243

```

const RCC_AHB1LPENR_REGISTER: u32 = RCC_REGISTER + 0x50; // Low
power (sleep) mode, page 250, 252,
unsafe {
    // Enable `GPIOD` by setting the `bit3` to `1` for both
    registers.
    *(RCC_AHB1ENR_REGISTER as *mut u32) = 1 << 3;
    *(RCC_AHB1LPENR_REGISTER as *mut u32) = 1 << 3;
}

// `GPIOD` register mapping address, in `reference manual` (page
65, `STM32F4xx register boundary addresses`).
const GPIOD_REGISTER: u32 = 0x4002_0c00;

// GPIO port mode register (GPIOx_MODER) address, `reference
manual` (page 281).
const GPIOD_MODER: u32 = GPIOD_REGISTER + 0x00;
let gpiod_moder_mut_ptr: *mut u32 = GPIOD_MODER as *mut u32; // 
Mutable raw pointer
let gpiod_moder_ptr: *const u32 = GPIOD_MODER as *const u32; // 
Immutable raw pointer
unsafe {
    // Set `GPIOD` pin12 ~ pin15 to OUTPUT mode

    // Keep the prev value and add (`|`) new setting:
    // bit 25, 24 set to `01`
    // bit 27, 26 set to `01`
    // bit 29, 28 set to `01`
    // bit 31, 30 set to `01`
    //
    // As the "GPIOD_BSRR" does nothing when set bit to `0`, so
    actually, we even don't
        // need the `|=` for keeping the prev value. But we keep that
        just doing in the normal
        //
        // way.
        //
        *gpiod_moder_mut_ptr |= (1 << 24) | (1 << 26) | (1 << 28) |
}

```

```
(1 << 30);

        // Let's print the "GPIOD_MODER" register bit value (32bit, 4
bytes), and it should be:
        // 0b01010101000000000000000000000000
        //
        // From right to left is bit0 ~ bit31, only bit24, bit26, bit
28, bit30 set to `1`.
#[cfg(feature = "enable-debug")]
let _ = hprintln!("GPIOD_MODER: {:#034b}", *gpiod_moder_ptr);
}

// GPIO port output type register (GPIOx_OTYPER) address,
`reference manual` (page 281).
// As the output type `push-pull` is `0`, then we don't need to
set `GPIOD_OTYPER` explicitly.
// const GPIOD_OTYPER: u32 = GPIOD_REGISTER + 0x04;

// GPIO port bit set/reset register (GPIOx_BSRR) address,
`reference manual` (page 284).
const GPIOD_BSRR: u32 = GPIOD_REGISTER + 0x18;
let gpiod_bsrr_mut_ptr = GPIOD_BSRR as *mut u32;

// Setup GPIOD.P12 ~ P15 to output mode with `

unsafe {
    // Set bit (pin) 12 ~ 15 to `1` to turn on 4 LEDs.
    //
    // As the "GPIOD_BSRR" does nothing when setting bit to `0`,
so actually, we even don't
        // need the |=` for keeping the previous value.
    *gpiod_bsrr_mut_ptr = (1 << 12) | (1 << 13) | (1 << 14) | (1
<< 15);
}

#[cfg(feature = "enable-debug")]
let _ = hprintln!("\nDelay 1s.....\n");
```

```
dumb_delay(10000);

unsafe {
    // Set bit (pint) 12 + 16, 13 + 16 to `1` to turn off 2 LEDs.
    //
    // As the "GPIOD_BSRR" does nothing when setting bit to `0`,
    so actually, we even don't
    // need the `|=` for keeping the previous value.
    *gpiod_bsrr_mut_ptr = (1 << (12 + 16)) | (1 << (13 + 16));
}

loop {}
}
```

- How to run

we don't need `PAL` or `HAL` crate anymore, as we will use low-level implementation:

```
cargo watch -c --exec 'run --bin gpio_led_by_register --features "enable-debug"'
```

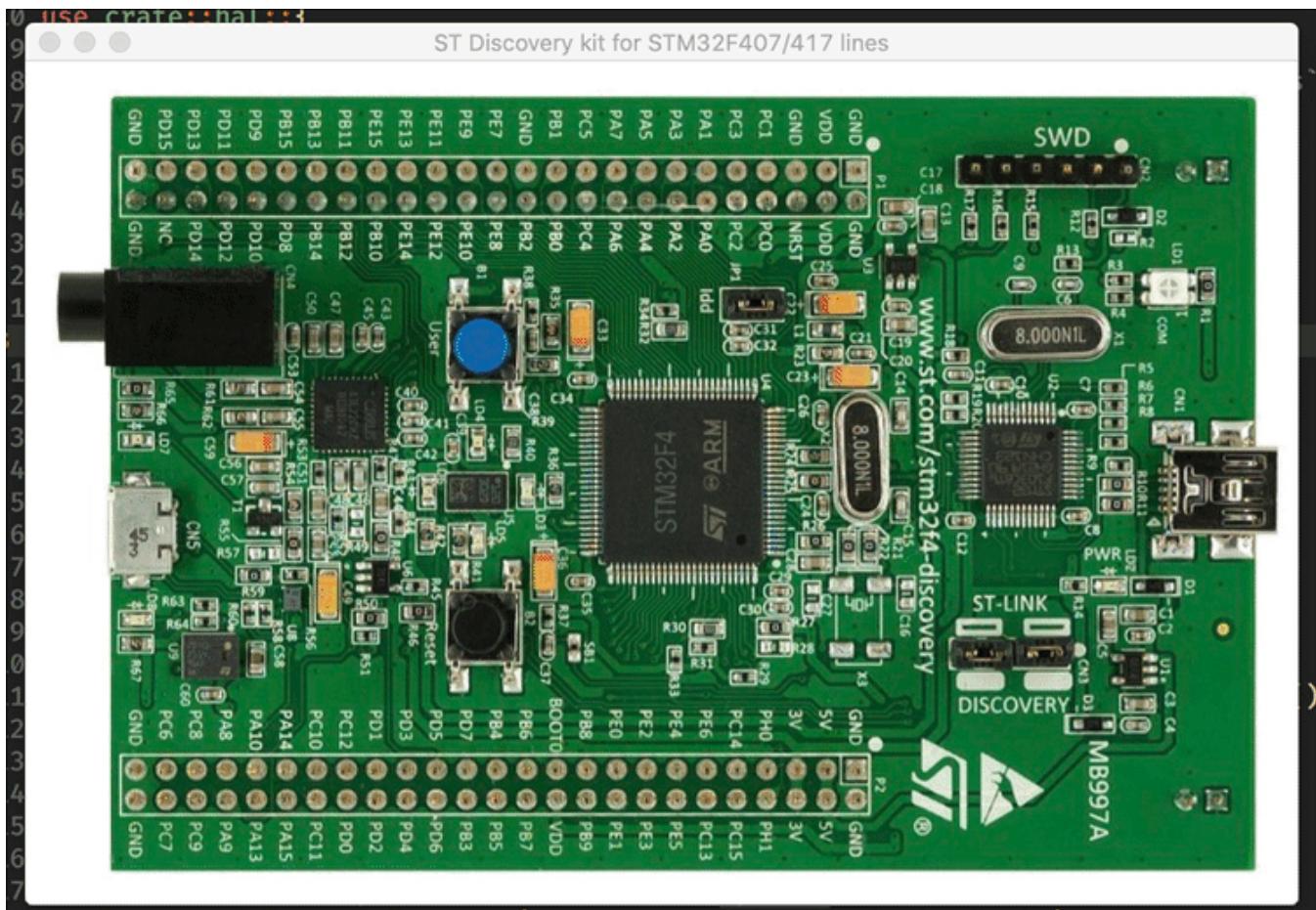
Every time you save `demo/src/bin/gpio_led_by_register.rs`, `cargo run --bin gpio_led_by_register` will run again.

And you should be able to see the console log like below:

```
Finished dev [unoptimized + debuginfo] target(s) in 0.18s
Running `qemu-system-gnueclipse -cpu cortex-m4 -mcu STM32F407VG -machine STM32F4-Discovery -semihosting-config enable=on,target=native -kernel target/thumbv7em-none-eabi/debug/examples/gpio_led_by_register`
STM32F4 GPIO Register Led demo is running >>>
GPIO MODER: 0b01010101000000000000000000000000
[led:green on]
[led:orange on]
[led:red on]
[led:blue on]

Delay 1s.....
[led:green off]
[led:orange off]
```

Also, see 4 LEDs on and 2 off after 1s in dev board UI:



5.5 Let's fix the bug in release build

Ok, so far, it works well in the **debug** mode. But actually it won't work like what we expected in the **release** mode.

Let's give it a try by running the commands below:

```
# Build and strip the release mode binary
cargo-strip --target thumbv7em-none-eabi --bin gpio_led_by_register --
release

# Run that release mode binary in `QEMU`
qemu-system-gnueclipse -cpu cortex-m4 -mcu STM32F407VG -machine
STM32F4-Discovery -semihosting-config enable=on,target=native -kernel
target/thumbv7em-none-eabi/release/gpio_led_by_register
```

And you should see **all LEDs are off and never on!!!** Wow, what happened there???

Let's take a look at the special lines below:

```

60:          *gpiod_moder_mut_ptr |= (1 << 24) | (1 << 26) | (1 << 28) | (1
<< 30);

84:          *gpiod_bsrr_mut_ptr = (1 << 12) | (1 << 13) | (1 << 14) | (1
<< 15);

95:          *gpiod_bsrr_mut_ptr = (1 << (12 + 16)) | (1 << (13 + 16));

```

For explaining the **potential bug** there, plz have a look the sample code below:

```

fn main() {
    let mut a = 10u8;
    println!("a: {}", a);

    let ptr_to_a = &mut a as *mut u8;
    unsafe {
        *ptr_to_a = 50u8;
        *ptr_to_a = 100u8;
        *ptr_to_a = 200u8;
        println!("a: {}", a);
    }
}

```

When building with `--release`, LLVM tries to optimize the code. As we assigned three times to the same memory which `ptr_to_a` points to, then LLVM may think and see the code like this:

```

let ptr_to_a = &mut a as *mut u8;
unsafe {
    // *ptr_to_a = 50u8;
    // *ptr_to_a = 100u8;
    *ptr_to_a = 200u8;
    println!("a: {}", a);
}

```

That's why our `*gpiod_moder_mut_ptr` be assigned with the `unexpected` value and caused the code work not correct.

So, how to fix it? That's easy, use `core::ptr::write_volatile()` and `core::ptr::read_volatile()` when we deal with register pointer:

```

60:     core::ptr::write_volatile(gpiod_moder_mut_ptr, (1 << 24) | (1 <<
26) | (1 << 28) | (1 << 30));
84:     core::ptr::write_volatile(gpiod_bsrr_mut_ptr, (1 << 12) | (1 <<
13) | (1 << 14) | (1 << 15));
95:     core::ptr::write_volatile(gpiod_bsrr_mut_ptr, (1 << (12 + 16)) |
(1 << (13 + 16)));

```

The fixed version is in [gpio_led_by_register_fixed.rs](#)

Try it right now, it should work as we expected:

```

cargo-strip --target thumbv7em-none-eabi --bin gpio_led_by_register_fixed
--release
qemu-system-gnuarmeclipse -cpu cortex-m4 -mcu STM32F407VG -machine
STM32F4-Discovery -semihosting-config enable=on,target=native -kernel
target/thumbv7em-none-eabi/release/gpio_led_by_register_fixed

```

5.6 The fun part, code comparison

As maybe some of you are wondering which `coding solution` is better: The `HAL` one? or the `Low-level` one?

Let's make a code comparison to have a look (left-side is `HAL`, right-side is `Low-level`):

<pre> 1 // Open `GPIO` and configure all pins use `output` mode with 1 // `push_pull` output type >> let gpiod: Parts = stm32407_peripherals.GPIO_D_split(); 3 >> let mut green_led: PD12<Output<PushPull>> = gpiod.pd12.into_push_pull_output(); >> let mut orange_led: PD13<Output<PushPull>> = gpiod.pd13.into_push_pull_output(); >> let mut red_led: PD14<Output<PushPull>> = gpiod.pd14.into_push_pull_output(); >> let mut blue_led: PD15<Output<PushPull>> = gpiod.pd15.into_push_pull_output(); 8 9 // Set all pins to `High` >> green_led.set_high().unwrap(); >> orange_led.set_high().unwrap(); >> red_led.set_high().unwrap(); >> blue_led.set_high().unwrap(); 14 15 // Set all pins to `Low` >> green_led.set_low().unwrap(); >> green_led.set_low().unwrap(); >> orange_led.set_low().unwrap(); >> red_led.set_low().unwrap(); >> blue_led.set_low().unwrap(); ~ ~</pre>	<pre> 1 // Open `GPIO` and configure all pins use `output` mode with 1 // `push_pull` output type 1 const RCC_REGISTER: u32 = 0x40023800; 3 const RCC_AHB1ENR_REGISTER: u32 = RCC_REGISTER + 0x30; // page 242, 243 4 const RCC_AHB1LPENR_REGISTER: u32 = RCC_REGISTER + 0x50; // Low power (sleep) mode, page 250, 252, >> unsafe { 6 *(RCC_AHB1ENR_REGISTER as *mut u32) = 1 << 3; 7 *(RCC_AHB1LPENR_REGISTER as *mut u32) = 1 << 3; 8 } 9 10 const GPIOD_REGISTER: u32 = 0x40020c00; 11 const GPIOD_MODER: u32 = GPIOD_REGISTER + 0x00; >> let gpiod_moder_mut_ptr: *mut u32 = GPIOD_MODER as *mut u32; // Mutable raw pointer >> let gpiod_moder_ptr: *const u32 = GPIOD_MODER as *const u32; // Immutable raw pointer >> unsafe { 15 *gpiod_moder_mut_ptr = (1 << 24) (1 << 26) (1 << 28) (1 << 30); 16 } 17 18 // Set all pins to `High` 19 const GPIOD_BSRR: u32 = GPIOD_REGISTER + 0x18; >> let gpiod_bsrr_mut_ptr = GPIOD_BSRR as *mut u32; 21 >> unsafe { *gpiod_bsrr_mut_ptr = (1 << 12) (1 << 13) (1 << 14) (1 << 15); } 23 24 // Set all pins to `Low` >> unsafe { *gpiod_bsrr_mut_ptr = (1 << (12 + 16)) (1 << (13 + 16)); }</pre>
--	---

- `HAL` pros and cons:
 - It looks like less code (total lines for the same purpose).

- It can fit all `STM32` series, just change the `features` in `Cargo.toml`.
- But of course, you need to spent more time to learn the `HAL` crate and get familiar with it (concepts, structs, modules and functions).

- `Low-level` pros and cons:
 - Sometimes a little more code to setup the registers.
 - Not guaranteed can fit for all `STM32` series (actually, that's not possible).
 - It's simple and good for hardware background developer: Just open the reference manual and check the particular register, then start to code. All you needed just the basic computer knowledge: bit wise operation.
 - As no more `PAC` or `HAL` needed, then you got full-control and output the binary size as small as possible.

*So that means no right answer, it totally depends on **YOU**:*

5.7 Why we pick low-level

For the rest of the chapters, we pick the low-level (pure register controlling) code style for all demos, why?

No matter what knowledge we're learning, usually 2 steps we can follow:

1. *We only need to know how to use it. For example, turning on a light bulb or turning it off, that's simple and fit the requirement as a normal user.*
2. *We need to know how it works, then we're able to change it, even improve it. For example, if you're an energy-saving light bulb company, then you have to figure out how the light bulb works and improve it, that's another story.*

That means there isn't an absolute right answer, it's totally up to you, as you know what you want. But **we will pick the No.2 way to continue learning and use low-level register controlling style to code for the rest of demos**. Why?

- If you know how this works, then no more secrets you don't know, you're able to build anything you want. And you should have the ability to work on professional `STM32` project in Rust.

- When you're working on your unique project, you got full control. How to say that?
 - The `PAC` or `HAL` crate both are designed for generic use cases, may not suit your unique hardware product situation. Sometimes, you found that it's pretty not straightforward to reach what you want based on those crates.
 - Those crates are contributed by many people with different background and skill experience, it will have bugs. When you face that, you can't get fixed immediately as that's out of your control. For example, you can't ask for somebody to fix the bug you encountered as soon as possible (as you need that be fixed on your hardware product). That does not make sense for a generic purpose share library.

So that's why we should figure out the theory and the low-level implementation, then we got the benefits below:

1. *We only rely on the STM official reference manual.*
2. *We got full control for picking the easy way and straight ahead solution to code.*
3. *We can apply immediate fix or improvement idea or solution at any given time.*
4. *After we got real experience, we can build our own `PAC` or `HAL` crate and contribute back to the community.*

6. Simple brief of `Clock`

The `Clock` is a very important component in `MCU`, it provides the pulse for all components and peripherals to make sure they work correctly. `MCU` can't work without a stable clock signal, just like a human can't live without a stable blood pulse.

Because not everyone got solid electricity knowledge, then let's make it easy. Before start coding your first `STM32` project, you need to know about the following concepts.

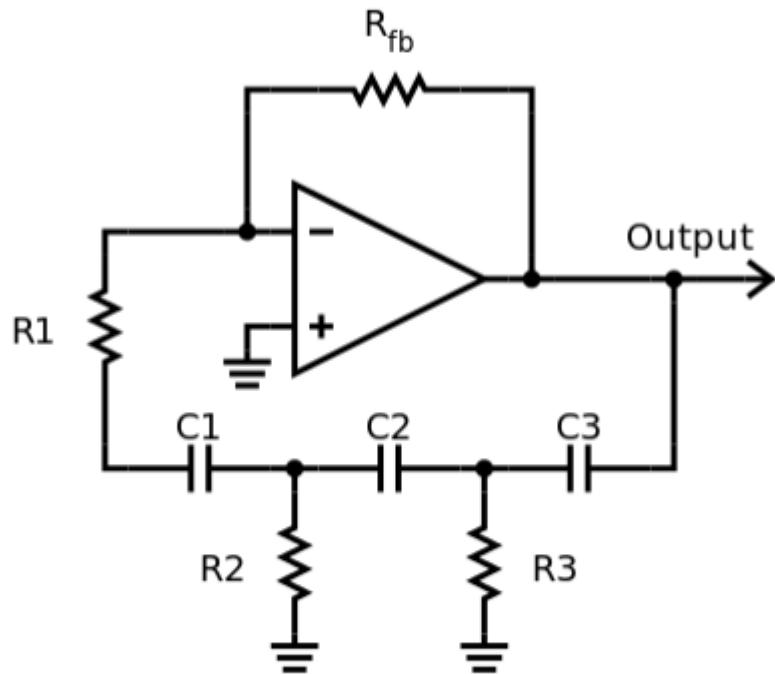
6.1 What is clock source selecting?

The MCU runs on a specified working frequency, that's why we need to set the system clock (SYSCLK) working frequency. Usually, that frequency generated by multiple Clock Sources .

So, we can use the default clock source chose by the chip or we need to pick the one we need, and that process is called Clock Source Selecting .

6.2 What exactly the Clock is?

The Clock we're talking about actually is Oscillator . If you google it or go to the wiki about oscillator (RC oscillator, crystal oscillator), it just a circuit, for example, it may look like below:



A phase-shift oscillator

The physical look & feel will look like this:

Crystal oscillator



Yes, that's the `Clock` we're talking about. The only thing you need to keep in mind is that: **That oscillator can generate a stable clock signal to drive all components and peripherals to work correctly.**

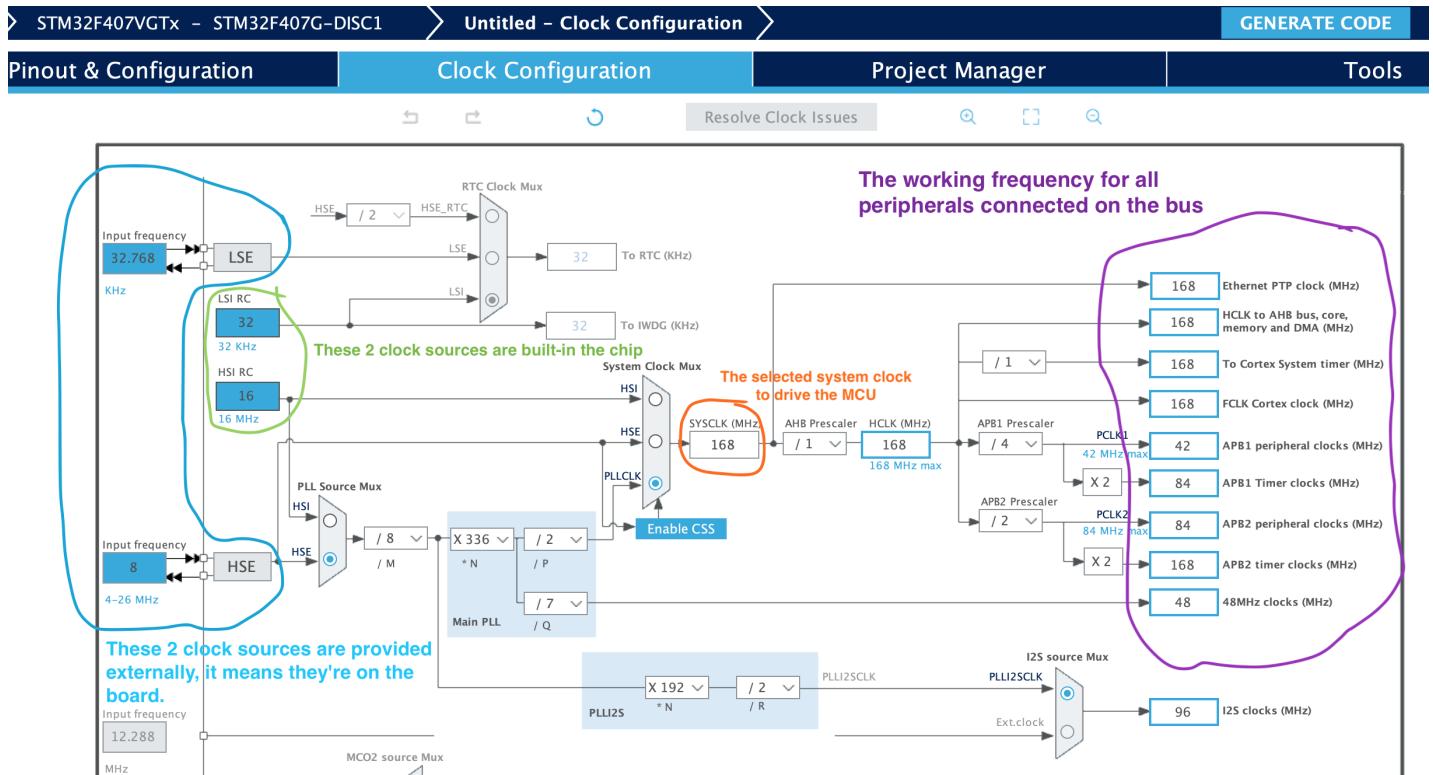
You still can code your program without fully understand what that means, then no worry at this moment:)

Two major `Clock` type in the [reference manual](#):

- Internal: it means the oscillator circuit is inside the `STM32` chip.
- External: it means the oscillator component is outside the `STM32` chip, usually soldered onboard.

6.3 What a `Clock tree diagram` looks like?

The below diagram is a screenshot from `STMCubeMX` projet, it shows a pretty straightforward strategy of clock source selecting:



Yes, it looks very complicated and scary for the first time, but relax, it's not that hard actually:)

So what information we got from the diagram?

- Based on the **blue** highlighted, we know that there are 2 external clock sources can connect to the chip for different purposes.
- Based on the **green** highlighted, we know that there are 2 internal clock sources inside the chip for different purposes.
- The **orange** highlighted shows what the final system clock (**SYSCLK**) working frequency will be used.
- The **purple** highlighted let us know what exact working frequency on the particular peripherals.

That's it, that's enough for us at this moment.

Tips:

- STMCubeMX** is a **STMCube** project initialization and code generation tools which you can download [here](#).

- *STMCubeMX just an optional tools for us, as it generates the C++ code, not the Rust code. But for the Clock source selecting, that diagram is super helpful for us, good to have.*

6.4 Let's dive deep into the `clock source selecting`

First thing first, there are a few kinds of `clocks` in the [reference manual](#) starts from page **215**, but we only need to focus on the three of them below:

- **HSE**

High-Speed External clock signal, usually, it's external onboard oscillator hardware with the fixed frequency. Make sure you check the hardware datasheet before setting `HSE` value (unit in **Hertz**).

- **HSI**

High-Speed Internal clock signal, it's an internal 16 MHz RC oscillator.

- **PLL**

This stuff is complicated, as it stands for **Phase-Locked Loop**. It sounds scary for you, as you have no idea what that means. Briefly, it takes the input frequency and uses different factor settings to change the output frequency.

So, let's have a close look at the `Clock source selecting`:

We can pick one of the paths below as the clock source and calculate the `SYSCLK` frequency:

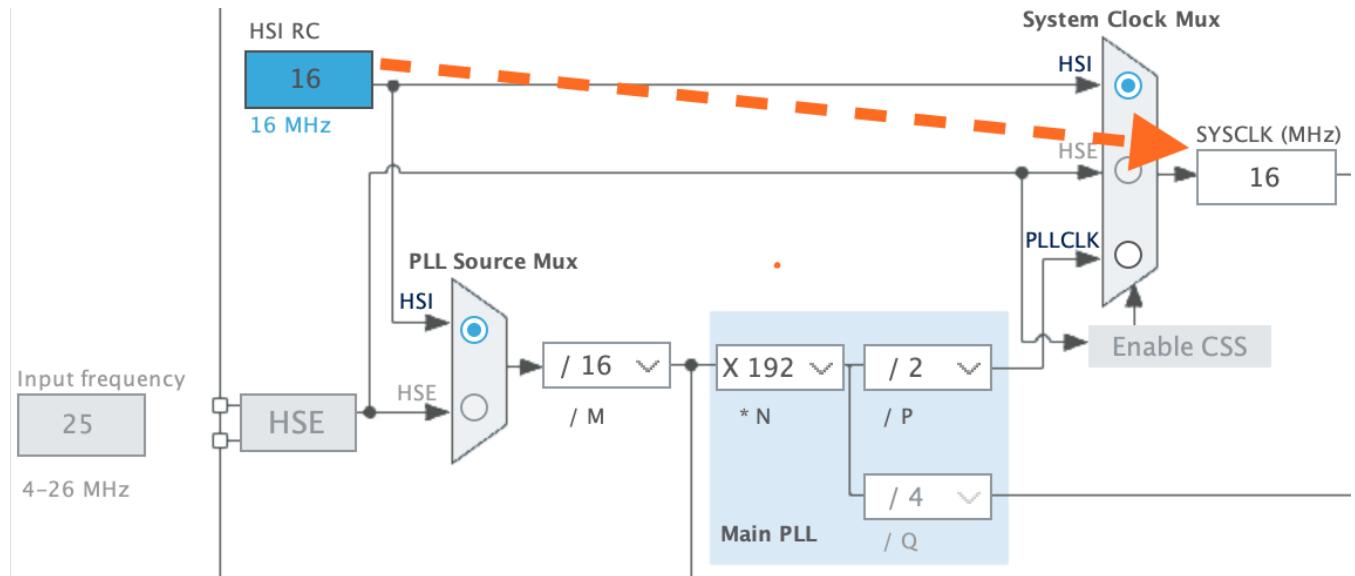
- `HSI` ----> `SYSCLK`
- `HSE` ----> `SYSCLK`
- `PLL` ----> $(\text{HSI or HSE}) / \text{PLL_M} * \text{PLL_N} / \text{PLL_P}$ ----> `SYSCLK`

As you can see, it's not that hard:)

When the expected frequency is higher than `HSI` or `HSE` can offer, then you have to use `PLL` as clock source!!!

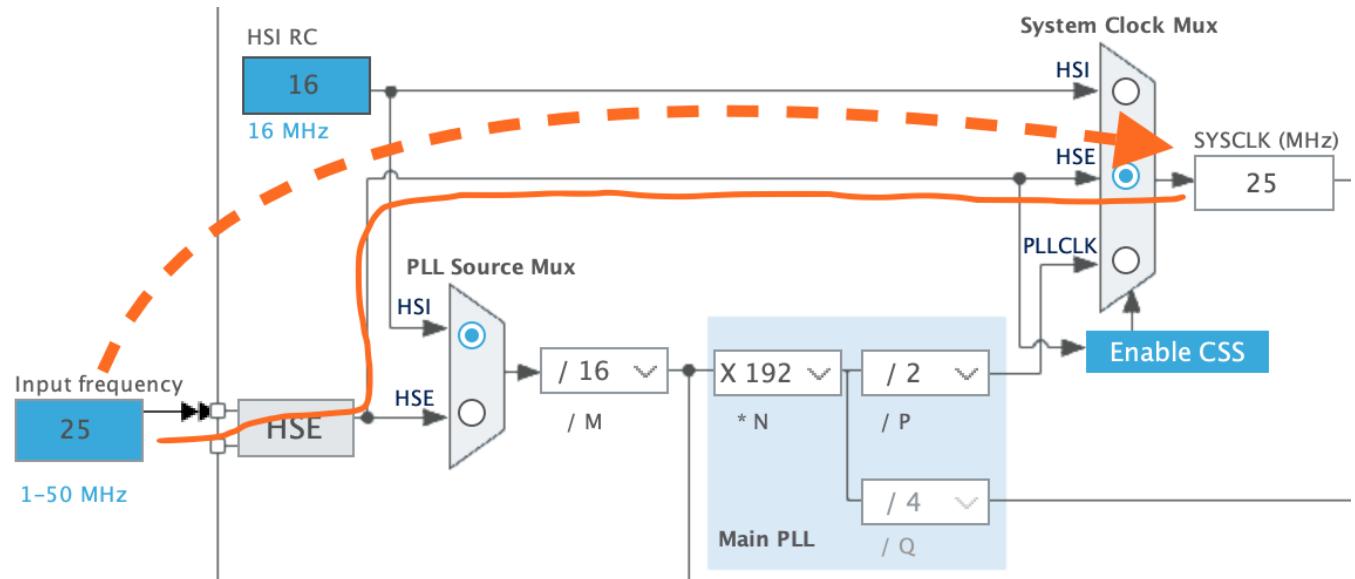
Let's have a look at them one by one:

- **HSI** --> **SYSCLK**:



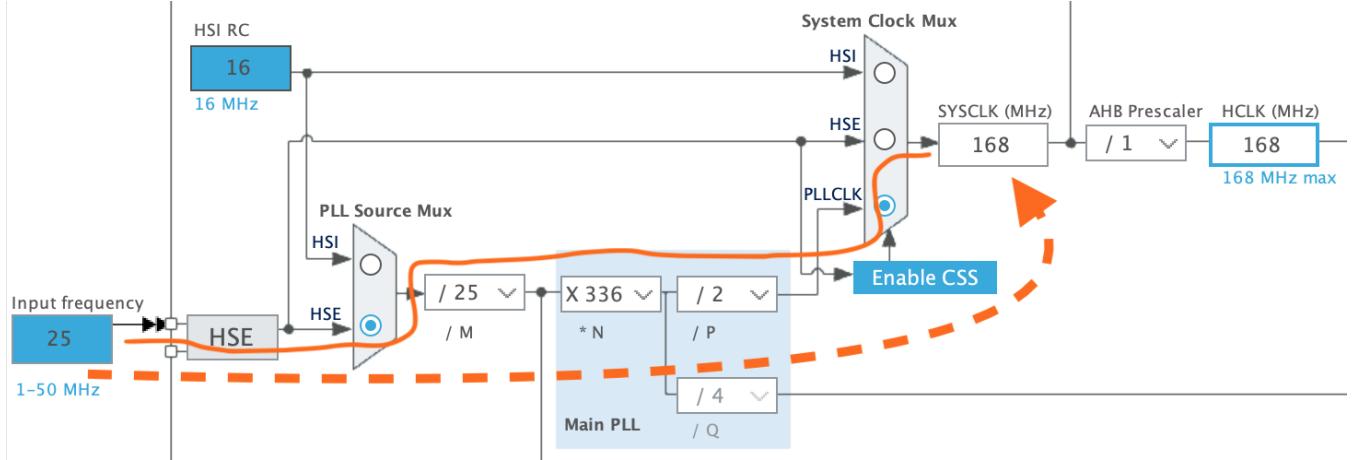
This is the case of **HSI** as the clock source. You can see the **SYSCLK** get clock signal directly from **HSI** and the final frequency is **16MHz**.

- **HSE** --> **SYSCLK**:



This is the case of **HSE** as the clock source, also call **HSE bypass mode** (as not go through **PLL**). You can see the **SYSCLK** get clock signal directly from **HSE** and the final frequency is **25MHz** (equal to **HSE** offered frequency).

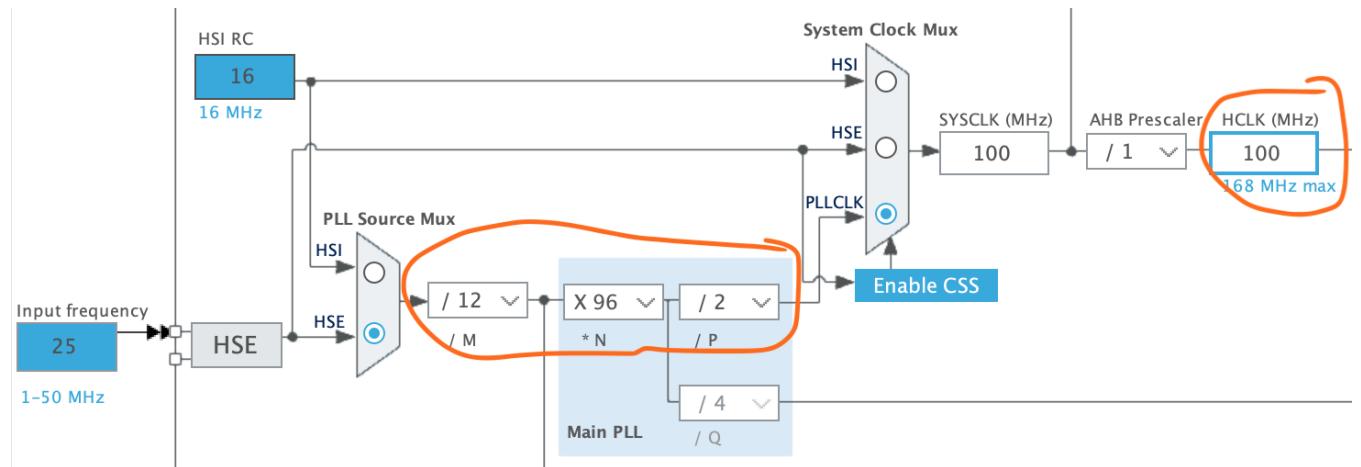
- **PLL** ----> (HSI or HSE) / PLL_M * PLL_N / PLL_P ---> **SYSCLK**:



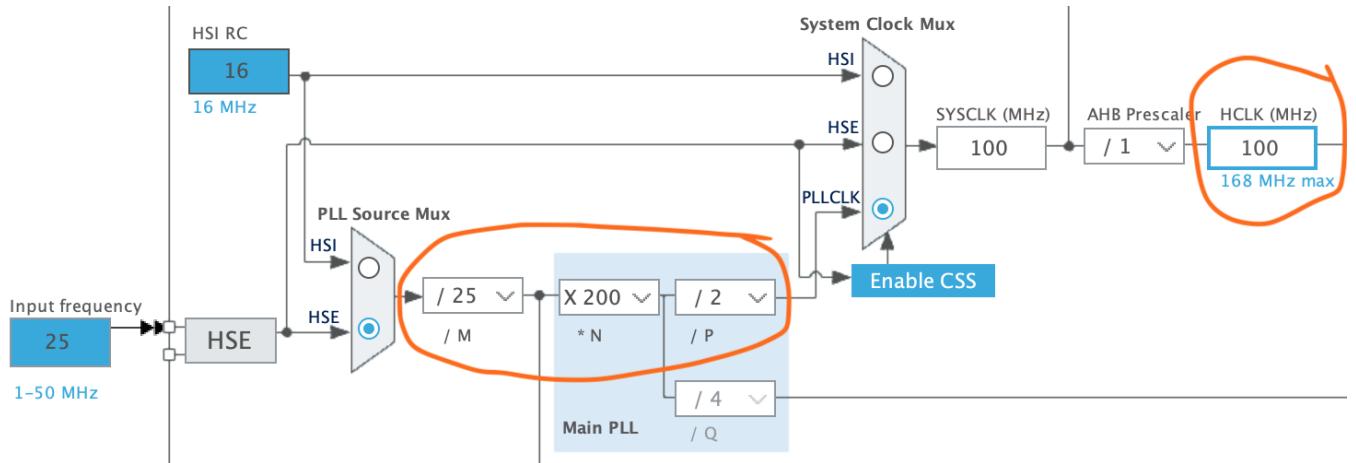
This is the case of **HSE through PLL** as the clock source. You can see the **SYSCLK** get clock signal from **HSE** first, and then go through **PLL** factors (**M/N/P**) calculation, finally, got the frequency is **168MHz**.

For the **PLL_M/N/P**, usually, you don't need to worry about, as **STMCubeMX** will figure out the combination for you when you change the expected frequency in **HCLK**. But you can change it by yourself.

For example, when I change the **HCLK** frequency to **100MHz** like below, **STMCubeMX** calculates the combination for me:



But I can change the combination like below and got the same result:



Here are the rules if you want to change the combination by yourself:

- When using **PLL** as clock source, we should calculate **SYSCLK** frequency with the following formula:

$$\text{PLL_VCO} = (\text{HSE_FREQUENCY or HSI_FREQUENCY} / \text{PLL_M}) * \text{PLL_N}$$

$$\text{SYSCLK} = \text{PLL_VCO} / \text{PLL_P}$$

'VCO' stands for 'Voltage-Controlled Oscillator'

- Tips for picking the right factor value:

- PLL_M**: We can always make it equal to the **HSI_FREQUENCY** or **HSE_FREQUENCY**, then:

(HSE_FREQUENCY or HSI_FREQUENCY / PLL_M) always return 1

which easier to do the rest calculation.

- PLL_P**: We can try start from 2, then **PLL_M** and **PLL_P** already fixed, only left the **PLL_N** to try.

But keep in mind that **PLL_M/N/P** value must in the range provided in the reference manual (page 227).

So the suggestion is always going to **STM32CubeMX** and use the automatic combination or change your settings in the UI, as it will tell you when your value is not working.

6.5 Let's talk about **clock source selecting registers handling**

We need to go through all the steps below for picking a clock source target to the particular working frequency:

1. Enable **HSE** and wait for it stable if we use **HSE**.
2. Set the **AHB prescaler, APB1 prescaler, APB2 prescaler**.
3. Setup flash read latency.
4. Set **PLL factors MNPQ**.
5. Enable **PLL** and wait for it stable.

For each step, we need to deal with different register, we will walk through them one by one later.

Before that, let's define some **enum** types and **struct** to describe the **clock**:

- The clock source type we will use in the demo:

```
#[derive(Debug, Clone, PartialEq)]
pub enum ClockSource {
    Hsi,
    HsiThroughPll,
    HseThroughPll,
}
```

- The clock data structure which includes all related information in the **clock tree diagram**, and we only focus on related settings and the final working frequency output:

```
pub struct RccClocks {  
    // HSI fixed frequency  
    hsi: Option<MegaHertz>,  
    // Onboard HSE fixed frequency  
    hse: Option<MegaHertz>,  
    // The clock source we picked  
    clock_source: ClockSource,  
    // SYSCLK calculated frequency  
    system_clock: Option<MegaHertz>,  
    // HCLK calculated frequency  
    hardware_cpu_clock: Option<MegaHertz>,  
    // AHB bus prescaler  
    ahb_prescaler: Option<u32>,  
    // PLL factors  
    pll_m: Option<u32>,  
    pll_n: Option<u32>,  
    pll_p: Option<u32>,  
    pll_q: Option<u32>,  
    // APB1 periheral calculated frequency  
    apb1_peripheral_clock: Option<MegaHertz>,  
    // APB1 timer calculated frequency  
    apb1_timer_clock: Option<MegaHertz>,  
    // APB2 periheral calculated frequency  
    apb2_peripheral_clock: Option<MegaHertz>,  
    // APB2 timer calculated frequency  
    apb2_timer_clock: Option<MegaHertz>,  
}
```

As you can see, the `MegaHertz` frequency unit type above allows easier to convert a number (`u32`) into frequency unit (`Hz`, `KHz`, `MHz`), here is the source code:

```
#[derive(PartialEq, PartialOrd, Clone, Copy)]
pub struct Hertz(pub u32);

#[derive(PartialEq, PartialOrd, Clone, Copy)]
pub struct KiloHertz(pub u32);

#[derive(PartialEq, PartialOrd, Clone, Copy)]
pub struct MegaHertz(pub u32);

// impl From<MegaHertz> for u32 {
// fn from(value: MegaHertz) -> u32 {
// value.0
// }
// }

impl From<u32> for MegaHertz {
    fn from(value: u32) -> MegaHertz {
        MegaHertz(value / 1_000_000)
    }
}

impl From<u32> for KiloHertz {
    fn from(value: u32) -> KiloHertz {
        KiloHertz(value / 1_000)
    }
}

impl From<u32> for Hertz {
    fn from(value: u32) -> Hertz {
        Hertz(value)
    }
}

impl Into<Hertz> for KiloHertz {
    fn into(self) -> Hertz {
        Hertz(self.0 * 1_000)
```

```

    }

}

impl Into<Hertz> for MegaHertz {
    fn into(self) -> Hertz {
        Hertz(self.0 * 1_000_000)
    }
}

impl Into<KiloHertz> for MegaHertz {
    fn into(self) -> KiloHertz {
        KiloHertz(self.0 * 1_000)
    }
}

```

So, let's have a look at each register one by one:)

6.5.1 RCC clock control register (`RCC_CR`)

[reference manual](#) page 224:

7.3.1 RCC clock control register (`RCC_CR`)

Address offset: 0x00

Reset value: 0x0000 XX83 where X is undefined.

Access: no wait state, word, half-word and byte access

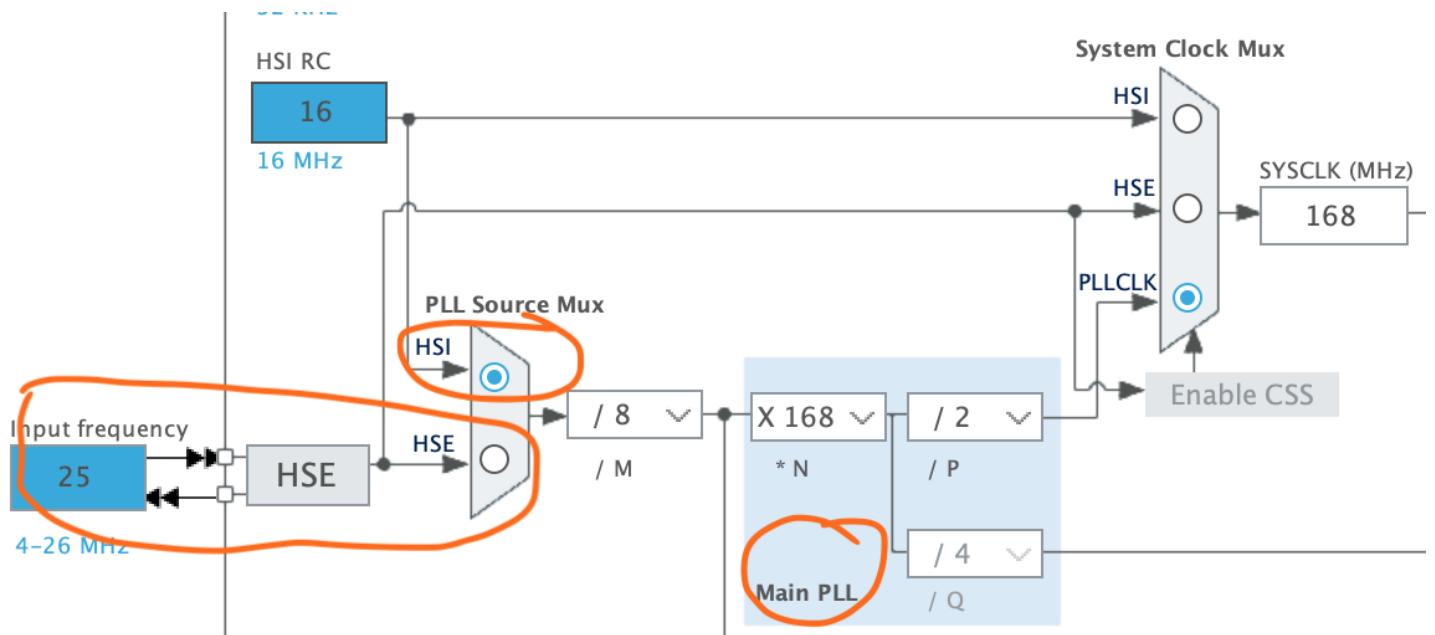


What information we got from this diagram?

- bit0 means use `HSI` as clock source, bit1 means `HSI` is stable. These 2 bits will set to 1 after power on, as `HSI` is the default clock source.

- `bit16` need to set to `1` if you decide to use `HSE` as clock source. After setting `bit16` to `1`, you should wait for `bit17` become `1` which means `HSE` is stable.
- `bit24` need to set to `1` if you decide to use `HSI` or `HSE` through `PLL` as clock source. After setting `bit24` to `1`, you should wait for `bit25` become `1` which means `PLL` is stable.
- Also, keep in mind that you should finish setting `PLL` factors before you set `bit24` (`PLL`) to `1`, as you can't set `PLL` factors after `PLL` is on!!!

It's all about the highlighted settings in the diagram below:



Here is the source: [demo/src/register_utils/rcc_clock_control_register.rs](#)

When the final demo runs, the `RCC_CR` register debug info will look like below:

```
[ RCC clock control register (RCC_CR) ]:
value: 00000001100000000000000000000000
High speed internal (HSI) clock enable: false
High speed internal (HSI) clock stable: false
High speed external (HSE) clock enable: false
High speed external (HSE) clock stable: false
HSE oscillator bypassed with an external clock: false
Clock security system enable: false
Main PLL (PLL) enable: true
Main PLL (PLL) is ready: true
PLLI2S is enable: false
PLLI2S is ready: false
```

6.5.2 RCC clock configuration register (RCC_CFGR)

[reference manual](#) page 228:

Reset and clock control for STM32F405xx/07xx and STM32F415xx/17xx(RCC)

RM0090

7.3.3 RCC clock configuration register (RCC_CFGR)

Address offset: 0x08

Reset value: 0x0000 0000

Access: 0 ≤ wait state ≤ 2, word, half-word and byte access

1 or 2 wait states inserted only if the access occurs during a clock source switch.

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
MCO2		MCO2 PRE[2:0]			MCO1 PRE[2:0]			I2SSC R	MCO1		RTCPRE[4:0]				
rw		rw	rw	rw	rw	rw	rw	rw	rw		rw	rw	rw	rw	rw
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
PPRE2[2:0]			PPRE1[2:0]			Reserved			HPRE[3:0]			SWS1	SWS0	SW1	SW0
rw	rw	rw	rw	rw	rw				rw	rw	rw	r	r	rw	rw

What information we got from this diagram?

- bit0 ~ bit1 controls the final clock switching.

Bits 3:2 **SWS**: System clock switch status

Set and cleared by hardware to indicate which clock source is used as the system clock.

- 00: HSI oscillator used as the system clock
- 01: HSE oscillator used as the system clock
- 10: PLL used as the system clock
- 11: not applicable

Bits 1:0 **SW**: System clock switch

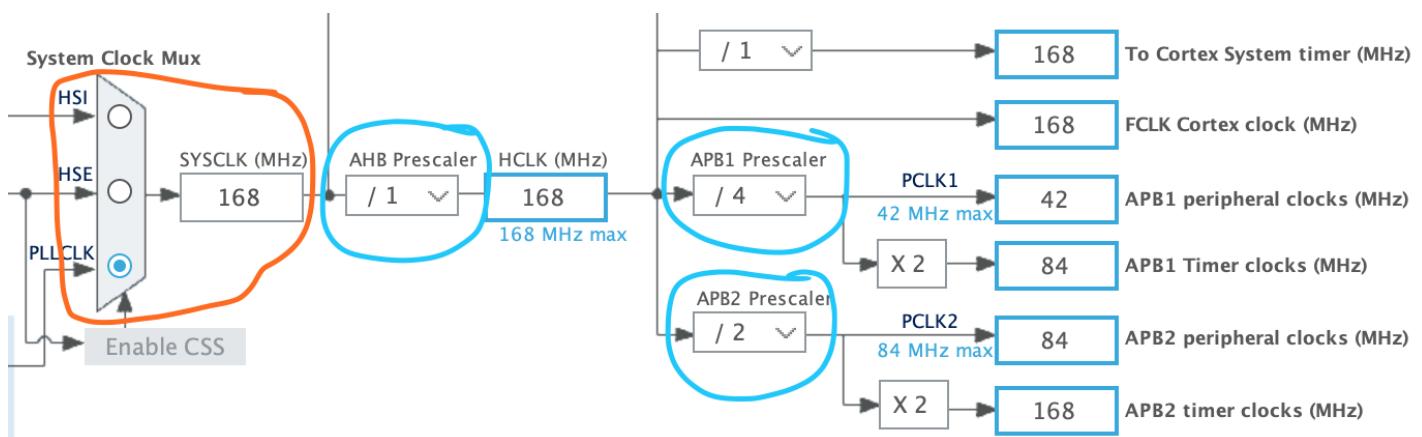
Set and cleared by software to select the system clock source.

Set by hardware to force the HSI selection when leaving the Stop or Standby mode or in case of failure of the HSE oscillator used directly or indirectly as the system clock.

- 00: HSI oscillator selected as system clock
- 01: HSE oscillator selected as system clock
- 10: PLL selected as system clock
- 11: not allowed

- `bit2 ~ bit3` represents whether the switched clock is stable or not.
- `bit4 ~ bit7` controls the `AHB bus prescaler` which uses to calculate the `HCLK` by `SYSCLK` frequency.
- `bit10 ~ bit12` controls the `APB low speed prescaler (APB1)`.
- `bit13 ~ bit15` controls the `APB high speed prescaler (APB2)`.

It's all about the highlighted settings in the diagram below:



Here is the source: [demo/src/register_utils/rcc_clock_config_register.rs](#)

When the final demo runs, the `RCC_CFGR` register debug info will look like below:

```
[ RCC clock configuration register (RCC_CFGR) ]:  
value: 00000000000000000000000000001010  
System clock selected: PllSelectedAsSystemClock // bits: 0b10  
System clock status: PllUsedAsSystemClock // bits: 0b10  
AHB prescaler: 1 // bits: 0b0000  
APB low speed prescaler (APB1): 1 // bits: 0b000  
APB high speed prescaler (APB2): 1 // bits: 0b000
```

6.5.3 Flash access control register (FLASH_ACR)

[reference manual](#) page 80:

3.5 Read interface

3.5.1 Relation between CPU clock frequency and Flash memory read time

To correctly read data from Flash memory, the number of wait states (LATENCY) must be correctly programmed in the Flash access control register (FLASH_ACR) according to the frequency of the CPU clock (HCLK) and the supply voltage of the device.

The prefetch buffer must be disabled when the supply voltage is below 2.1 V. The correspondence between wait states and CPU clock frequency is given in [Table 10](#) and [Table 11](#).

Note: On STM32F405xx/07xx and STM32F415xx/17xx devices:

- when $V_{OS} = '0'$, the maximum value of $f_{HCLK} = 144 \text{ MHz}$.
- when $V_{OS} = '1'$, the maximum value of $f_{HCLK} = 168 \text{ MHz}$.

On STM32F42xxx and STM32F43xxx devices:

- when $V_{OS[1:0]} = '0x01'$, the maximum value of f_{HCLK} is 120 MHz.
- when $V_{OS[1:0]} = '0x10'$, the maximum value of f_{HCLK} is 144 MHz. It can be extended to

You need to set the correct WS value based on what HCLK frequency you're using!!!

MHz. It can be extended to

1.8 to 2.1 V.

[STM32F43xxx](#) for details on

Table 10. Number of wait states according to CPU clock (HCLK) frequency (STM32F405xx/07xx and STM32F415xx/17xx)

Wait states (WS) (LATENCY)	HCLK (MHz)			
	Voltage range 2.7 V - 3.6 V	Voltage range 2.4 V - 2.7 V	Voltage range 2.1 V - 2.4 V	Voltage range 1.8 V - 2.1 V Prefetch OFF
0 WS (1 CPU cycle)	$0 < \text{HCLK} \leq 30$	$0 < \text{HCLK} \leq 24$	$0 < \text{HCLK} \leq 22$	$0 < \text{HCLK} \leq 20$
1 WS (2 CPU cycles)	$30 < \text{HCLK} \leq 60$	$24 < \text{HCLK} \leq 48$	$22 < \text{HCLK} \leq 44$	$20 < \text{HCLK} \leq 40$
2 WS (3 CPU cycles)	$60 < \text{HCLK} \leq 90$	$48 < \text{HCLK} \leq 72$	$44 < \text{HCLK} \leq 66$	$40 < \text{HCLK} \leq 60$
3 WS (4 CPU cycles)	$90 < \text{HCLK} \leq 120$	$72 < \text{HCLK} \leq 96$	$66 < \text{HCLK} \leq 88$	$60 < \text{HCLK} \leq 80$
4 WS (5 CPU cycles)	$120 < \text{HCLK} \leq 150$	$96 < \text{HCLK} \leq 120$	$88 < \text{HCLK} \leq 110$	$80 < \text{HCLK} \leq 100$
5 WS (6 CPU cycles)	$150 < \text{HCLK} \leq 168$	$120 < \text{HCLK} \leq 144$	$110 < \text{HCLK} \leq 132$	$100 < \text{HCLK} \leq 120$
6 WS (7 CPU cycles)		$144 < \text{HCLK} \leq 168$	$132 < \text{HCLK} \leq 154$	$120 < \text{HCLK} \leq 140$
7 WS (8 CPU cycles)			$154 < \text{HCLK} \leq 168$	$140 < \text{HCLK} \leq 160$

First thing first, we need to know *Why we have to set this flash prefetch latency?*

The explanation above is the answer: ***There is a special relation between CPU clock frequency and Flash memory read time.***

Then we have to make it right after we change the **HCLK** frequency!!!

So, here is the register info in page 65 and 98:

0x4002 3C00 - 0x4002 3FFF	Flash interface register	AHB1	Section 3.9: Flash interface registers
0x4002 3800 - 0x4002 3BFF	RCC		Section 7.3.24: RCC register map on page 265
0x4002 3000 - 0x4002 33FF	CRC		Section 4.4.4: CRC register map on page 115
0x4002 2800 - 0x4002 2BFF	GPIOK		Section 8.4.11: GPIO register map on page 287

Embedded Flash memory interface

RM0090

3.9 Flash interface registers

3.9.1 Flash access control register (FLASH_ACR) for STM32F405xx/07xx and STM32F415xx/17xx

The Flash access control register is used to enable/disable the acceleration features and control the Flash memory access time according to CPU frequency.

Address offset: 0x00

Reset value: 0x0000 0000

Access: no wait state, word, half-word and byte access



Bits 31:13 Reserved, must be kept cleared.

What information we got from this diagram?

- bit0 ~ bit2 controls the flash prefetch latency setting:

Bits 2:0 **LATENCY[2:0]**: Latency

These bits represent the ratio of the CPU clock period to the Flash memory access time.

- 000: Zero wait state
- 001: One wait state
- 010: Two wait states
- 011: Three wait states
- 100: Four wait states
- 101: Five wait states
- 110: Six wait states
- 111: Seven wait states

Tips for picking the correct latency value:

After you changed the `HCLK` frequency in `STMCubeMX` UI, back to the `Pinout & Configuration` tab, click on `RCC` on the left side, then you're able to see the correct latency setting for the particular frequency like below:

Home > **STM32F407VGTx** > test.ioc – Pinout & Configuration >

Pinout & Configuration

Clock Configuration

Software Packs

RCC Mode and Configuration

Mode

- High Speed Clock (HSE) **Crystal/Ceramic Resonator**
- Low Speed Clock (LSE) **Disable**
- Master Clock Output 1
- Master Clock Output 2
- Audio Clock Input (I2S_CKIN)

HCLK frequency is 168MHz and VDD is 3.3V. Then based on the flash latency table, “Flash Latency(WS)” should be “5 WS”

Configuration

Reset Configuration

<input checked="" type="checkbox"/> NVIC Settings	<input checked="" type="checkbox"/> GPIO Settings
<input checked="" type="checkbox"/> Parameter Settings	<input checked="" type="checkbox"/> User Constants

Configure the below parameters :

System Parameters

VDD voltage (V)	3.3 V
Instruction Cache	Enabled
Prefetch Buffer	Enabled
Data Cache	Enabled
Flash Latency(WS)	5 WS (6 CPU cycle)

RCC Parameters

HSI Calibration Value	16
HSE Startup Timeout ...	100
LSE Startup Timeout ...	5000

- `bit8` needs to set to `1` for enabling the prefetch.

- bit9 needs to set to 1 for enabling the instruction cache.
- bit10 needs to set to 1 for enabling the data cache.

Here is the source: [demo/src/register_utils/flash_access_control_register.rs](#)

When the final demo runs, the `FLASH_ACR` register debug info will look like below:

```
[ Flash access control register (FLASH_ACR) ]:
FLASH_ACR value: 0b00000000000000000000000011100000101
Flash read latency: FiveWaitState6CpuCycles,      // bits: 0b101
Prefetch enabled: true,                          // bits: 0b1
Instruction cache enabled: true,                // bits: 0b1
Data cache enabled: true,                      // bits: 0b1
```

6.5.4 RCC PLL configuration register (RCC_PLLCFGR)

[reference manual](#) page 226:

7.3.2 RCC PLL configuration register (RCC_PLLCFGR)

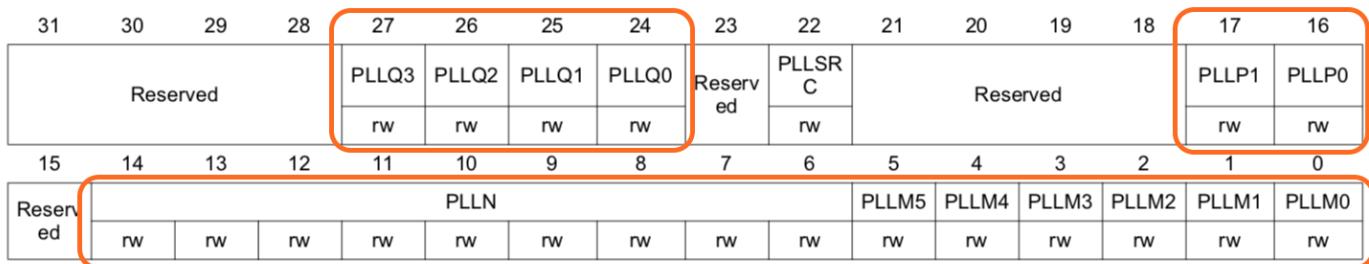
Address offset: 0x04

Reset value: 0x2400 3010

Access: no wait state, word, half-word and byte access.

This register is used to configure the PLL clock outputs according to the formulas:

- $f_{(VCO \text{ clock})} = f_{(\text{PLL clock input})} \times (\text{PLLN} / \text{PLLM})$
- $f_{(\text{PLL general clock output})} = f_{(\text{VCO clock})} / \text{PLLP}$
- $f_{(\text{USB OTG FS, SDIO, RNG clock output})} = f_{(\text{VCO clock})} / \text{PLLQ}$

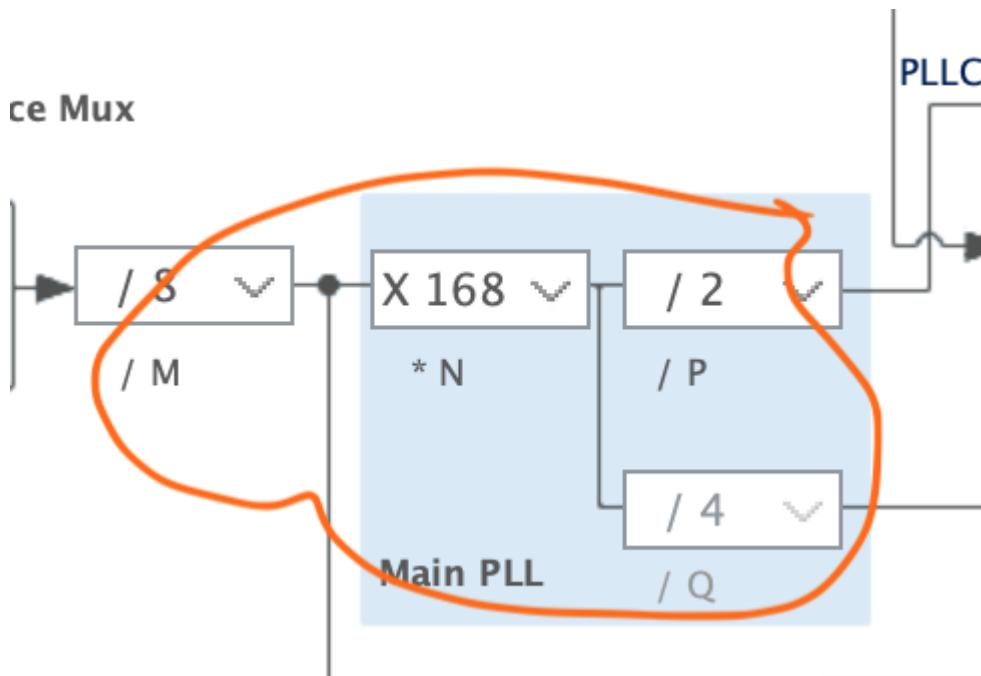


Bits 31:28 Reserved, must be kept at reset value.

What information we got from this diagram?

- bit0 ~ bit5 controls the `PLL M` factor.
- bit6 ~ bit14 controls the `PLL N` factor.
- bit16 ~ bit17 controls the `PLL P` factor.
- bit24 ~ bit27 controls the `PLL Q` factor.

It's all about the highlighted settings in the diagram below:



Here is the source: [demo/src/register_utils/rcc_pll_config_register.rs](#)

When the final demo runs, the `RCC_CFGR` register debug info will look like below:

```
[ RCC PLL configuration register (RCC_PLLCFGR) ]:  
RCC_PLLCFGR value: 0b00000100010000100101010000001000  
Main PLL M: Ok(8),      // bits: 0b001000  
Main PLL N: Ok(336),    // bits: 0b101010000  
Main PLL P: Ok(2),      // bits: 0b10  
Main PLL q: Ok(4),      // bits: 0b0100  
Main PLL source: "HSE", // bits: 0b1
```

6.6 Finally, let's put all together: System clock demo

- Make sure your `.cargo/config` has the settings below:

We need to use the `runner` config without `-nographic`, then `QEMU` will open a dev board GUI, so we can see the blinking LED.

```
[target.thumbv7em-none-eabi]
runner = "qemu-system-gnueclipse -cpu cortex-m4 -mcu STM32F407VG -
machine STM32F4-Discovery -semihosting-config enable=on,target=native
-kernel"
```

- All the previous source code links:
 - [demo/src/clock_frequency.rs](#)
 - [demo/src/rcc_clock_settings.rs](#)
 - [demo/src/clock_utils.rs](#)
 - [demo/src/register_utils/flash_access_control_register.rs](#)
 - [demo/src/register_utils/rcc_clock_config_register.rs](#)
 - [demo/src/register_utils/rcc_clock_control_register.rs](#)
 - [demo/src/register_utils/rcc_pll_config_register.rs](#)
- Create `demo/src/bin/setup_and_print_system_clock.rs` with the following code:

```
#![allow(warnings)]
#![no_std]
#![no_main]

// We have to use the attribute to locate the module file!
#[path = "../clock_frequency.rs"]
mod clock_frequency;
#[path = "../clock_utils.rs"]
mod clock_utils;
#[path = "../register_utils/flash_access_control_register.rs"]
mod flash_access_control_register;
#[path = "../register_utils/rcc_clock_config_register.rs"]
mod rcc_clock_config_register;
#[path = "../register_utils/rcc_clock_control_register.rs"]
mod rcc_clock_control_register;
#[path = "../rcc_clock_settings.rs"]
mod rcc_clock_settings;
#[path = "../register_utils/rcc_pll_config_register.rs"]
mod rcc_pll_config_register;

use cortex_m_rt::entry;
use panic_semihosting as _;

#[cfg(feature = "enable-debug")]
use cortex_m_semihosting::hprintln;

use crate::clock_utils::{ClockSource, RccClocks};

/// 
#[entry]
fn main() -> ! {
    #[cfg(feature = "enable-debug")]
    let _ = hprintln!("STM32F4 setup and print system clock demo is
running >>>>");

    #[cfg(feature = "enable-debug")]
    {

```

```

    // RccClocks::setup_system_clock(ClockSource::Hsi);
    // RccClocks::setup_system_clock(ClockSource::HsiThroughPll);
    RccClocks::setup_system_clock(ClockSource::HseThroughPll);

    // Print all related registers debug info
    RccClocks::print_system_clock_info();
}

loop {}
}

```

- About different feature settings:

- In `Cargo.toml`, we defined 2 optional features:

```

[features]
use-weact-black-pill = []
use-stm32f407g-disc1 = []

```

- In `demo/src/rcc_clock_settings.rs`, we defined different conditional compilation block against to different feature:

```

#[cfg(feature = "use-stm32f407g-disc1")]
pub mod clock_source_selecting {
    // constants define here
}

#[cfg(feature = "use-weact-black-pill")]
pub mod clock_source_selecting {
    // constants define here
}

```

- How to run

- Use `use-stm32f407g-disc1` feature:

```
// cd demo  
cargo watch -c --exec 'run --bin setup_and_print_system_clock --  
features "enable-debug use-stm32f407g-disc1"'
```

Then you should be able to see the console log like below:

```
QEMU 2.8.0-9 monitor - type 'help' for more information
(qemu) STM32F4 setup and print system clock demo is running >>>>

[ RccClocks ]: {
    hsi: "16MHz",
    hse: "8MHz",
    clock_source: HseThroughPll,
    system_clock: "168MHz",
    hardware_cpu_clock: "168MHz",
    pll_m: Some(
        8,
    ),
    pll_n: Some(
        336,
    ),
    pll_p: Some(
        2,
    ),
    pll_q: Some(
        4,
    ),
    ahb_prescaler: Some(
        1,
    ),
    apb1_peripheral_clock: "42MHz",
    apb1_timer_clock: "84MHz",
    apb2_peripheral_clock: "84MHz",
    apb2_timer_clock: "168MHz",
}
clock_switch_status_bits: 0b10
still_not_stable: false
Waiting for clock switch become stable>>>>

[ RCC clock control register (RCC_CR) ]:
value: 0000000011000000000000000000000000000000
High speed internal (HSI) clock enable: false
High speed internal (HSI) clock stable: false
```

```

High speed external (HSE) clock enable: false
High speed external (HSE) clock stable: false
HSE oscillator bypassed with an external clock: false
Clock security system enable: false
Main PLL (PLL) enable: true
Main PLL (PLL) is ready: true
PLL2S is enable: false
PLL2S is ready: false

[ RCC clock configuration register (RCC_CFGR) ]:
value: 000000000000000000000000000000001010
System clock selected: PllSelectedAsSystemClock // bits: 0b10
System clock status: PllUsedAsSystemClock // bits: 0b10
AHB prescaler: 1 // bits: 0b0000
APB low speed prescaler (APB1): 1 // bits: 0b000
APB high speed prescaler (APB2): 1 // bits: 0b000

[ RCC PLL configuration register (RCC_PLLCFGR) ]:
RCC_PLLCFGR value: 0b000001000100001001010100000001000
Main PLL M: Ok(8), // bits: 0b001000
Main PLL N: Ok(336), // bits: 0b101010000
Main PLL P: Ok(2), // bits: 0b10
Main PLL q: Ok(4), // bits: 0b0100
Main PLL source: "HSE", // bits: 0b1

[ Flash access control register (FLASH_ACR) ]:
FLASH_ACR value: 0b0000000000000000000000000000000111000000101
Falsh read latency: FiveWaitState6CpuCycles, // bits: 0b101
Prefetch enabled: true, // bits: 0b1
Instruction cache enabled: true, // bits: 0b1
Data cache enabled: true, // bits: 0b1bash

```

- Use `use-wexact-black-pill` feature:

```
// cd demo  
cargo watch -c --exec 'run --bin setup_and_print_system_clock --  
features "enable-debug use-weact-black-pill"'
```

And you should be able to see the console log like below:

```
QEMU 2.8.0-9 monitor - type 'help' for more information
(qemu) STM32F4 setup and print system clock demo is running >>>>

[ RccClocks ]: {
    hsi: "16MHz",
    hse: "25MHz",
    clock_source: HseThroughPll,
    system_clock: "100MHz",
    hardware_cpu_clock: "100MHz",
    pll_m: Som (
        25,
    ),
    pll_n: Som (
        200,
    ),
    pll_p: Som (
        2,
    ),
    pll_q: Som (
        4,
    ),
    ahb_prescaler: Som (
        1,
    ),
    apb1_peripheral_clock: "50MHz",
    apb1_timer_clock: "100MHz",
    apb2_peripheral_clock: "100MHz",
    apb2_timer_clock: "100MHz",
}
clock_switch_status_bits: 0b10
still_not_stable: false
Waiting for clock switch become stable>>>>

[ RCC clock control register (RCC_CR) ]:
value: 00000001100000000000000000000000
High speed internal (HSI) clock enable: false
High speed internal (HSI) clock stable: false
```

```

High speed external (HSE) clock enable: false
High speed external (HSE) clock stable: false
HSE oscillator bypassed with an external clock: false
Clock security system enable: false
Main PLL (PLL) enable: true
Main PLL (PLL) is ready: true
PLL2S is enable: false
PLL2S is ready: false

[ RCC clock configuration register (RCC_CFGR) ]:
value: 000000000000000000000000000000001010
System clock selected: PllSelectedAsSystemClock // bits: 0b10
System clock status: PllUsedAsSystemClock // bits: 0b10
AHB prescaler: 1 // bits: 0b0000
APB low speed prescaler (APB1): 1 // bits: 0b000
APB high speed prescaler (APB2): 1 // bits: 0b000

[ RCC PLL configuration register (RCC_PLLCFGR) ]:
RCC_PLLCFGR value: 0b00000100010000100011001000011001
Main PLL M: Ok(25), // bits: 0b011001
Main PLL N: Ok(200), // bits: 0b011001000
Main PLL P: Ok(2), // bits: 0b10
Main PLL q: Ok(4), // bits: 0b0100
Main PLL source: "HSE", // bits: 0b1

[ Flash access control register (FLASH_ACR) ]:
FLASH_ACR value: 0b000000000000000000000000111000000011
Falsh read latency: ThreeWaitState4CpuCycles, // bits: 0b011
Prefetch enabled: true, // bits: 0b1
Instruction cache enabled: true, // bits: 0b1
Data cache enabled: true, // bits: 0b1

```

7. Simple brief of Interrupts

An `interrupt`, or `IRQ`, is an exception signalled by a peripheral, or generated by a software request. Yes, `interrupt` actually just an `exception` type in the `Cortex-M4` exception model.

`interrupt` has the following features:

- Run asynchronous:

*All interrupts are **asynchronous to instruction execution**. In the system, peripherals use interrupts to communicate with the processor.*

- With different states:

- `Inactive`:

The exception is not active and not pending.

- `Pending`:

The exception is waiting to be serviced by the processor.

- `Active`:

An interrupt request from a peripheral or from software can change the state of the corresponding interrupt to pending.

An exception that is being serviced by the processor but has not completed.

Note: An exception handler can interrupt the execution of another exception handler. In this case both exceptions are in the active state.

- `Active and pending`: *The exception is being serviced by the processor and there is a pending exception from the same source.*

- With different priorities:

Lower value means higher priority.

- With a specified `IRQ` number (`IRQn`):

`IRQn` points to the particular memory address. When the `interrupt` happens, the code in that memory will be executed asynchronously.

Below is the Cortex-M4 exception tables:

Table 17. Properties of the different exception types

Exception number ⁽¹⁾	IRQ number ⁽¹⁾	Exception type	Priority	Vector address or offset ⁽²⁾	Activation
1	-	Reset	-3, the highest	0x00000004	Asynchronous
2	-14	NMI	-2	0x00000008	Asynchronous
3	-13	Hard fault	-1	0x0000000C	-
4	-12	Memory management fault	Configurable ⁽³⁾	0x00000010	Synchronous
5	-11	Bus fault	Configurable ⁽³⁾	0x00000014	Synchronous when precise Asynchronous when imprecise
6	-10	Usage fault	Configurable ⁽³⁾	0x00000018	Synchronous
7-10	-	-	-	Reserved	-
11	-5	SVCall	Configurable ⁽³⁾	0x0000002C	Synchronous
12-13	-	-	-	Reserved	-
14	-2	PendSV	Configurable ⁽³⁾	0x00000038	Asynchronous

Table 17. Properties of the different exception types (continued)

Exception number ⁽¹⁾	IRQ number ⁽¹⁾	Exception type	Priority	Vector address or offset ⁽²⁾	Activation
15	-1	SysTick	Configurable ⁽³⁾	0x0000003C	Asynchronous
16 and above	0 and above	Interrupt (IRQ)	Configurable ⁽⁴⁾	0x00000040 and above ⁽⁵⁾	Asynchronous

As you can see an exception can be executed in synchronous or asynchronous. So, We should use Rust Concurrency Model to think when dealing with interrupts. Please keep that in mind, it's super important!!!

The last thing you should know is Exception handler, it just a function to be called when exception happens.

- **Interrupt Service Routines (ISRs):**

Interrupts IRQ0 to IRQ81 are the exceptions handled by ISRs.

- **Fault handlers:**

Hard fault, memory management fault, usage fault, bus fault are fault exceptions handled by the fault handlers.

- **System handlers:**

NMI, PendSV, SVCall SysTick, and the fault exceptions are all system exceptions that are handled by system handlers.

7.1 How interrupt works?

For explaining how the interrupt works or say how an `ISR` (Interrupts Service Routine) gets called, we should take a look at the `Vector Table` first:

Figure 11. Vector table

Exception number	IRQ number	Offset	Vector
255	239	0x03FC	IRQ239
.	.	.	.
.	.	.	.
18	2	0x004C	IRQ2
17	1	0x0048	IRQ1
16	0	0x0044	IRQ0
15	-1	0x0040	Systick
14	-2	0x003C	PendSV
13		0x0038	Reserved
12			Reserved for Debug
11	-5	0x002C	SVCall
10			Reserved
9			
8			
7			
6	-10	0x0018	Usage fault
5	-11	0x0014	Bus fault
4	-12	0x0010	Memory management fault
3	-13	0x000C	Hard fault
2	-14	0x0008	NMI
1		0x0004	Reset
		0x0000	Initial SP value

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When hardware or software event occurred, MCU will call the Exception Handler or Interrupt Service Routine (ISR) to do something related to that event. But the question is how the MCU knows that where to find that particular function to call it? The answer prints on the Vector Table, that's the fixed memory layout for particular MCU.

Before diving into NVIC, let's have a quick look at how to handle the SysTick exception handler.

7.2 Let's handle the **SysTick** exception

The quick brief of **SysTick**:

We've already learned the `clock` in previous chapters, then we know that after selecting and applying the `clock source`, the CPU clock runs in the expected frequency just like a pulse to drive all peripherals and components.

For example, if the `HCLK` frequency is `168MHz`, that means **168,000,000** system ticks happen per second. There are four registers below related to the **SysTick**:

4.5 SysTick timer (STK)

The processor has a 24-bit system timer, SysTick, that counts down from the reload value to zero, reloads (wraps to) the value in the `STK_LOAD` register on the next clock edge, then counts down on subsequent clocks.

When the processor is halted for debugging the counter does not decrement.

Table 54. System timer registers summary

Address	Name	Type	Required privilege	Reset value	Description
0xE000E010	STK_CTRL	RW	Privileged	0x00000000	<i>SysTick control and status register (STK_CTRL) on page 247</i>
0xE000E014	STK_LOAD	RW	Privileged	Unknown	<i>SysTick reload value register (STK_LOAD) on page 248</i>
0xE000E018	STK_VAL	RW	Privileged	Unknown	<i>SysTick current value register (STK_VAL) on page 249</i>
0xE000E01C	STK_CALIB	RO	Privileged	0xC0000000	<i>SysTick calibration value register (STK_CALIB) on page 250</i>

That's in the [stm32-cortexm4-mcus-and-mpus-programming-manual.pdf](#) page 246.

- `STK_CTRL`:

It controls enable or disable the system tick timer functionality and generate **SysTick** event.

- `STK_LOAD`:

It defines the `Reload Value` which `STK_VAL` register used to countdown from that value to zero.

- `STK_VAL`:

It holds the current countdown value, this value minus 1 per system tick cycle. After the countdown to 0. Two things will happen:

- The `bit16` in `STK_CTRL` will auto flip to `1` which represents finish a one-trip countdown from `Reload Value` to `0`. This bit will be reset to `0` after reading from `STK_CTRL` to make sure the even only happens once.
- One `SysTick` event will be generated and the `SysTick` exception handler gets called (if defined that function).

For generating the `SysTick` (event) per millisecond, here are the steps:

1. Calculate the total system ticks amount for 1 millisecond, then set that value to `STK_LOAD` register:

```
(cpu_clock_frequency_in_hertz / 1000) - 1
```

4.5.2 SysTick reload value register (STK_LOAD)

Address offset: 0x04

Reset value: 0x0000 0000

Required privilege: Privileged

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved								RELOAD[23:16]							
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
RELOAD[15:0]															
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Bits 31:24 Reserved, must be kept cleared.

Bits 23:0 RELOAD: RELOAD value

The LOAD register specifies the start value to load into the STK_VAL register when the counter is enabled and when it reaches 0.

Calculating the RELOAD value

The RELOAD value can be any value in the range 0x00000001-0x00FFFFFF. A start value of 0 is possible, but has no effect because the SysTick exception request and COUNTFLAG are activated when counting from 1 to 0.

The RELOAD value is calculated according to its use:

- I To generate a multi-shot timer with a period of N processor clock cycles, use a RELOAD value of N-1. For example, if the SysTick interrupt is required every 100 clock pulses, set RELOAD to 99.
- I To deliver a single SysTick interrupt after a delay of N processor clock cycles, use a RELOAD of value N. For example, if a SysTick interrupt is required after 100 clock pulses, set RELOAD to 99.

Because the `STK_LOAD` register only got 24 bit to save the current countdown value which means you can't set it too big, as that will cause overflow.

2. Set the correct clock source to `STK_CTRL` register `bit2` and set `bit1` to `1` if you want to generate the `SysTick` exception:

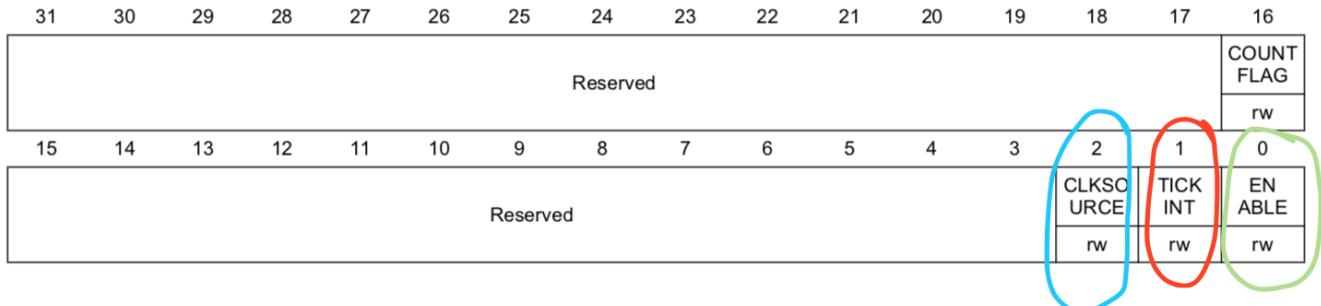
4.5.1 SysTick control and status register (STK_CTRL)

Address offset: 0x00

Reset value: 0x0000 0000

Required privilege: Privileged

The SysTick CTRL register enables the SysTick features.



Bits 31:17 Reserved, must be kept cleared.

Bit 16 COUNTFLAG:

Returns 1 if timer counted to 0 since last time this was read.

Bits 15:3 Reserved, must be kept cleared.

Bit 2 **CLKSOURCE**: Clock source selection

Selects the clock source.

0: AHB/8

1: Processor clock (AHB)

Bit 1 **TICKINT**: SysTick exception request enable

0: Counting down to zero does not assert the SysTick exception request

1: Counting down to zero asserts the SysTick exception request.

Note: Software can use COUNTFLAG to determine if SysTick has ever counted to zero.

Bit 0 **ENABLE**: Counter enable

Enables the counter. When ENABLE is set to 1, the counter loads the RELOAD value from the LOAD register and then counts down. On reaching 0, it sets the COUNTFLAG to 1 and optionally asserts the SysTick depending on the value of TICKINT. It then loads the RELOAD value again, and begins counting.

0: Counter disabled

1: Counter enabled

3. Reset the `STK_VAL` register value to `0`.

4.5.3 SysTick current value register (STK_VAL)

Address offset: 0x08

Reset value: 0x0000 0000

Required privilege: Privileged

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved								CURRENT[23:16]							
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
CURRENT[15:0]															
rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw	rw

Bits 31:24 Reserved, must be kept cleared.

Bits 23:0 **CURRENT**: Current counter value

The VAL register contains the current value of the SysTick counter.

Reads return the current value of the SysTick counter.

A write of any value clears the field to 0, and also clears the COUNTFLAG bit in the STK_CTRL register to 0.

- Enable the countdown by setting 1 to `STK_CTRL` register `bit0`, then timer starts to countdown and will set `STK_CTRL` register `bit16` to 1 when countdown to 0.

- `SysTick` timer register util is here:
 - [demo/src/register_utils/system_tick_timer_register.rs](#)
- Create [demo/src/bin/interrupt_system_tick.rs](#) with the following code:

```
#![allow(warnings)]
#![no_std]
#![no_main]

#[path = "../clock_frequency.rs"]
mod clock_frequency;
#[path = "../clock_utils.rs"]
mod clock_utils;
#[path = "../register_utils/flash_access_control_register.rs"]
mod flash_access_control_register;
#[path = "../register_utils/rcc_clock_config_register.rs"]
mod rcc_clock_config_register;
#[path = "../register_utils/rcc_clock_control_register.rs"]
mod rcc_clock_control_register;
#[path = "../rcc_clock_settings.rs"]
mod rcc_clock_settings;
#[path = "../register_utils/rcc_pll_config_register.rs"]
mod rcc_pll_config_register;
#[path = "../interrupt_utils/system_tick.rs"]
mod system_tick;
#[path = "../register_utils/system_tick_timer_register.rs"]
mod system_tick_timer_register;

use cortex_m_rt::{entry, exception};
use panic_semihosting as _;

#[cfg(feature = "enable-debug")]
use cortex_m_semihosting::hprintln;

use crate::clock_utils::{ClockSource, RccClocks};
use system_tick::SystemTickInterrupt;
use system_tick_timer_register::SystemTickTimer;

#[entry]
fn main() -> ! {
    #[cfg(feature = "enable-debug")]
    let _ = hprintln!("STM32F4 system tick interrupt demo is running");
}
```

```
>>>>");

let rcc_clock =
RccClocks::setup_system_clock(ClockSource::HseThroughPll);

SystemTickTimer::enable(rcc_clock.get_cpu_clock_frequency_in_hertz(),
true);

#[cfg(feature = "enable-debug")]
{
    // RccClocks::print_system_clock_info();
    SystemTickTimer::print_config();
}

loop {}
}

#[exception]
fn SysTick() {
    // One feature of the `cortex_m_rt` is that:
    //
    // "Initializing static variables before the program entry
    point."
    //
    // So the `static mut u32` variable here should be defined before
    the `entry` and
    // make a `let SAME_NAME_VAR: &mut u32;` here for making the
    compiler happy to
    // pass the borrow checker.
    //
    // That's why we can use `*SAME_NAME_VAR` to set the static
    variable below;
    static mut current_past_milliseconds_count: u32 = 0u32;

    *current_past_milliseconds_count += 1;

#[cfg(feature = "enable-debug")]
```

```
{  
    let seconds_passed = (*current_past_milliseconds_count /  
1000) as u32;  
    if *current_past_milliseconds_count % 1000 == 0 {  
        hprintln!("seconds_passed: {}", seconds_passed);  
    }  
}  
}
```

- How to run

```
// cd demo  
cargo watch -c --exec 'run --bin interrupt_system_tick --features  
"enable-debug use-stm32f407g-disc1"'
```

7.3 Let's have close look at how the `SysTick` exception handler function be called

So far, we know the `#[exception]` macro can make a function become an `Exception Handler`, but how it works under the hood? What's the secret behind that? Let's review the code again:

```

#[exception]
fn SysTick() {
    // One feature of the `cortex_m_rt` is that:
    //
    // "Initializing static variables before the program entry point."
    //
    // So the `static mut u32` variable here should be defined before the
    // `entry` and
    // make a `let SAME_NAME_VAR: &mut u32;` here for making the compiler
    happy to
    // pass the borrow checker.
    //
    // That's why we can use `*SAME_NAME_VAR` to set the static variable
    below;
    static mut current_past_milliseconds_count: u32 = 0u32;
    //
    *current_past_milliseconds_count += 1;
    //
    #[cfg(feature = "enable-debug")]
    {
        let seconds_passed = (*current_past_milliseconds_count / 1000) as
u32;
        if *current_past_milliseconds_count % 1000 == 0 {
            hprintln!("seconds_passed: {}", seconds_passed);
        }
    }
}

```

Even the comment above looks very clear, but we still don't know how that `static mut u32` definition looks like. So let me introduce the `cargo expand` command. Why we need that? That's because `#[exception]` actually is a `procedure macro`. If you open this [link](#) you should able to see the source code like below:

```

#[proc_macro_attribute]
pub fn exception(args: TokenStream, input: TokenStream) -> TokenStream {
    let mut f = parse_macro_input!(input as ItemFn);

    // Ignore the rest source code.....
}

```

Briefly, a procedure macro will take the source you wrote as the `input`, then do something smart in the implementation, for example, implement some `trait` for your `struct`, etc. Then the macro generates back the final source code as the `output` which will pipe into the compiler, that's how procedure macro works.

Let's walk through the steps below before we can run `cargo expand`:

- Install it

```
cargo install cargo-expand
```

- Because `cargo expand` relies on unstable compiler flags so it requires a `nightly` toolchain to be installed, though does not require `nightly` to be the default toolchain or the one with which `cargo expand` itself is executed. If the default toolchain is one other than `nightly`, running `cargo expand` will find and use `nightly` anyway.

```
# Install the essential target to nightly toolchain
rustup +nightly target add thumbv7em-none-eabi thumbv7em-none-eabihf

# Double check installed
rustup +nightly target list | grep installed
```

So, let's run the `cargo expand` and show the secret:

```
cargo expand --bin interrupt_system_tick --features "enable-debug use-stm32f407g-disc1"
```

It prints a lot, but we only focus on the bottom part like below:

```

use cortex_m_rt::{entry, exception};
use panic_semihosting as _;
#[cfg(feature = "enable-debug")]
use cortex_m_semihosting::hprintln;
use crate::clock_utils::{ClockSource, RccClocks};
use system_tick::SystemTickInterrupt;
use system_tick_timer_register::SystemTickTimer;
#[doc(hidden)]
#[export_name = "main"]
pub unsafe extern "C" fn __cortex_m_rt_main_trampoline() {
    __cortex_m_rt_main()
}
fn __cortex_m_rt_main() -> ! {
    #[cfg(feature = "enable-debug")]
    let _ = ::cortex_m_semihosting::export::hstdout_str(
        "STM32F4 system tick interrupt demo is running >>>\n",
    );
    let rcc_clock = RccClocks::setup_system_clock(ClockSource::HseThroughPll);
    SystemTickTimer::enable(rcc_clock.get_cpu_clock_frequency_in_hertz(), true);
    #[cfg(feature = "enable-debug")]
    { [ cfg ( feature = "enable-debug" ) ] { SystemTickTimer::print_config(); }
    }
    loop {}
}
#[doc(hidden)]
#[export_name = "SysTick"]
pub unsafe extern "C" fn __cortex_m_rt_SysTick_trampoline() {
    __cortex_m_rt_SysTick({
        static mut current_past_milliseconds_count: u32 = 0u32;
        &mut current_past_milliseconds_count
    })
}
fn __cortex_m_rt_SysTick(#[allow(non_snake_case)] current_past_milliseconds_count: &mut u32) {
{
    extern crate cortex_m_rt;
    cortex_m_rt::Exception::SysTick;
}
*current_past_milliseconds_count += 1;
#[cfg(feature = "enable-debug")]
{ [ cfg ( feature = "enable-debug" ) ] { let seconds_passed = (*current_past_milliseconds_count / 1000) as u32;
    if *current_past_milliseconds_count % 1000 == 0 {
        ::cortex_m_semihosting::export::hstdout_fmt(::core::fmt::Arguments::new_v1(
            &["seconds_passed: ", "\n"],
            &match (&seconds_passed,) {
                (arg0,) => ::core::fmt::ArgumentV1::new(
                    arg0,
                    ::core::fmt::Display::fmt,
                ),
            },
        )));
    }
}
}
}

```

Let's only focus on the highlighted part and make it simple like below:

```

#[export_name = "SysTick"]
pub unsafe extern "C" fn __cortex_m_rt_SysTick_trampoline() {
    __cortex_m_rt_SysTick({
        static mut YOUR_STATIC_VAR_NAME_HERE: u32 = 0u32;
        &mut YOUR_STATIC_VAR_NAME_HERE
    })
}
fn __cortex_m_rt_SysTick(#[allow(non_snake_case)]
YOUR_STATIC_VAR_NAME_HERE: &mut u32) {
{
    extern crate cortex_m_rt;
    cortex_m_rt::Exception::SysTick;
}
*YOUR_STATIC_VAR_NAME_HERE += 1;

// Ignore the non-important part
}

```

What information we got from the code above?

- `SysTick` is the `Exception Handler` (function name) which defined in the `Vector Table` we saw in chapter **7.1**.
- `__cortex_m_rt_EXCEPTION_NAME_trampoline` `extern` function will call the `__cortex_m_rt_EXCEPTION_NAME` function and pass in the static variable definition block when calling it.

That's it, it looks simple.

By the way, do you figure out what you need to do if you want to call a specific `ISR` (Interrupt Service Routine)? Is it just replace the `EXCEPTION_NAME` to the `IRQ_NUMBER` like (`IRQ2`, `IRQ3`)? I leave it to you to figure out:)

Two more things:

- For the complicated function name
`__cortex_m_rt_EXCEPTION_NAME_trampoline` and
`__cortex_m_rt_EXCEPTION_NAME` is that necessary? The answer is **NO**, you can replace to whatever name you want, as the `#[export_name =`

"EXCEPTION_NAME"] attribute is the place to declare what exception handler function name you're dealing with.

- If you don't familiar with the `extern` keyword or why it needs to be `unsafe`, here are the links can help you:
 - [Keyword `extern`](#)
 - [extern reference](#), please read the `function` and `statics` section.

So finally, we figured out the pattern for calling the particular `Exception Handler` without using the `#[exception]` procedure macro:

- If you want to use `static` variable:

```
#[export_name = "EXCEPTION_NAME"]
pub unsafe extern "C" fn EXCEPTION_NAME_handler_wrapper() {
    EXCEPTION_NAME_handler({
        static mut YOUR_STATIC_VAR_NAME_HERE: TYPE_HERE =
        VAR_INIT_VALUE_HERE;
        &mut YOUR_STATIC_VAR_NAME_HERE
    })
}

fn EXCEPTION_NAME_handler(#[allow(non_snake_case)]
    YOUR_STATIC_VAR_NAME_HERE: &mut TYPE_HERE) {
    // Your handler code here
}
```

- If you don't need the static variable:

```
#[export_name = "EXCEPTION_NAME"]
pub unsafe extern "C" fn EXCEPTION_NAME_handler_wrapper() {
    EXCEPTION_NAME_handler()
}

fn EXCEPTION_NAME_handler() {
    // Your handler code here
}
```

Here is the new version to replace the `#[exception]` macro one:

```
#[export_name = "SysTick"]
pub unsafe extern "C" fn system_tick_exception_handler_wrapper() {
    system_tick_exception_handler({
        static mut current_past_milliseconds_count: u32 = 0u32;
        &mut current_past_milliseconds_count
    })
}

fn system_tick_exception_handler(
    #[allow(non_snake_case)] current_past_milliseconds_count: &mut u32,
) {
    *current_past_milliseconds_count += 1;
    //
    #[cfg(feature = "enable-debug")]
    {
        let seconds_passed = (*current_past_milliseconds_count / 1000) as
u32;
        if *current_past_milliseconds_count % 1000 == 0 {
            hprintln!("New version, seconds_passed: {}", seconds_passed);
        }
    }
}
```

Full version is here: [demo/src/bin/interrupt_system_tick_new_version.rs](#)

Let's build a production version (no `enable-debug` feature) to see what we got:

```
cargo clean
cargo-strip --target thumbv7em-none-eabi --bin
interrupt_system_tick_new_version --features "use-stm32f407g-disc1" --
release --verbose
```

We got the very small size binary: 8.5K `interrupt_system_tick_new_version*`

Then, let's put back the `enable-debug` feature and run it again:

```
cargo clean
cargo-strip --target thumbv7em-none-eabi --bin
interrupt_system_tick_new_version --features "enable-debug use-
stm32f407g-disc1" --release --verbose

# Run it in qemu
qemu-system-gnuarmeclipse -cpu cortex-m4 -mcu STM32F407VG -machine
STM32F4-Discovery -semihosting-config enable=on,target=native -kernel
target/thumbv7em-non
e-eabi/release/interrupt_system_tick_new_version
```

It works as expected:

```
[ System Tick Timer Control Register (STK_CTRL) ]:
value: 00000000000000000000000000000011
Counter enabled: true // bits: 0b1
Counting down to zero to asserts the SysTick exception request: true // bits: 0b1
Clock source: "Processor clock (AHB)" // bits: 0b1
Timer counted to 0: false // bits: 0b0

[ System Tick Timer Reload Register (STK_LOAD) ]:
value: 00000000000000010100100000011111
Reload value: 167999 // bits: 0b000000101001000000111111
New version, seconds_passed: 1
New version, seconds_passed: 2
New version, seconds_passed: 3
```