

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-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
```

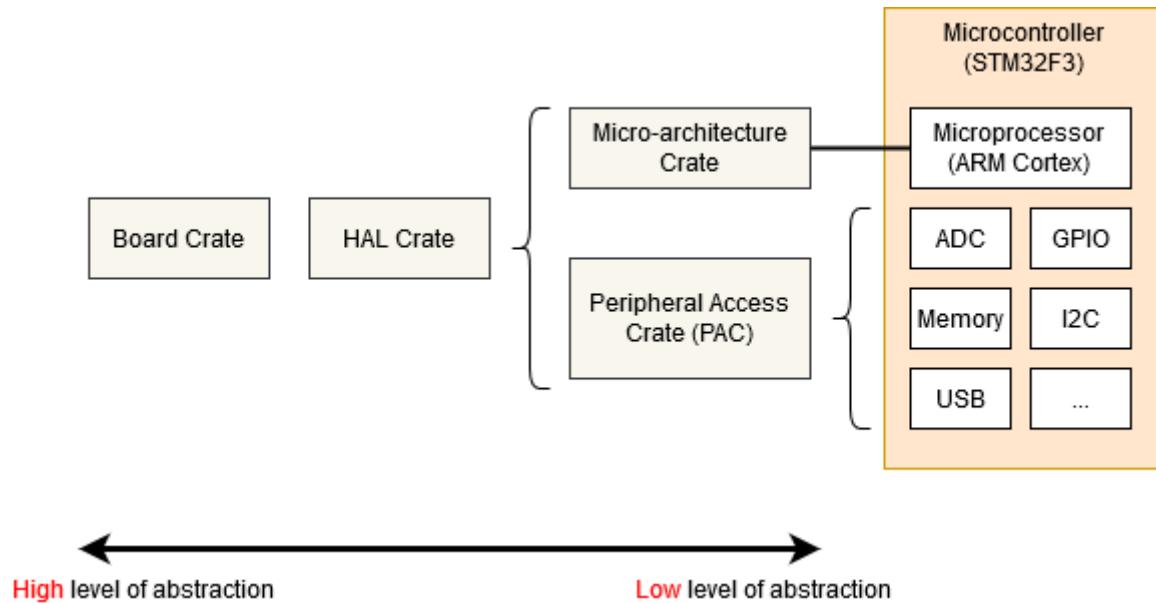
3.4 Run hello example in hardware

- 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 microcontrollers 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-gnuarmeclipse -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
//
// `GPIO.D.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.GPIO.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.

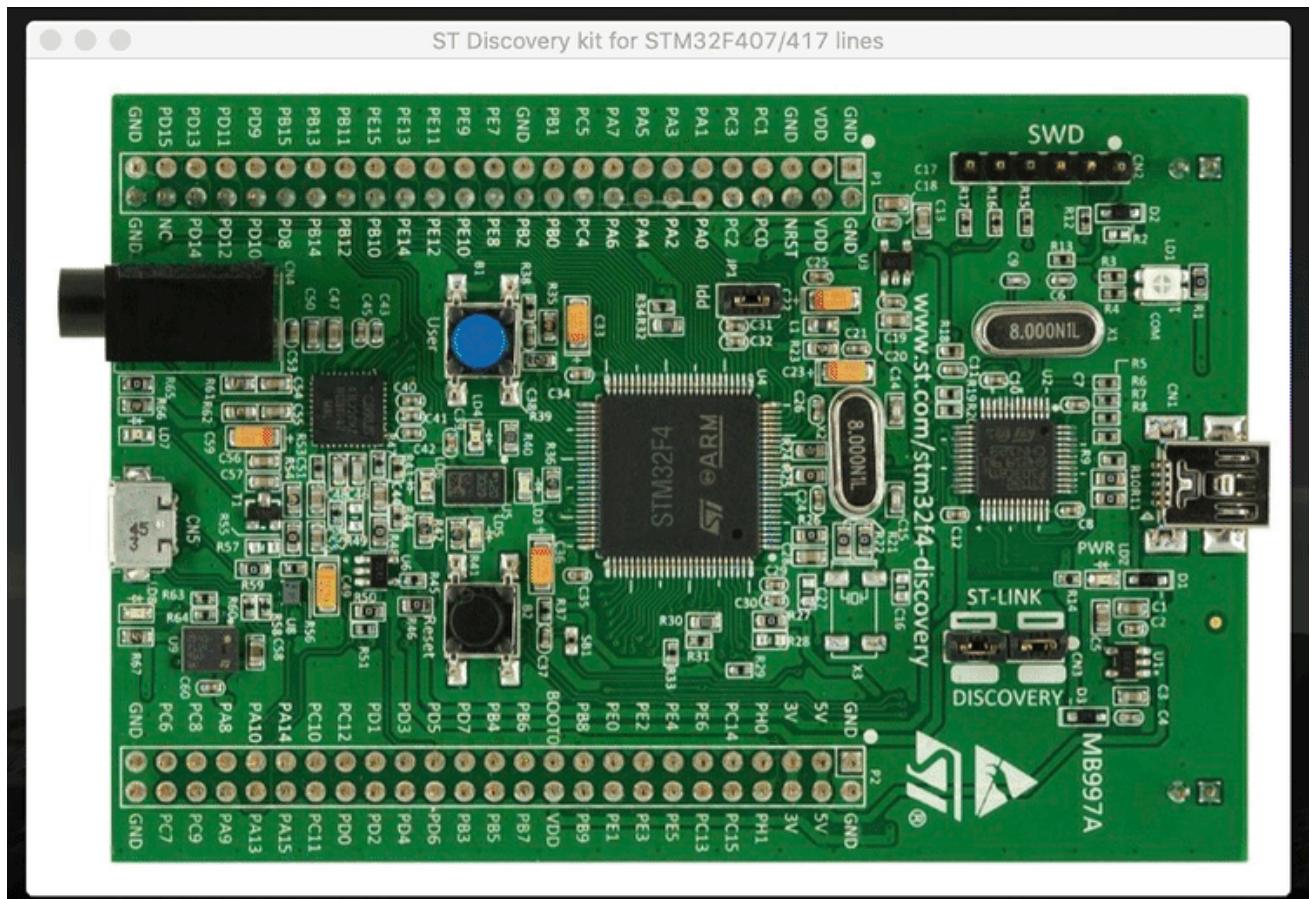
And you should be able to see the console log like below:

```

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-gnuarmel -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:



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

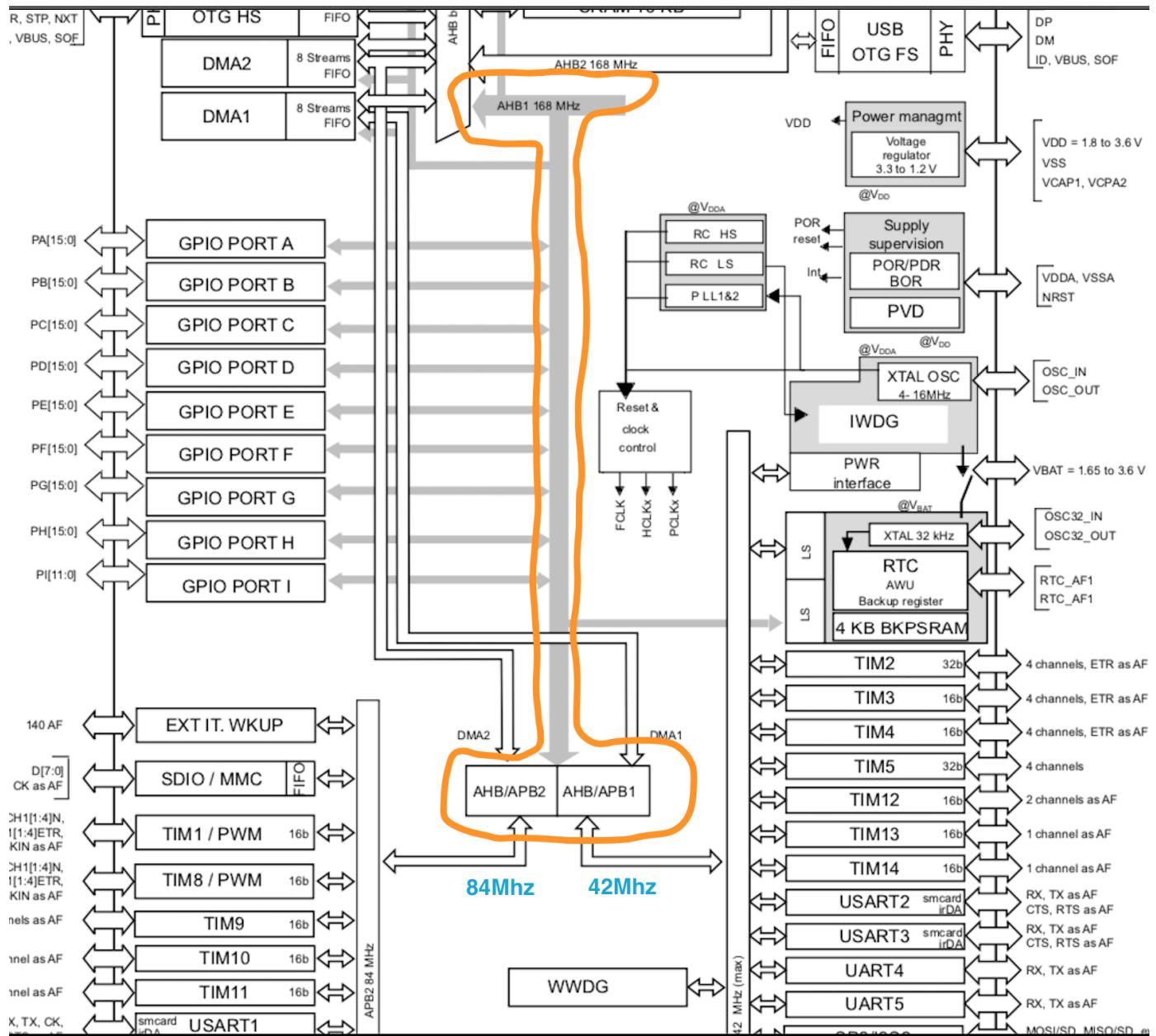
```
pub struct RegisterBlock {  
    pub moder: MODER,  
    pub otyper: OTYPER,  
    pub ospeedr: OSPEEDR,  
    pub pupdr: PUPDR,  
    pub idr: IDR,  
    pub odr: ODR,  
    pub bsrr: BSRR,  
    pub lckr: LCKR,  
    pub afrl: AFRL,  
    pub afrh: AFRH,  
}
```

[-] 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_with!STM32F407VG_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)

RM0090

7.3.10 RCC AHB1 peripheral clock enable register (RCC_AHB1ENR)

Address offset: 0x30

Reset value: 0x0010 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	ETHMA CEN	Reserved		DMA2E N	DMA1E N	CCMDAT ARAMEN	Res.	BKPSR AMEN	Reserved		
	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			GPIOIE N	GPIOH EN	GPIOG EN	GPIOF EN	GPIOEEN	GPIOD EN	GPIOC EN	GPIOB EN	GPIOA EN	
			rw				rw	rw	rw	rw	rw	1 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		BKPSRA M LPEN	SRAM 2 LPEN	SRAM 1 LPEN	
	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
FLITF LPEN	Reserved		CRC LPEN	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	1 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	AHB1	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
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		Section 8.4.11: GPIO register map on page 287
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 = 0b00000011iu8;
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

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							
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							

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

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.

Set '1' to `bsbitX` to set 'High'
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_BSSR** 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 **GPIOB_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 **GPIOB_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-gnuarmeclipse -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 (pins) 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 >>>  

GPIOD_MODER: 0b01010101000000000000000000000000  

[led:green on]  

[led:orange on]  

[led:red on]  

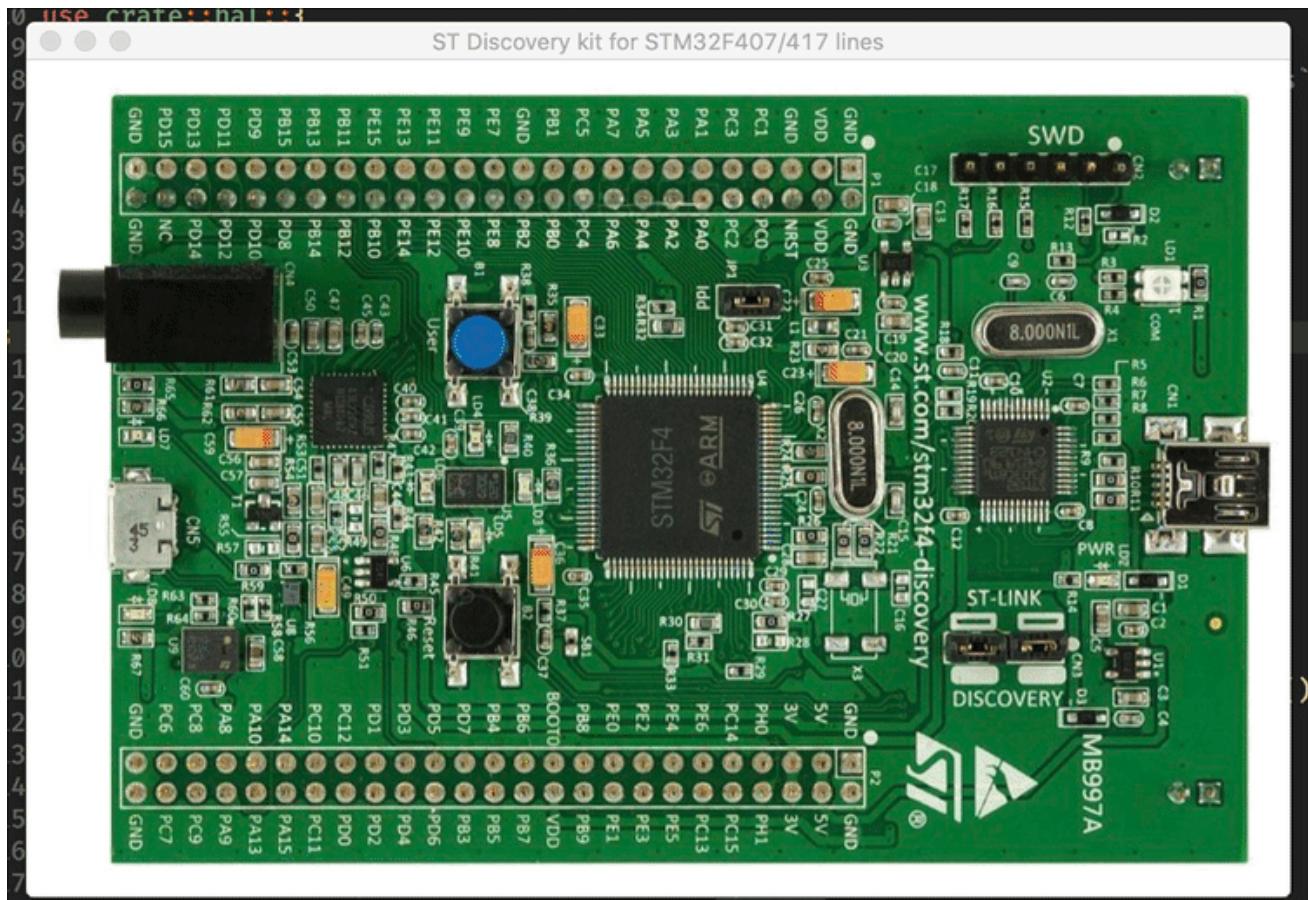
[led:blue on]  

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-gnueabihf -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**):

- **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.

6.1 Simple clock brief

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.

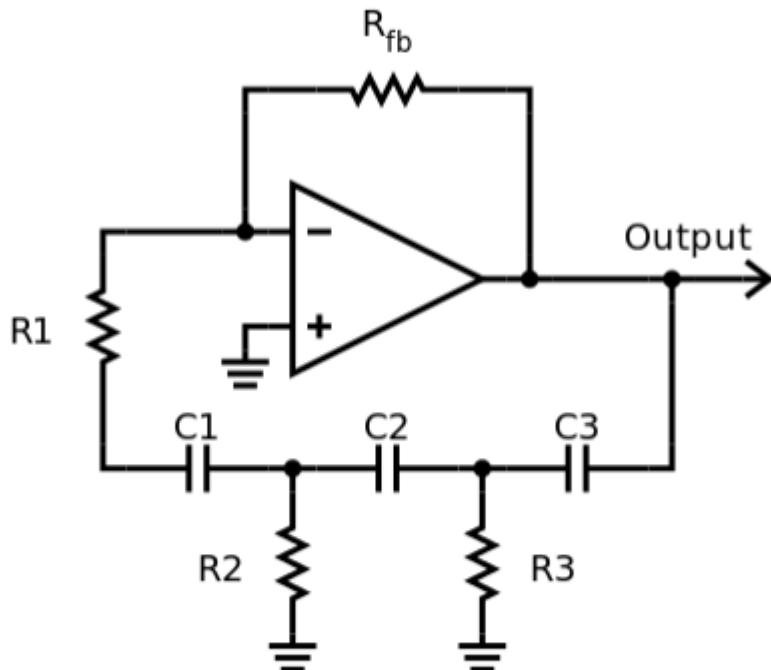
6.2 What is clock source selecting?

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**.

6.3 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.

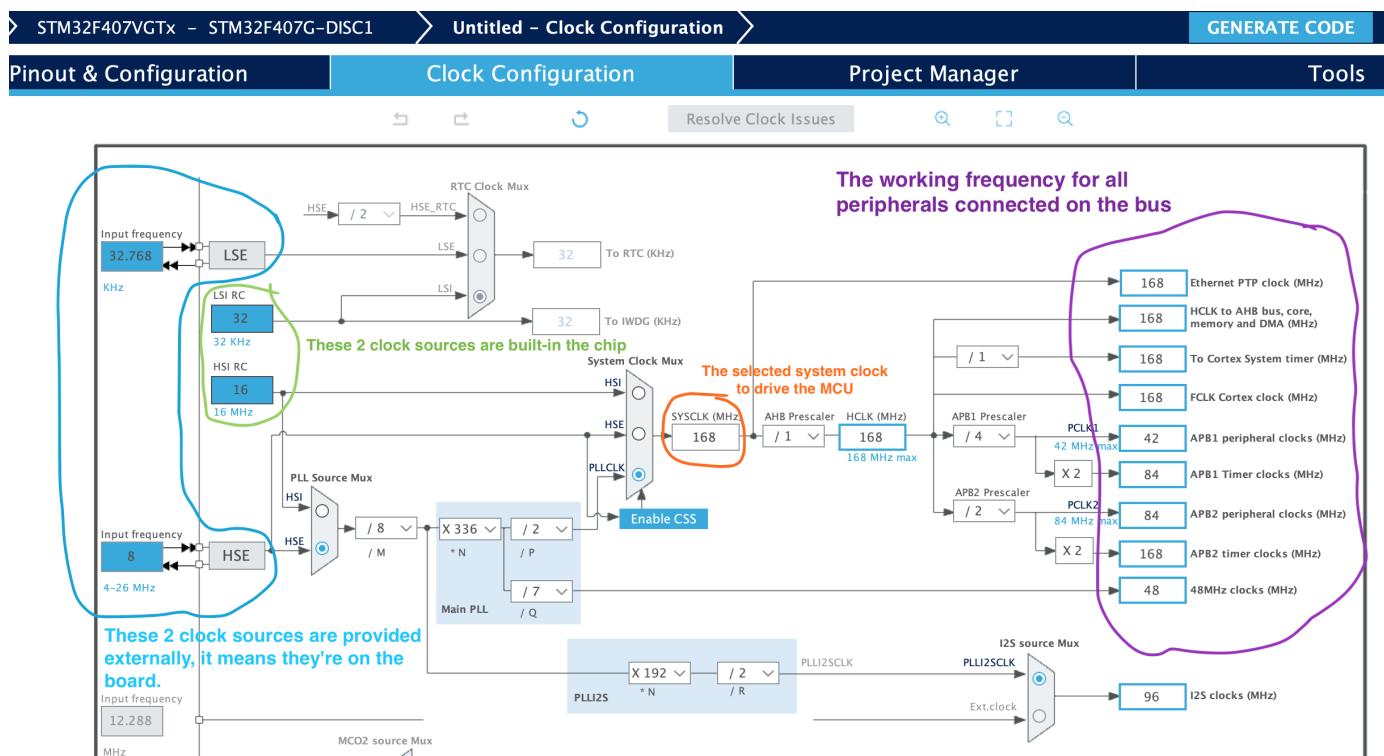
You still can code your program without fully understand what that means, then no worry at this moment:)

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.

6.4 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.

6.5 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:

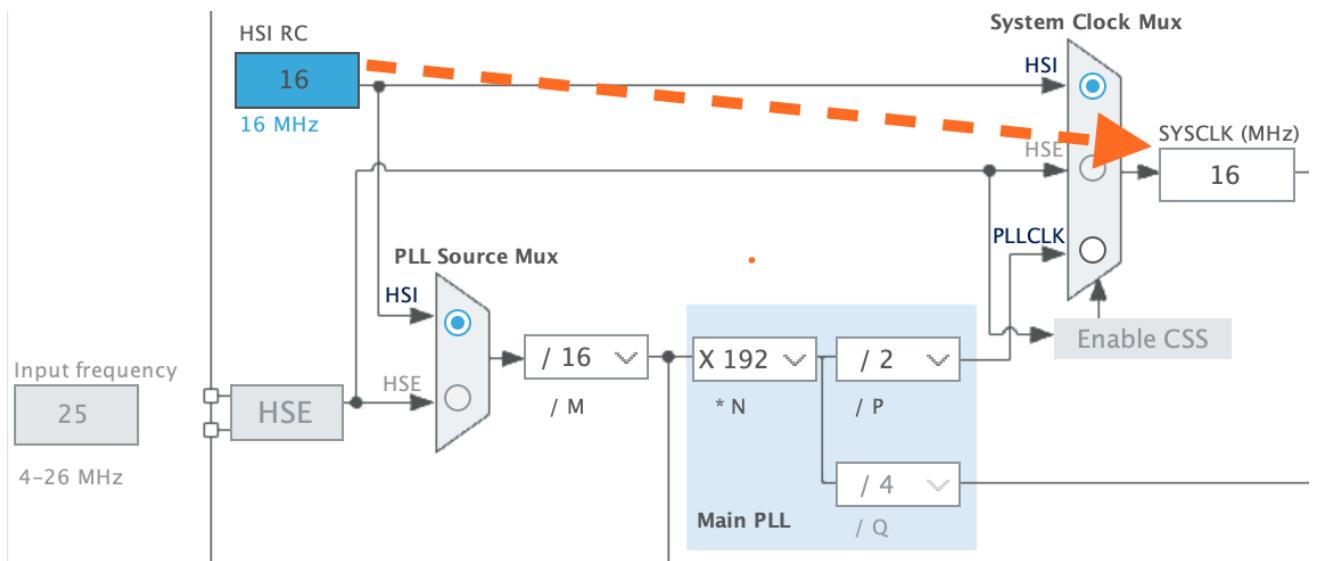
- **HSI** ----> **SYSCLK**
- **HSE** ----> **SYSCLK**
- **PLL** ----> (HSI or HSE) / PLL_M * PLL_N / PLL_P ----> **SYSCLK**

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!!!

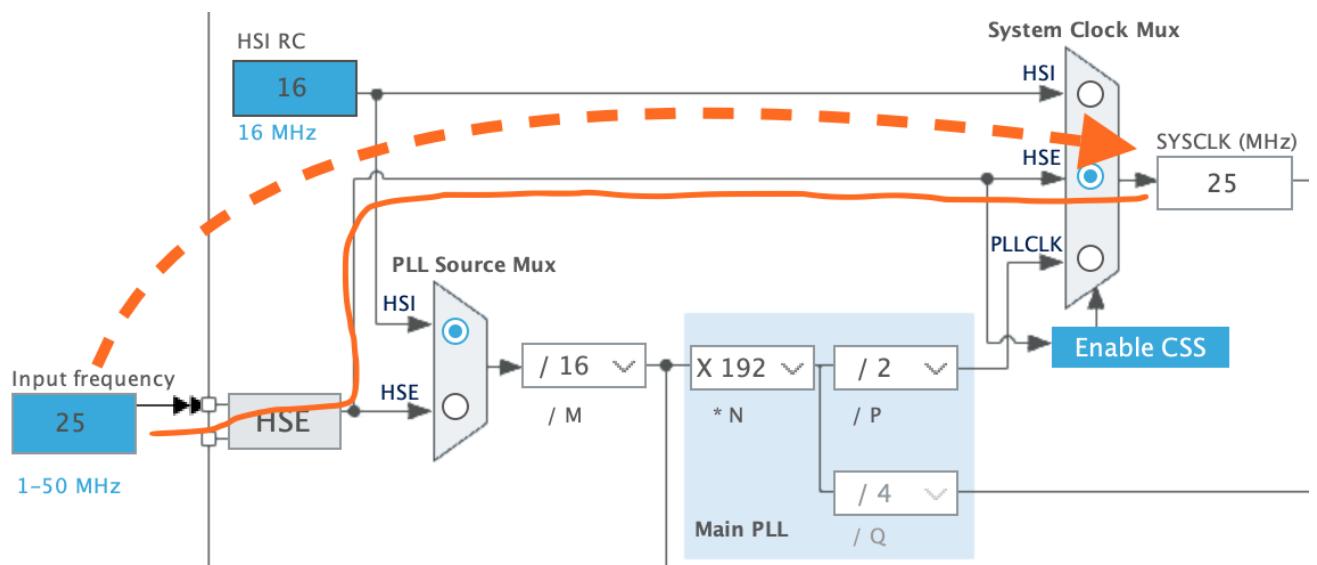
Let's have a look at them one by one:

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



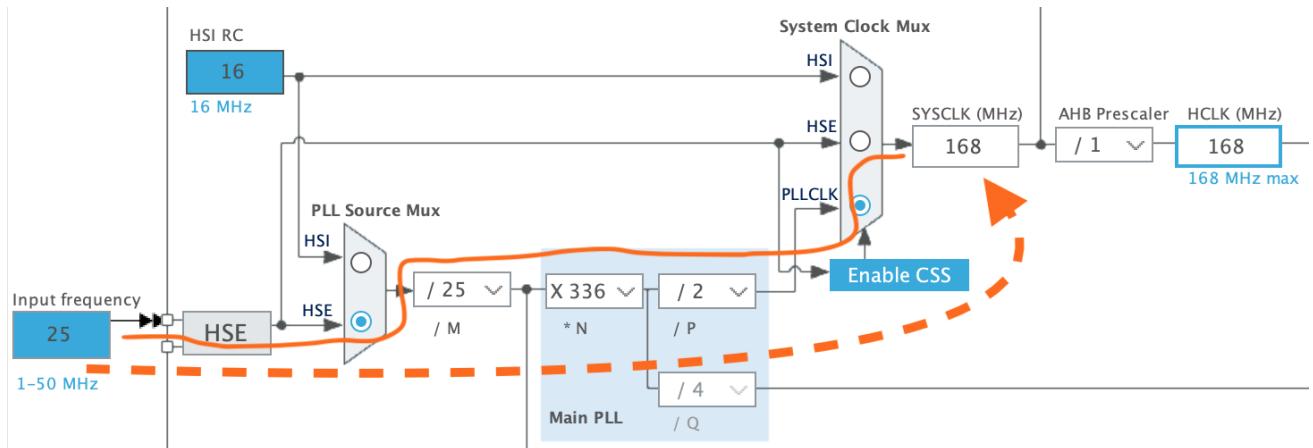
This is the case of **HSI** as the clock source. You can see the **SYSCLK** get clock signal directly from **HSI** and the final frequency is **16MHz**.

- **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).

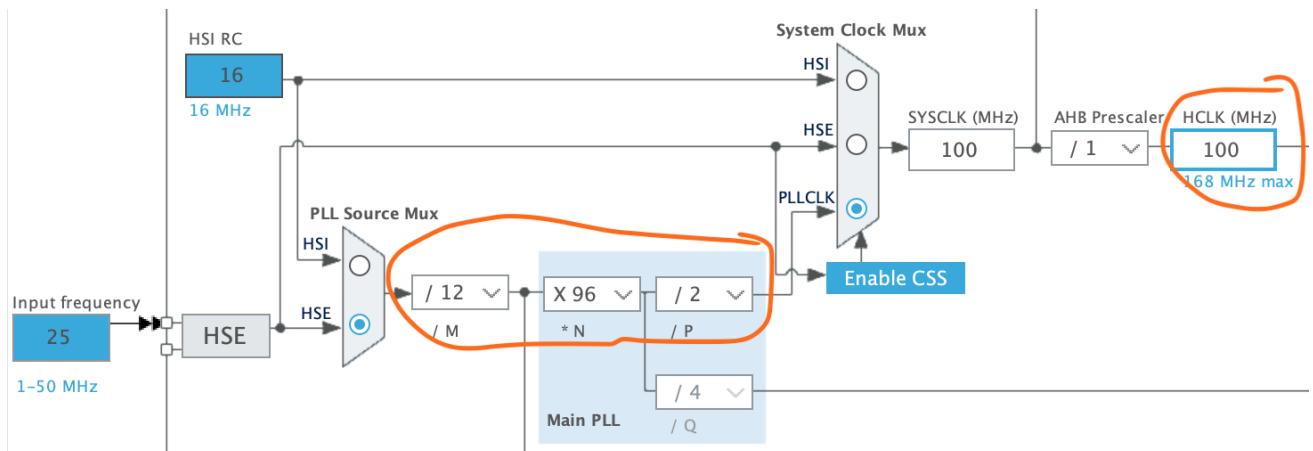
- **PLL** ----> (HSI or HSE) / PLL_M * PLL_N / PLL_P ----> **SYSCLK**:



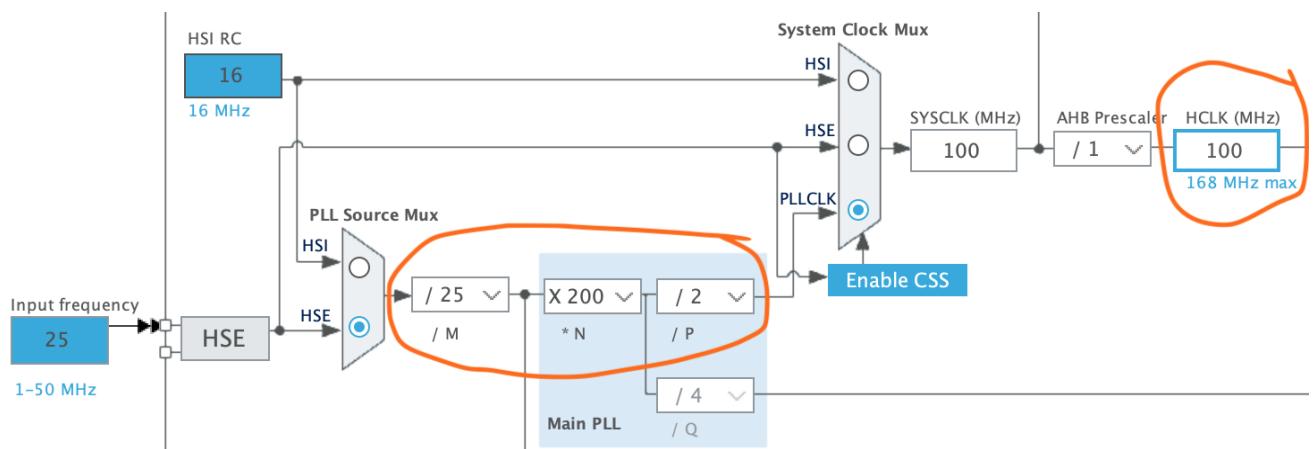
This is the case of **HSE through PLL** as the clock source. You can see the **SYSCLK** get clock signal from **HSE** first, and then go through **PLL** factors (**M/N/P**) calculation, finally, got the frequency is **168MHz**.

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:

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

6.6 System clock settings demo

Let's write some code to demonstrate the system clock settings.