

ESS: Lab 1

Problem Statement

A project has arisen from a logistics company. The company ships a wide variety of products, ranging from fresh fruit and vegetables to paintings and scientific equipment across the globe. If an item arrives damaged then the company has to pay compensation, via their insurance company. The number of claims made in the past two years has increased dramatically, resulting in a consequent increase in their insurance premiums. This is affecting the profitability of their business and their relationships with their clients. To address this state of affairs, the CTO of the company has come up with the idea of a 'smart-pallet', a sensor-rich platform that will be embedded within a conventional pallet and provide diagnostics on the journey that a particular consignment has been on.

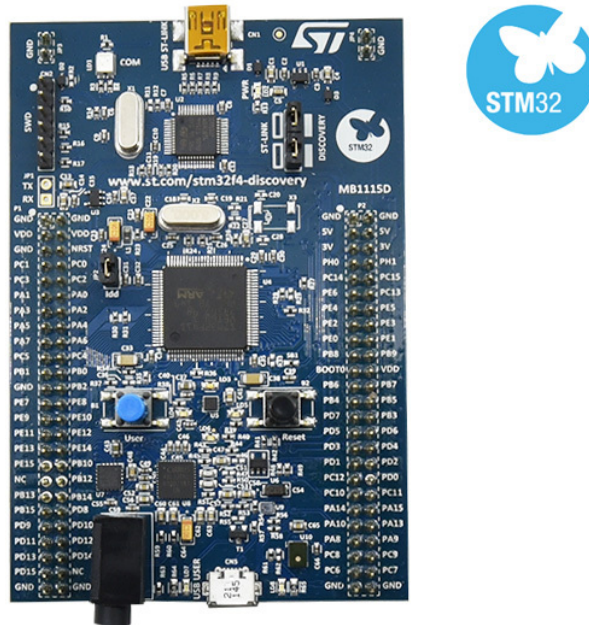
The key high level requirements are:

- R1: Measure vibration
- R2: Measure impact
- R3: Measure pallet tilt angle
- R4: Measure pallet storage temperature
- R5: Measure pallet humidity
- R6: Simple user display of pallet status (ok/damaged)
- R7: Logging capability
- R8: Wireless upload capability for IoT integration
- R9: Battery powered, long-life essential
- R10: Extremely low cost (US\$3 in quantity)
- R11: Rugged integration to IP67 standards

As the software team, you are required to make a rapid prototype to demonstrate the feasibility of the approach and impress the client. The hardware team are building a first hardware prototype, but it will not be ready for two weeks. In order to work in parallel, you will start coding with the intention of being able to readily shift onto the hardware platform when it becomes available.

Development Kit

To make a rapid start on our application, we are going to use the STM32F4 Discovery Board. This is an evaluation kit / development board made by STMicroelectronics, featuring an Arm Cortex-M4 processor. The Arm Cortex-M4 processor is essentially an Arm Cortex-M3 processor with the addition of a FPU (floating point unit) and associated DSP (digital signal processing) instructions. It is a very powerful processor, and for the end application, is way over spec. However, as it is under £15, it is an inexpensive way of doing rapid prototyping.



- STM32F411VET6 microcontroller featuring a 32-bit Arm Cortex-M4 core, 512 KB Flash, 128 KB RAM in an LQFP100 package
- On-board ST-LINK/V2 with selection mode switch to use the kit as a standalone ST-LINK/V2 (with SWD connector for programming and debugging)
- ST MEMS LSM303DLHC or LSM303AGR 3-axis accelerometer
- ST MEMS MP45DT02 or IMP34DT05 audio sensor, omni-directional digital microphone
- CS43L22, audio DAC with integrated class D speaker driver
- Four user LEDs, LD3 (orange), LD4 (green), LD5 (red) and LD6 (blue)
- Two push buttons (user and reset)
- Extension header for all LQFP100 I/Os for quick connection to prototyping board and easy probing

STM32CubeIDE 1.18.0

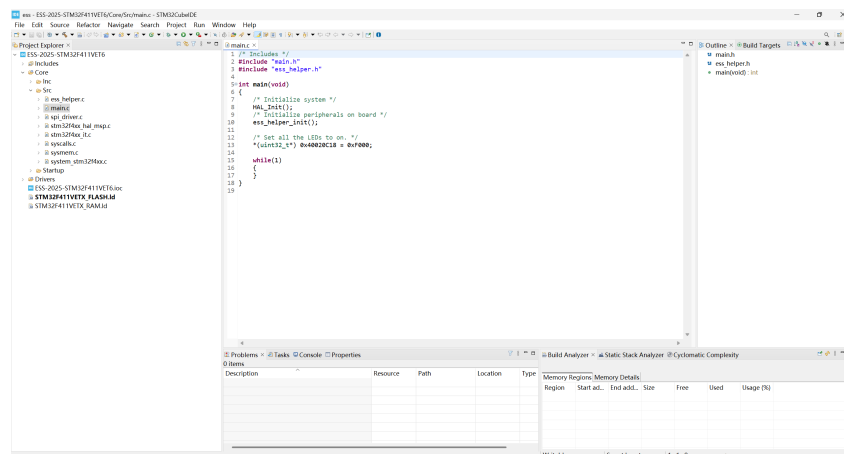
To write the C code for the microcontroller, we are going to use STM32CubeIDE 1.18.0. This consists of a C-compiler, a debugger and an IDE. It is supported by Arm, so is widely used in industry (along with competitors like IAR). Fortunately, it is a cross-platform IDE which runs in Windows, Linux and MacOS, so you can easily install the IDE on your own device¹. Without loss of generality, we use Windows operating system as an example. We will be using STM32CubeIDE during the week to build and test our application.

Task 1:

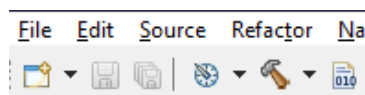
Initial bringup

A skeleton application has been created and is available as a public Github repo at <https://github.com/XinyuHou97/ESS2025>. This is a project which has been setup with the correct clock frequency, libraries and some basic initialization. Create a new workspace within the IDE when prompted. Download/clone the repo and open `ESS2025/ess-skeleton` within the IDE by using the "Open Projects from File System" option in the File menu.

This should open the project in STM32CubeIDE, which should look like this:



You can now try and build the project (use the fifth button from the left (hammer), or press Ctrl+B)

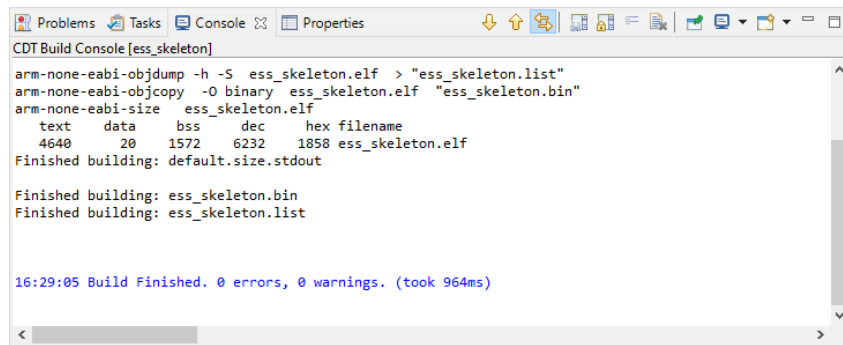


If all goes well, your project should build without any errors, as shown in the build window in the bottom of the window.

You can now flash (download) the code to the discovery board, by clicking the 'Run' button:

For the first time you run this project on the board, there might be some configurations that are needed. Click 'Apply and Close', then 'OK':

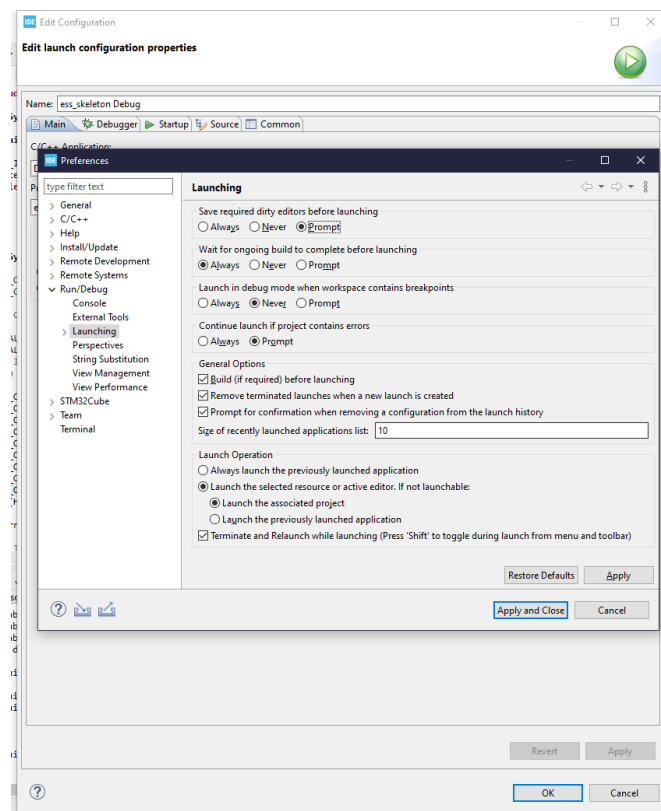
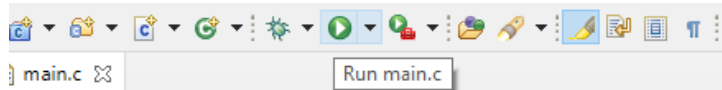
¹To download STM32CubeIDE, navigate your Internet browser to <https://www.st.com/en/development-tools/stm32cubeide.html>



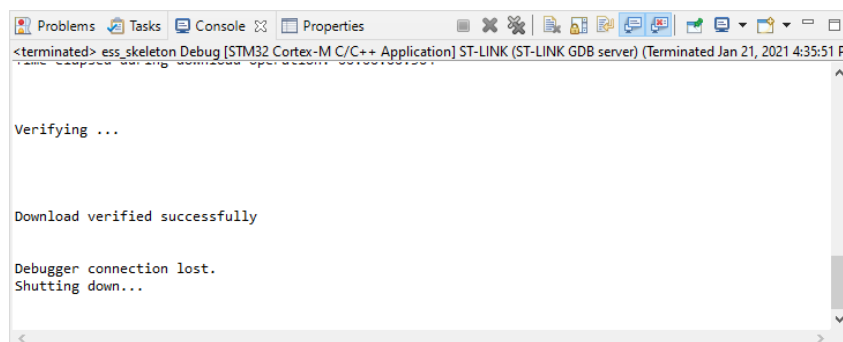
```
CDT Build Console [ess_skeleton]
arm-none-eabi-objdump -h -S ess_skeleton.elf > "ess_skeleton.list"
arm-none-eabi-objcopy -O binary ess_skeleton.elf "ess_skeleton.bin"
arm-none-eabi-size ess_skeleton.elf
text    data    bss    dec    hex filename
4640    20    1572    6232    1858 ess_skeleton.elf
Finished building: default.size.stdout

Finished building: ess_skeleton.bin
Finished building: ess_skeleton.list

16:29:05 Build Finished. 0 errors, 0 warnings. (took 964ms)
```



It should program the board and end up with the following output:



```
<terminated> ess_skeleton Debug [STM32 Cortex-M C/C++ Application] ST-LINK (ST-LINK GDB server) (Terminated Jan 21, 2021 4:35:51 PM)
Time elapsed during download operation: 00:00:00.000

Verifying ...

Download verified successfully

Debugger connection lost.
Shutting down...
```

If it throws up an error in any of the above-mentioned steps, just ask for help!

Your board is now running the code that has been written, and should be doing... nothing. The four user LEDs in the middle of the board should all be off. We will now try and write something useful in the next steps.

First Steps: Basic display

Task 2:

Making something happen

Our first task will be to tackle **R6**: 'Simple display of pallet status'. We are going to use the four on-board LEDs as a display. The advantage of starting with this requirement is that customers are always impressed by flashing lights, as it gives a visual indication that the hardware is actually working. Consulting the datasheet, we can see that the LEDs are connected to Port D 12 (PD12), PD13, PD14 and PD15. They need to be driven high (written with a 1) to turn them on or driven low (written with a 0) to turn them off.

By digging very deep in the datasheet for this particular microcontroller, we find that memory location `0x40020C14` corresponds to the output register for Port D². In C, we can write to a register at a known address by treating it as a pointer and then dereferencing it.

Change your main code to the following:

```
int main(void) {
    /* Initialize system */
    HAL_Init();
    /* Initialize peripherals on board */
    ess_helper_init();
    // Set all the LEDs to on.
    *(uint32_t*)0x40020C14 = 0xF000;
    while (1) {

    }
}
```

In the new line `*(uint32_t*)0x40020C14 = 0xF000;`, we are making a pointer from the address (`uint32_t *`), dereferencing it (`*`) and then setting the top bits (PD12 to PD15) to 1. Build and program this into your device. What happens?

Solution:

All LEDs should turn on and stay on.

²Port D has a bunch of other registers that can set the mode, the direction of the pins, the input state, the speed of the pins etc. More on this later.

- (a) Modify your code to turn on only one LED at a time to determine which color LED is connected to each port pin.

Solution:

- PD12: LED_GREEN
- PD13: LED_ORANGE
- PD14: LED_RED
- PD15: LED_BLUE

Task 3:

Writing a simple LED driver

We know that we can control individual LEDs, but the mechanism we have for doing so is not very programmer friendly. We want to build a Hardware Abstraction Layer (HAL)³ to shield us from the details of which register to address and which bit to set/clear.

- (a) List some reasons why using a HAL is a good idea

Solution:

- A HAL leads to decoupling between the software and the hardware being used.
- It is relatively straightforward to port to a different platform by modifying code in one place.
- A properly written HAL can make testing easier.

- (b) At a minimum, we need to do the following:

- Initialize an LED.
- Set an LED (turn it on).
- Clear an LED (turn it off).

As an API, we start with the following to turn on and off the green LED.

```
// Initialize the green LED.
void led_green_init(void);
// Turn the green LED on
void led_green_on(void);
// Turn the green LED off
void led_green_off(void);
```

³The libraries we are using is called "STM32 Hardware Abstraction Layer (HAL) driver". However, here the HAL means the concept, not this specific library. In fact, we are trying not to rely on the STM32 HAL driver too much to get a deeper understanding of Embedded Systems.

To make life easy, start by writing these prototypes directly in the `main.c` file above the function definition for `main(void)`. What should the default behaviour be for your LEDs when they are initialized? What is your justification for this? Should it be the same for all peripherals?

Solution:

A sensible default action is to turn the LED off. This is extremely important for actuators like motors which if initialized in the wrong state could cause injuries or death. There are some cases in which we want to initialize something as being on as a default action, such as powering up a slave device.

- (c) Write your code and check that everything works i.e you can turn on the Green LED using the following code:

```
// Main loop
led_green_init();
led_green_on();
while (1) {

}
```

Solution:

```
// ESS: Day 1_003
// Initialize the green LED.
void led_green_init(void)
{
    *(uint32_t*)0x40020C14 = 0x0000;
}

// Turn the green LED on
void led_green_on(void)
{
    *(uint32_t*)0x40020C14 = 0x1000;
}

// Turn the green LED off
void led_green_off(void)
{
    *(uint32_t*)0x40020C14 = 0x0000;
}

int main(void) {
    /* Initialize system */
    HAL_Init();
    /* Initialize peripherals on board */
    ess_helper_init();
}
```

```

// Main loop
led_green_init();
led_green_on();
while (1) {

}

```

- (d) The solution we have at the moment is pretty hardcoded, which can make future modifications more challenging. Instead of using constants like `0x1000` to set a particular LED, a more elegant way is to construct the constant, by passing in the pin number. This can be stored locally in a variable `led_green_pin`. Then, when we call `led_green_on()` and `led_green_off()` these routines will work out the constant needed. [hint, use shifts e.g. `mask = 0x01 << bits_position;`]

```

// this stores the led pin we are going to use
// we declare as static to restrict the scope to this file
static uint32_t led_green_pin;
// Initialize the green LED.
// Supply a pin number between 0 and 15
void led_green_init(uint32_t pin);
// Turn the green LED on
void led_green_on(void);
// Turn the green LED off
void led_green_off(void);

```

Solution:

```

// This stores the led pin we are going to use
// We declare as static to restrict the scope to this file
static uint32_t led_green_pin;

// Function Declarations
// We declare them first;
// so, we can reference them in code above their definition.
// E.g., call led_green_off() in led_green_init() before
// defining it
void led_green_init(uint32_t pin);
void led_green_on(void);
void led_green_off(void);

// Initialize the green LED.
// Supply a pin number between 0 and 15
void led_green_init(uint32_t pin)
{
    led_green_pin = pin;
}

```



```

        led_green_off();
    }

    // Turn the green LED on
    // Left shift (<<) selects correct bit.
    // Or assignment (|=) applies bit change to register
    // while leaving other bits untouched.
    void led_green_on(void)
    {
        *(uint32_t*)0x40020C14 |= 0x01 << led_green_pin;
    }

    // Turn the green LED off
    // Left shift (<<) selects correct bit.
    // Bitwise not (~) sets this bit to 0 and other bits to 1.
    // And assignment (&=) applies bit change to register
    // while leaving other bits untouched.
    void led_green_off(void)
    {
        *(uint32_t*)0x40020C14 &= ~ (0x01 << led_green_pin);
    }

    int main(void)
    {
        /* Initialize system */
        HAL_Init();
        /* Initialize peripherals on board */
        ess_helper_init();
        // Set up the LED
        led_green_init(12);
        // Turn LED on
        led_green_on();
    }

```

Task 4:

Generic LED driver

The LED driver we have at the moment works but is pretty ugly. For example, writing LED drivers for each colour LED would lead to a lot of duplication, violating the DRY (don't repeat yourself) software engineering principle. A better way would be to decouple the logic from the actual pin. We could then supply the name of the LED to be turned on/off to a standardized API. One of the best ways of doing this is to use an abstract datatype (ADT) to carry around the state/configuration of each LED. In C, we can make an ADT by making a struct containing all the state we need.

```

// Use a define for the address of the PORTD output register
#define PORTD ((volatile uint32_t*)0x40020C14)
// Generic struct to encapsulate LED state.
struct LEDstruct
{
    volatile uint32_t * port; // the LED register
    uint32_t pin; // 0..15
};

```

It will get pretty painful writing struct LEDstruct all the time, so we can create our own 'type' like so:

```

// Use a define for the address of the PORTD output register
#define PORTD ((volatile uint32_t*)0x40020C14)
// Generic struct to encapsulate LED state.
struct LEDstruct
{
    volatile uint32_t * port; // the LED register
    uint32_t pin; // 0..15
};
// Typedef for an LED struct - this is a shorthand
// that defines a new type for encapsulating LED state
typedef struct LEDstruct LED_t;

```

Our API now looks like the following (again, for now, we just are writing in `main.c`).

```

// Function Declarations
void led_init(LED_t * led, volatile uint32_t * port, uint32_t pin);
void led_on(LED_t * led);
void led_off(LED_t * led);

```

(a) Write the code to turn on and off any LED. What was challenging about this?

Solution:

The challenge here is that we are modifying individual bits, but affecting the shared (global) register. There are two ways of handling this - either reuse the port register itself or shadow it by creating a shadowed variable. We will take the first approach, but in many cases, the second approach leads to cleaner, more decoupled code, especially if something else is sharing that port register.

```

// Use a define for the address of the PORTD output register
#define PORTD ((volatile uint32_t*)0x40020C14)
// Generic struct to encapsulate LED state.
struct LEDstruct
{
    volatile uint32_t * port; // the LED register
    uint32_t pin; // 0..15
};

```

```

// Typedef for an LED struct - this is a shorthand
// that defines a new type for encapsulating LED state
typedef struct LEDstruct LED_t;

// Function Declarations
void led_init(LED_t * led, volatile uint32_t * port, uint32_t pin);
void led_on(LED_t * led);
void led_off(LED_t * led);

// Function Definitions

// Initialize an LED, start in off-state
void led_init(LED_t * led, volatile uint32_t * port, uint32_t pin)
{
    led->port = port;
    led->pin = pin;
    // and turn it off
    led_off(led);
}

// Turn the green LED on
void led_on(LED_t * led)
{
    *led->port |= 0x01 << (led->pin);
}

// Turn the green LED off
void led_off(LED_t * led)
{
    *led->port &= ~ (0x01 << (led->pin));
}

int main(void) {
    // create the green led ADT
    LED_t led_green;
    LED_t led_orange;
    LED_t led_blue;
    LED_t led_red;
    /* Initialize system */
    HAL_Init();
    /* Initialize peripherals on board */
    ess_helper_init();
    // Set up the leds
    led_init(&led_green, PORTD, 12);
    led_init(&led_orange, PORTD, 13);
    led_init(&led_red, PORTD, 14);
    led_init(&led_blue, PORTD, 15);
    // Set up their values
    led_on(&led_green);
    led_off(&led_green);
    led_on(&led_red);
    led_on(&led_blue);
    led_on(&led_orange);
    while (1) {

    }
}

```

- (b) Write a simple delay function by using a `while` loop. Your function should have an API like this, giving about a 1000 msec (1 second) delay for an input of 1000.

```
void delay_msec(uint32_t delay);
```

Solution:

The solution is just to use a while/for loop which just spins the processor and does nothing. Again, the only trick is that we have to fight against the all too clever compiler and insert a dummy operation in the middle of the loop, just so the whole loop does not get optimized away.

```
// Delay for a multiple of 1 msec
void delay_msec(uint32_t delay);

void delay_msec(uint32_t delay)
{
    // internal loop counter
    uint32_t k;
    // dummy variable to prevent compiler optimization
    volatile uint32_t internal_fake;
    while (delay-- >0)
    {
        for (k = 0; k <20000;k++)
        {
            internal_fake--;
        }
    }
}

int main(void) {
    // create the green led ADT
    LED_t led_green;
    LED_t led_orange;
    LED_t led_blue;
    LED_t led_red;
    /* Initialize system */
    HAL_Init();
    /* Initialize peripherals on board */
    ess_helper_init();
    // Set up the leds
    led_init(&led_green,PORTD,12);
    led_init(&led_orange,PORTD,13);
    led_init(&led_red,PORTD,14);
    led_init(&led_blue,PORTD,15);
    // Set up their values
    led_on(&led_green);
    led_off(&led_green);
    led_on(&led_red);
    led_on(&led_blue);
    led_on(&led_orange);
    while (1) {
        led_on(&led_green);
        delay_msec(1000);
        led_off(&led_green);
        delay_msec(1000);
    }
}
```

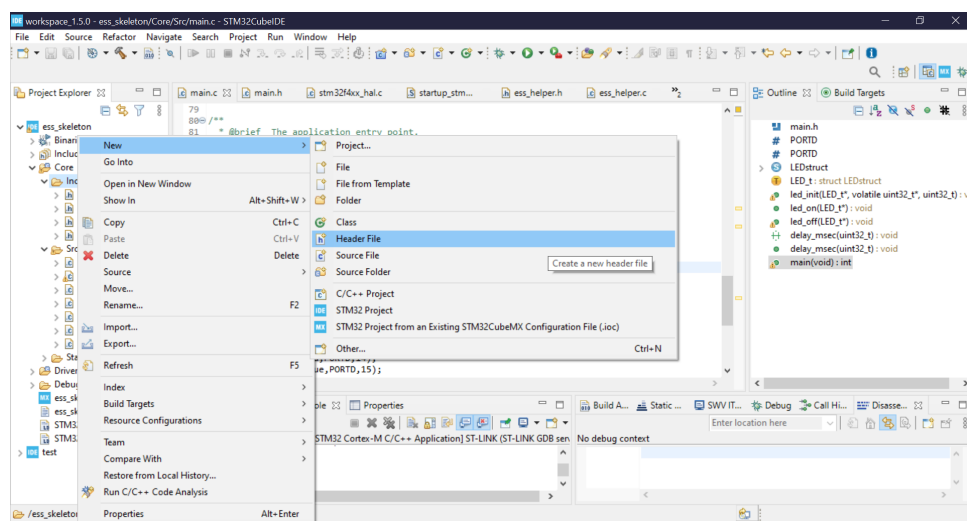
Task 5:

Refactoring

Now that we have written the LED driver, we are going to try and make it cleaner, by moving all the logic for the driver into its own files.

- (a) The first part is to *refactor* the code to make it clean. We are going to move all the LED code into two files: `led_driver.h` for the function declarations (API) and `led_driver.c` for the function definition (implementation). Then instead of having a `main.c` that is littered with code for the led_driver, we will delegate this to its own module.

- **Step 1:** On the left hand side, in the project layout, expand the 'Core' folder. Right-click and in the drop-down menu of the 'Inc' folder, navigate to "New" and then click 'Header File'.



Then create the `led_driver.h` file - note the name and that we have used a path which is in the Include paths of the project⁴.

Populate the `led_driver.h` file so it looks something like this:

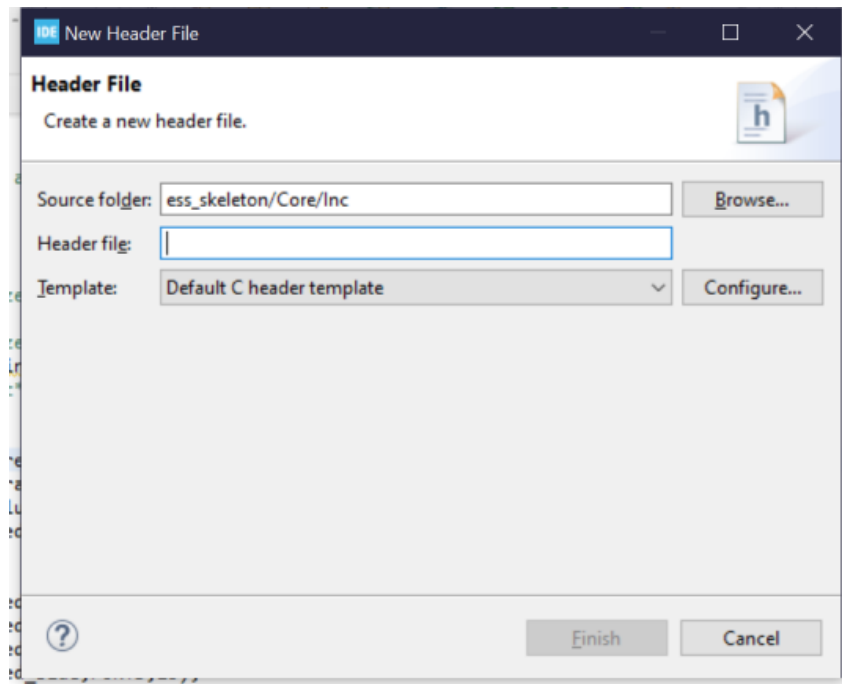
```
// file: led_driver.h

/**
 *          LED Driver
 *
 *
 * @author      Andrew Markham
 * @version     v1.0
 * @ide         STM32Cube
 * @license     GNU GPL v3
 */

#ifndef LED_DRIVER_H
#define LED_DRIVER_H

#include <stdint.h>
```

⁴If you want to use another directory to store your files, do not forget to change the include and source configurations of the C/C++ compiler



```
// Generic struct to encapsulate LED state.
struct LEDstruct
{
    volatile uint32_t * port; // the LED register
    uint32_t pin; // 0..15
};
// Typedef for an LED struct - this is a shorthand
// that defines a new type for encapsulating LED state
typedef struct LEDstruct LED_t;

// Function Declarations
void led_init(LED_t * led, volatile uint32_t * port, uint32_t pin);
void led_on(LED_t * led);
void led_off(LED_t * led);

#endif
```

- **Step 2:** Create the `led_driver.c` file in the same way as above (New-File), save the file in the same directory as 'main.c' (or any other directory you like, just make sure that you have the correct configuration of the compiler). Copy your implementation to this file, in the sections shown below.

```
// file: led_driver.c

#include "led_driver.h"

// Initialize an LED, start in off-state
void led_init(LED_t * led, volatile uint32_t * port, uint32_t pin)
{
    // your implementation
}

// Turn the LED on
void led_on(LED_t * led)
```

```

{
    // your implementation
}

// Turn the LED off
void led_off(LED_t * led)
{
    // your implementation
}

```

- **Step 3:** You now need to tell the `main.c` file that you are using an API defined in `led_driver.h`, using the following include statement:

```

/* Include core modules */
#include "main.h"
/* Include helper library */
#include "ess_helper.h"
// led driver
#include "led_driver.h"

```

- **Step 4:** Compile and run - if you get no errors, your code should be doing exactly as it did before, just a lot cleaner.

Task 6:

Reacting to input

The blue button is on PA0 (the other button is a reset button). It has been configured by `ess_helper_init()`; as an input pin. The register we need is `GPIOA->IDR`, which has been defined for us in the STM32F4 header files. If the last bit of `GPIOA->IDR` is 1, then the button is pressed. Otherwise the button is not pressed.

- When the button is pressed, turn on the green led.
- Once you have a button press working, see if you can use it to cycle through states, stop/start LEDs flashing etc.

Solution:

The following turns on the green led while the switch is pressed.

```

int main(void) {
    // shadow the PA input data register
    uint16_t shadow;
    // create the green led ADT
    LED_t led_green;
    LED_t led_orange;
    LED_t led_blue;
    LED_t led_red;
    /* Initialize system */
    HAL_Init();
    /* Initialize peripherals on board */
    ess_helper_init();
}

```

```

        // Set up the leds
        led_init(&led_green, PORTD, 12);
        led_init(&led_orange, PORTD, 13);
        led_init(&led_red, PORTD, 14);
        led_init(&led_blue, PORTD, 15);
        // Set up their values
        led_on(&led_green);
        led_off(&led_green);
        led_on(&led_red);
        led_on(&led_blue);
        led_on(&led_orange);
        while (1) {
            shadow = GPIOA->IDR;
            if (shadow & 0x01)
            {
                led_on(&led_green);
            }
            else
            {
                led_off(&led_green);
            }
        }
    }
}

```

Task 7:

★ Testing

Testing the LED driver by flashing LEDs is painful and a labour intensive technique. It also doesn't lend itself well to regression testing. It would be better to test the logic of the LED driver separately, to check that it is doing what we think it should be doing.

The best way of doing this is to pull out the `led_driver.h` and `led_driver.c` files and cross-compile them to run natively (i.e. on the desktop/laptop). We can then write a test harness around these files to check the operation. This would take a while to setup⁵, so we are just going to test on the hardware directly, but not watch the flashing lights.

We need some indication that a test has passed or failed. To do this, we can redirect `printf()` via the USB to a trace window. This takes a bit of magic to work out, but a skeleton which prints via debug is available.

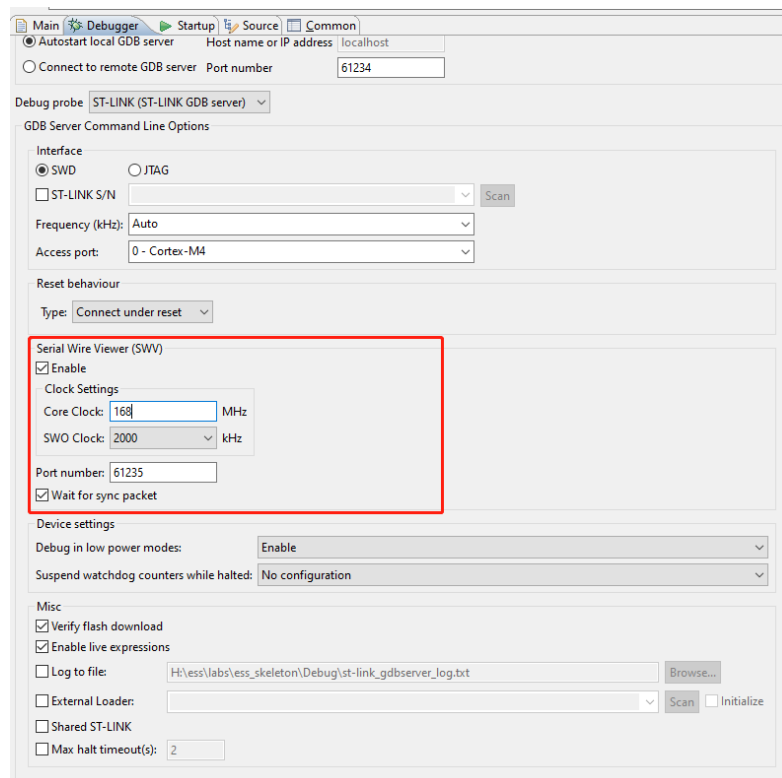
- (a) Configure your debugger to enable Serial Wire Viewer (SWV) with the below instructions.
- (b) Use `printf` to test the LED driver (i.e. add `printf("LED Green is on \n");`);

⁵however, you are welcome to do it, if you want. Just use gcc or your favourite C compiler.

Using printf() to debug with STM32CubeIDE

Before we go further into the powerful debugging tools included in STM32CubeIDE, we first introduce the way to enable a relatively old-fashioned debugging method—printf.

- **Step 0:** add `printf("LED Green is on \n");` at correct place. (inside `if (shadow & 0x01){}`)
- **Step 1:** On the left hand side, in the project layout, right click the project name 'ess_skeleton', navigate to 'Debug As', then click 'Debug Configurations...'. Switch to the second tab 'Debugger', Enable 'Serial Wire Viewer (SWV)', set the Core Clock to 16MHz as configured in the skeleton project. Click 'Apply' then 'Close'.

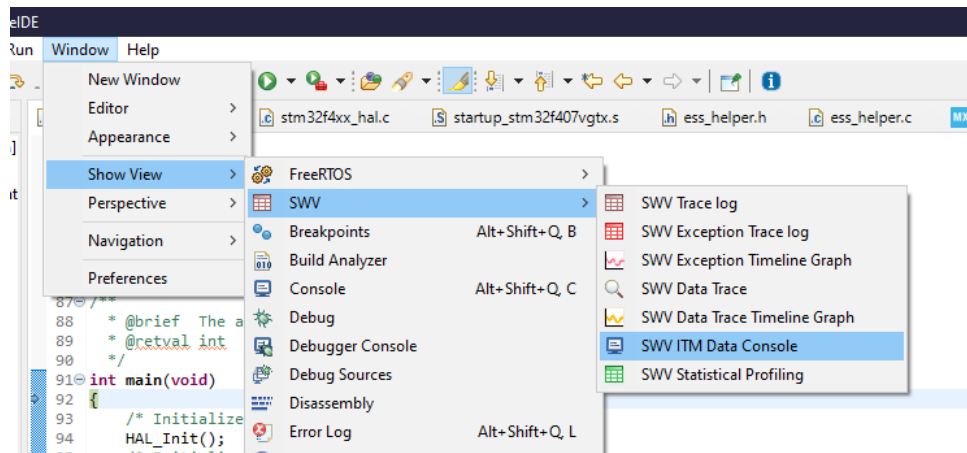


- **Step 2:** Add the following code to 'main.c' to redirect printf stream:

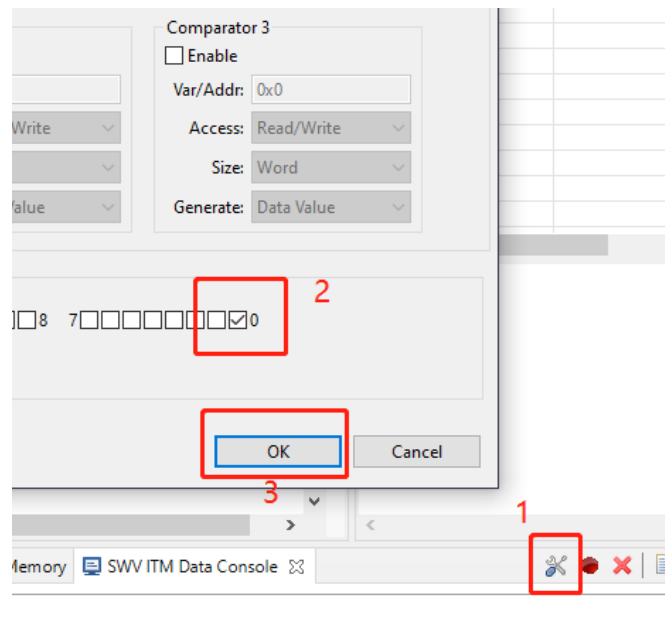
```
#include "stdio.h"

int _write(int file, char *ptr, int len)
{
    int i=0;
    for(i=0 ; i<len ; i++)
        ITM_SendChar((*ptr++));
    return len;
}
```

- **Step 3:** Enter debug mode by clicking the 'Debug' button at the left side next to 'Run'. After you enter debug mode, open the 'SWV ITM Data Console' following 'Window' → 'Show View' → 'SWV' → 'SWV ITM Data Console'. This is where your printf will be streamed to.



- **Step 4:** Open the SWV ITM Data Console Configuration, tick port 0, then click OK.



- **Step 5:** Before running your program in Debug mode, click 'Start Trace', then click 'Resume' or press F8 to continue running your program (your program will be halted by default when you enter Debug mode). You will see your printf content appearing in the Console.

To print float numbers with printf, Open your project Properties → C/C++ Build → Settings → MCU Settings, tick "Use float with printf from newlib-nano (-u_printf_float)".

