Embedded Programming with mbed-os

A Practical Course for Electronic Engineers

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1st Edition

Forward

Computers are digital electronic devices that interface to the real world. This module aims to give you an introduction to how computers interface to the real word in real-time, including both digital and analogue signals.

This course is designed for stage-3 undergraduate students in Electronics and/or Robotics, who have prior experience in both electronics and C programming. Most electronic devices contain at least one microcontroller (MCU), but that microcontroller will typically be interfaced to multiple peripherals, such as sensors, motors and communication interfaces. Such devices produce or consume data in real time.

MCUs typically work with real-world signals, many of which are asynchronous in nature. To avoid missing an event or losing data, they are required to respond to inputs and generate outputs in a timely and predictable manner. Often, response times are bounded, making it critical to guarantee responsiveness under all conditions.

The MCU is often required to service its inputs and outputs simultaneously (“concurrently”). Unlike an FPGA, a single core MCU can only perform one task at a time. In addition, most external input/output devices are much slower than the MCU, meaning the MCU often must wait for operations to complete, while still servicing other devices. This module is concerned with understanding the strategies, risks and limitations to overcome these problems in a safe and scalable way.

As the number of devices increases, so the complexity of your software grows. It is critical to write and structure software in a way that scales gracefully and that is testable. One popular approach is to divide your functionality into “software components”, or objects. This is known as Object Orientated Programming (OOP). You will learn the benefits and techniques to use software objects (mbed-os is an OOP framework) and the mechanism for creating and testing them. For this, you will learn the C++ language and the basics of OOP.

We will be using the mbed-os® framework from ARM, which can be thought of as a superset of the popular mbed classic. Both are object orientated frameworks. A key feature of mbed-os is the

ability to multi-task in a way that allows the engineer to safely manage real-time signals.

Intended Learning Outcomes

1. Critically discuss and apply reasoning to the operation of single-treaded and multi-threaded computer programs and manipulate data in advanced embedded platforms.
2. Develop structured algorithms that exploit concurrency and/or parallelism in modern microprocessors.
3. Use appropriate software tools to produce and debug programs to solve given problems and test solutions.

Setting the Right Pace

To complete all tasks will require self study and working in your own time. There may be additional tasks for those that finish early or want to do further self study.

You can take your kits home, so it is also possible to catch up on Wednesday afternoons, evenings and weekends.

Chapter 1

Digital Outputs

An introduction to mbed-os

Welcome to Advanced Embedded Programming.

This module is a first introduction to the subject of interfacing with the mbed-os® framework from ARM. The focus of this module is on software, written to work in modern electronic systems.

In this section you will learn to use / consume software components (objects) from the mbed frameworks, and later, you will learn how to create your own.

Activity 1.1 - Simple LED Circuit

In electronics, we mostly work with one (or both) of the following signals types :

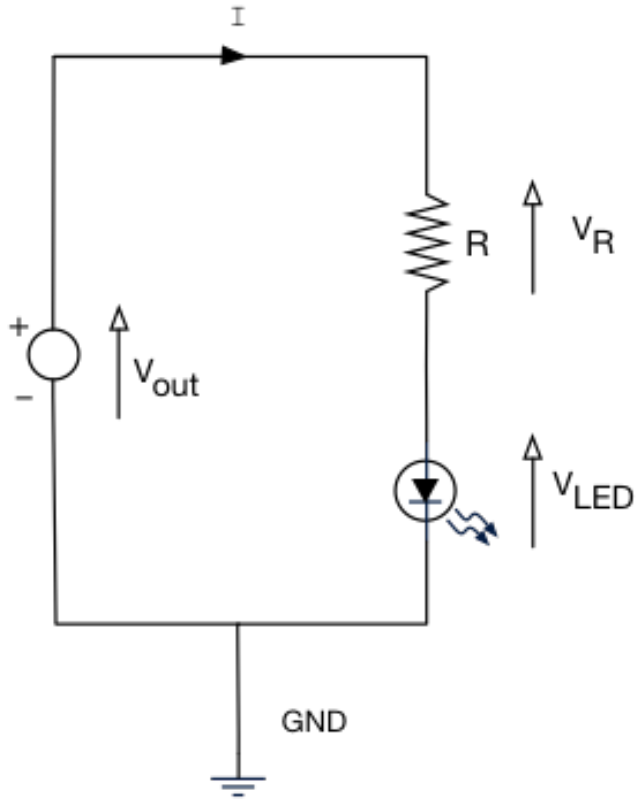
Analogue - where voltages and currents can take any value, typically between and upper and lower limit

Digital - where signal voltages can only be one of two possible values

For this section, the signals are all going to be digital. Let's start with a simple circuit schematic as shown.

All components should be mounted on the prototyping board provided, and nothing will work without a power supply!

Is obtained from the Nucleo Board.



LED Characteristics

In your kit, you are provided with three LEDs, red, green and amber. The data sheets for these devices are available. However, the most important characteristics for a clear visible brightness are as follows:

	current (approx.)	Voltage
RED	2mA	1.7V
AMBER	2mA	1.85V
GREEN	2mA	1.9V

LED Voltage at 2mA

You can drive much higher currents through these LED's but the additional perceived brightness is not significant. We want to keep current LOW for two reasons:

- The source of power for the LED will be our microcontroller. From the data sheet, the maximum output current is limited to 25mA for a single pin, up to a total maximum of 120mA for all pins.
- We want to (and should) try and save power
- There will be tolerances around these values, and they do not need to be precise.

Consider the green LED in the circuit above.

- The voltage source V_{out}=3.3V
- We want the current I=2mA
- For this current, from the LED data we expect V_{LED}=1.9V

TASK
Calculate R
As a simple test, wire up this circuit opposite on the prototyping board.
We are using the digital 3.3V and ground (GND) pins on the Nucleo board to power this circuit. See the glossary item Nucleo Board to help you find the 3.3V power pins (+3V3 and GND).
Confirm you found the correct pins on the header CN8.
Once confirmed, connect your F429ZI Nucleo board to the USB port of your PC, and the LED should light.
This confirms the power supply is working. Leave this connected as it will be used throughout this section.

Note that +3V3 and GND are the DIGITAL power sources, not to be confused with the analogue.

Activity 1.2 - Blinky

When learning to program a new language or framework, there are one or two traditional programs you almost always write - here is the most popular in the embedded software world, “blinky”.

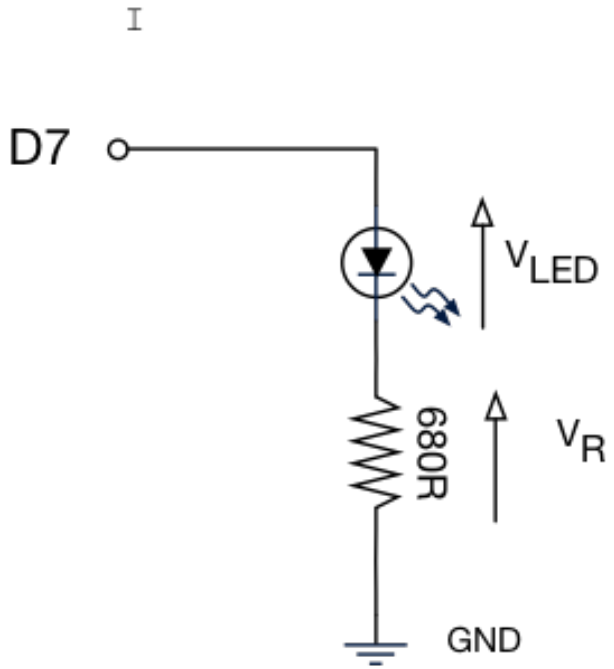
Before we write this software, first you modify the circuit.

- The figure opposite is the schematic for the blinky circuit.
- You will find the GPIO D7 labelled on the **Nucleo Board**.

If you we to write some code to flash the LED by referring to the microcontroller data sheet, there would be a number of things you would have to do, including:

- Set the mode of the GPIO pin (output, push/pull)
- Turn on the clock
- Set a bit somewhere in a register to set the output value
- Possibly write a for-loop to create a delay?

It’s good to know how to do this, but it’s not overly productive and will result in code written specifically for a small number of devices (or even just one device).



Using mbed Objects

Opposite is the source code for blinky written with mbed (task 1.2.1). Let's break this down line by line.

Firstly, consider a simple variable declaration in C, we might write something like this:

```
int x = 0;
```

The variable is called `x`, it's **data type** is `int` (integer) and it is initialised to the value 0.

Now let's look at one of the first lines in the Blinky code.

```
DigitalOut myled(D7);
```

This is the declaration and definition of the object variable `myled`, where the data type is `DigitalOut`. This is a custom data type that is included with mbed.

Note how a single parameter (the pin name) is passed. This is because when you initialise an **object**, you have the option to pass parameters that allow the object to initialise it's internal state.

Note how simple the code is!

```
//This is known as a "header file"
//In short, this copies and pastes the text file
//mbed.h into this code
#include "mbed.h"

//Create a DigitalOut "object" called myled
//Pass constant D7 as a "parameter"
DigitalOut myled(D7);

//The main function - all executable C / C++
//applications have a main function. This is
//our entry point in the software
int main() {

// ALL the code is contained in a
// "while loop"
    while(1)
    {
    //The code between the { curly braces }
    //is the code that is repeated
        myled = 1; // External LED is ON
        wait(1.0); // 1 second
        myled = 0; // LED is OFF
        wait(1.0); // External 1 second
    }
}
```

The complex details are hidden away inside the software component `DigitalOut`. We are using a `DigitalOut` component to set a pin (D7) high or low just by equating it to 1 or 0.

All the initialisation code, including write to registers to turn on the clock, set GPIO mode etc. are hidden inside the component `DigitalOut`.

When we add an instance of this component to our application, note we are also telling it which pin it is assigned to by passing a parameter. You can create more than one instance, but each instance must use a unique pin.

In our code, we say the the object `myled` is of an **instance** of type `DigitalOut`

One of the great things about components is that they hide the complex details inside, again very much like an electronic component. *We just have to work with it's external interface*. This promotes reuse and shorter / easier to write code[1].

The mbed framework contains many such components, such that if you rebuild you code on a different board, it should just work (you might have to change the pin assignments). We say it is **portable**.

C++ also supports something known as operator overloading (changing the contextual meaning of +,-,= etc..). This is used extensively on MBED to make the resulting code read more intuitively.

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[1] Consider the car as a useful analogy. You can learn to operate a car by using its interface (steering wheel, pedals and gear change stick). A car also has properties which can be monitored and sometimes changed, including:

- fuel level (read/modify)
- tyre pressure (read/modify)
- engine temperature (read only)

Details workings of a car are hidden from you. You do not need to take the engine apart to be able to drive a car. It's hard to build a car, but relatively easy to drive one. We call this *abstraction*. A software component (or object) is very similar in these respects. You don't need to see the inner workings of an object in order to use it. mbed includes a collection of very useful objects.

Consider the following line.

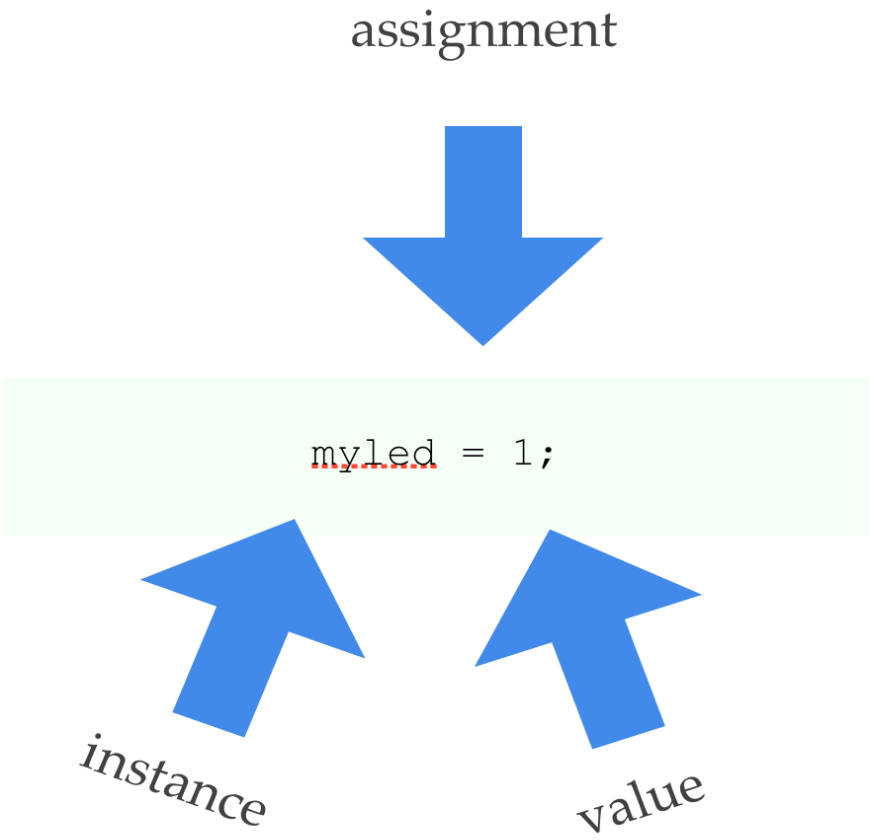
```
mled = 1;
```

Here we simply assign an integer value to an instance of `DigitalOut`, and the output pin D7 changes.

Such clarity and simplicity is possible because the component understands the '=' operator to mean "set the pin to this value".

That is because for `DigitalOut`, **mbed redefines the meaning of the = operator**.

We will meet a topic called "operator overloading" shortly where you will learn to do this yourself. Done well, this results in easy to read and debug code. Done badly, and you can end up with ambiguous code!



In C++ it is possible to redefine the function of the = assignment operator (and others) using a process known as *"operator overloading"*. This is a short cut for writing `myled.write(1);`

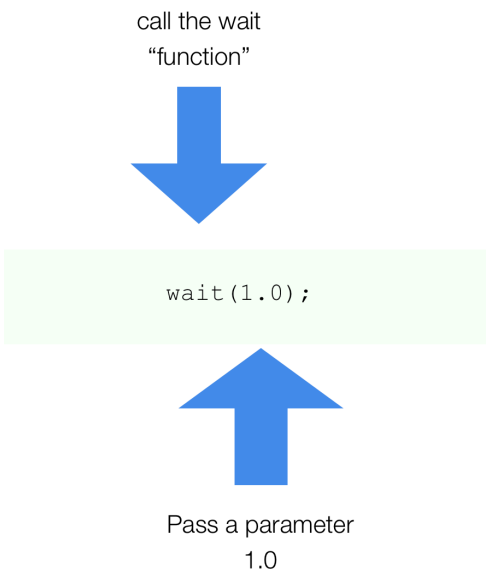
Now consider the next line:

```
wait(1.0);
```

`wait` is one of the global utility functions in mbed[2].

In this line of code, we are invoking a function “wait”. This simply delays execution for a specified time. This function is written for us (it is part of the mbed library).

`wait` has a single parameter. Note this time it is a fractional number. Note that when you invoke `wait()` in this way, the CPU can do nothing else. We say it is a blocking wait.



TASK 1.2.1
Modify the software to do the following
1. Change the ON time to 5s and the OFF time to 2.5s
2. Change the ON time to 1ms (0.001s) and the OFF time to 9ms
3. What do you observe about the LED in (2)?

What we’ve written is “blinky” - the classic starter application for embedded programming.

[2] See https://docs.mbed.com/docs/mbed-os-api-reference/en/latest/APIs/tasks/wait/

Activity 1.3 - Hello World

The other tradition is Hello World. This is normally the first program you write when learning to program on a desktop computer. However, we're a generous lot, and wanted you to enjoy both with mbed.

See the code opposite. Note the object `Serial`.

```
Serial pc(USBTX, USBRX);
```

This object has a "member function" (function that acts on the data inside the object) `baud` which sets the speed (bits/s).

```
pc.baud(9600);
```

Objects are sometimes said to have "methods" or "member functions" (fancy word for functions that belong to objects). These perform specific tasks that relate to the object (they will typically update it's internal state). You could compare this to a pin on a chip that performs a specific task when you pull it high or low. On doing so, a sequence of internal electronic states are updated.

Another function that Serial provides is `printf`.

```
pc.printf("Hello World\n");
```

The output of printf is sent to the `Serial` device represented by `pc`.

```
#include "mbed.h"

//Create an instance of a Serial
//object called pc.
//Transmit and receive pins have pre-defined
//names USBTX and USBRX
Serial pc(USBTX, USBRX);

int main()
{

//Set the baud rate property (bits per second)
    pc.baud(9600);

    //Call the printf method on pc
    pc.printf("Hello World\n");

    //Run in an infinite loop
    while(1) {
    }
}
```

Watch the following video

https://plymouth.cloud.panopto.eu/Panopto/Pages/Viewer.aspx?id=1f5a72c3-9458-4084-96b0-a5c9b973274f

Debugging with printf?

It is common to use `printf` function to debug embedded systems, and although a debugger is preferable during the development phase. It can also be invaluable for diagnostics and logging. However, it is also quite a complex function and can consume a significant amount of CPU time and memory.

Have a go at the following tasks:

TASK 1.3.1
Modify the software to write Hello World to the serial interface every 1s. Don't forget the new line character \n.
Hint - write your code inside the while loop.

Traffic Lights

Let's now combine what we've learned. In this example we will use `printf` to debug and trace our code.

TASK 1.3.2
Add two additional LED's to the breadboard. Don't forget to include the current limiting resistors.
Drive the three LEDs separately using D5, D6 and D7
Write some code to generate a traffic light sequence that repeats forever. RED, RED-AMBER, GREEN, FLASHING-AMBER then repeat (use a while loop)
Add `printf` statements for each state, and write to the terminal (for debug purposes).

TASK 1.3.3

TASK REMOVED

TASK 1.3.4

Modify your software to use a `BusOut` object instead of a `DigitalOut`

See https://developer.mbed.org/handbook/BusOut for details

```
#include "mbed.h"

Serial pc(SERIAL_TX, SERIAL_RX);

int main()
{
   char nameStr[30]; // array of chars (string)
   int age;          // integer to hold your age

   pc.scanf("%s %d", nameStr, &age);
   pc.printf("Hello %s \n\r", nameStr);
   pc.printf("You are %d \n", age);
}
```

TASK 1.3.5

Modify your software to use a `Ticker` to perform the flashing?

See https://developer.mbed.org/handbook/Ticker for details

This task requires is a little different as it uses an *interrupt* (a topic we will cover quite soon), and you need to read the documentation and look at the example code. You should get into the habit of reading the documentation on all the mbed Classes.

Serial Input

You can also type into the terminal and read the data from the Serial Interface.

Question: What statements are blocking in this code?

TASK 1.3.6

Build and test the code shown below. In a PuTTY terminal, enter a name followed by a space then a number and press enter.

Can you explain what is happening? If not ask! Change the code to ask for two numbers which you then multiply and send the answer to the terminal.

Using functions

You may recall C functions from previous years. Here is some revision:

ADDITIONAL TASK 1.3.7

The code opposite does the same as the previous example but the data input section has been moved to a separate **function**.

As a revision exercise, modify the code to move the output section to another function.

Note the variables nameStr and age are now outside of all the functions. They have “global scope” (can be reached from anywhere in your code).

Question: what is mean by global scope, and how does it differ from local scope?

```
#include "mbed.h"

Serial pc(SERIAL_TX, SERIAL_RX);

// array of chars (string)
char nameStr[30];
// integer to hold your age
int age;

void getData()
{
   pc.scanf("%s %d", nameStr, &age);
}

int main()
{
   getData();

   pc.printf("Hello %s \n\r", nameStr);
   pc.printf("You are %d \n", age);
}
```

ADDITIONAL TASK 1.3.9 (Challenge)

Read the keyboard input and translate into morse code.

Echo the morse code using LEDs - one colour for letters and another colour for numbers.

Begin with just one letter or number, and then a whole word or long number.

Output summary of time taken by each word to the console for transmission billing purposes.

Review

In this section, we wrote some very concise code that has only one task. There was no need for concurrency and assuming the `wait()` function is power-efficient, then nothing we have done is particularly wasteful of power.

LEDs were controlled using General Purpose Input / Output (GPIO). So we we have only considered a Digital Output.

We also used two more objects:

`BusOut` - for writing multiple GPIO pins

`Serial` - for communicating with a UART

In the next section, we add digital inputs, which brings new challenges if we still want to be power efficient and responsive.

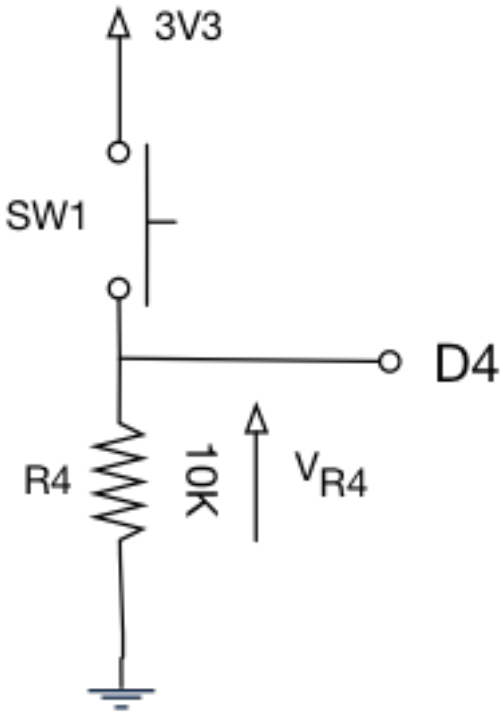
Chapter 2

Digital Inputs and Multiple Outputs

An introduction to mbed-os

In this section, we will look at digital inputs, and how we might use them to control digital outputs.

We will be using a simple "**push-to-make switch**" to generate a single digital bit of data.



Using a SPST switch as a digital input

Activity 3.1 - Simple Switch Input

Remember that a single digital signal is either ON or OFF. Numerically, we represent this as 1 or 0 (a single binary digit).

The simplest way to generate a single bit input signal is with a push switch (shown opposite). The schematic to generate a digital input is as follows.

Wire up this circuit on your prototype board.

Reminder!

Don't forget to set the platform to match the board you are using (e.g. F401RE or F429ZI)

Activity 3.2 - Reading Digital Inputs

Wire up 3 LED's as shown here. These will be used for outputs.

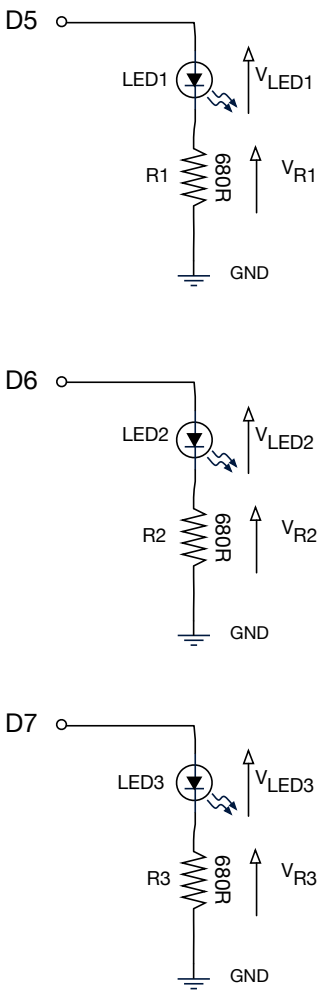
For this task, we are going to read the digital input using software. The objective is as follows:

- When the user depresses a button, the red LED switches ON and stays ON (until the system is reset).

Remember - the input is connected to D4.

Maybe unsurprisingly, we use a component called a `DigitalIn`.

TASK 3.2.1
Create a new project and paste in the code (below). Build and run to test.
When the yellow and green lights come on, press and release SW1.
Press the black RESET button on the Nucleo board to run again.
Question: which line(s) is considered to be blocking?
Task: Sketch a flow chart for this code



Under the hood, there is a significant amount of work going on to set up the hardware in the right mode. The specifics are also vendor / board dependent.

We benefit greatly from **hardware abstraction** provided by the mbed C++ classes `DigitalIn` and `DigitalOut`. mbed provide identical interfaces for all supported mbed compliant boards. This is an example of a **device driver**.

Once again, we use of the the component from mbed to make interfacing with hardware simple.

```
DigitalIn SW1(D4);
```

where `SW1` is an instance of `DigitalIn`, which can read pin D4.

A critical line in this code is as follows:

```
while (SW1 == 0) { }
```

While the digital input SW1 is equal to zero, this code **blocks the CPU** in a tight **polling loop**. This is also known as **spinning**.

This is NOT power or CPU efficient

Once the switch is pressed, an attempt to read SW1 will return a 1 and so the CPU will unblock.

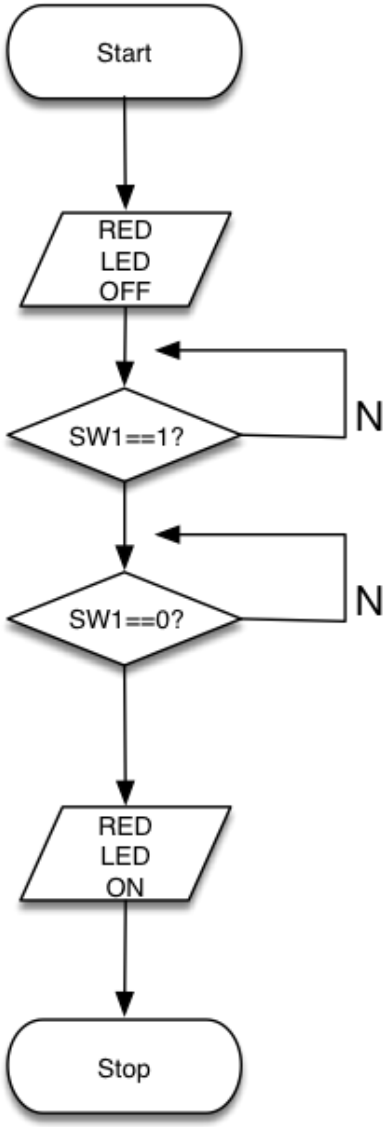
```
#include "mbed.h"

DigitalOut  red_led(D7);
DigitalOut  yellow_led(D6);
DigitalOut  green_led(D5);
DigitalIn   SW1(D4);

int main() {

    //Switch on Yellow and Green to indicate
    //that the code is running
    yellow_led = 1;
    green_led = 1;
    red_led = 0; //Set RED LED to OFF

    // Wait for SW1 to be pressed
    while (SW1 == 0) { }

    red_led = 1;    //Turn ON LED

    while (1) { }        //Repeat forever
}
```

TASK 3.2.2

Modify the code so that the red LED only comes on after the SW is pressed **and** then released
Hint: use the flow chart opposite as a guide
Test your solution. Is it entirely reliable?

You might have found this to be an unreliable solution (depending on how clean the switch contacts are).

In the next section, you will learn about “switch bounce” and how to avoid it.



Real World Signals

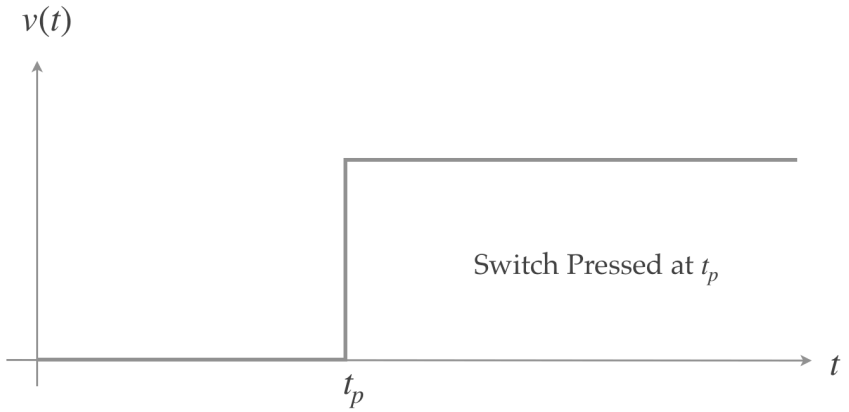
When working with physical hardware, both hardware and software engineers can take steps to reduce the probability of an erroneous input.

In almost every case, errors are probabilistic. You can never engineer the probability to zero (ok, philosophical point maybe, but often it's a very real issue).

As engineers, we have to recognise and mitigate against such failures, and at least know the probability and impact of failure.

A consumer gadget can accept a higher change of failure than an anti-lock braking system or fly-by-wire system in a commercial aircraft.

Some medical devices have to work with small and noisy signals from the human body, and have to use sophisticated mathematics and software to manage the error.

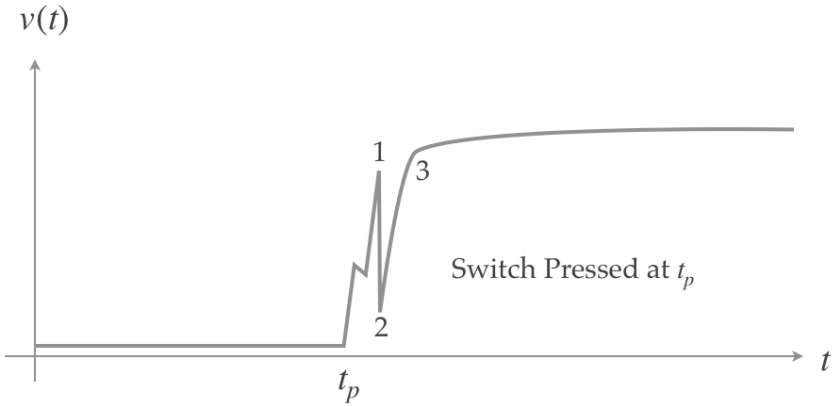


Ideal model of a digital signal generated from a mechanical switch

Switch Bounce

The reality is that mechanical switches are not perfect. Most switches suffer switch bounce to some degree.

As you can see in the second diagram opposite, the waveform is not a perfect step like the ideal.



Depicting switch bounce from a mechanical switch which could be registered as 3 events: (1)ON,(2)OFF, (3)ON.

There are two common phenomena we much consider:

Noise - random signals superimposed on top of the waveform

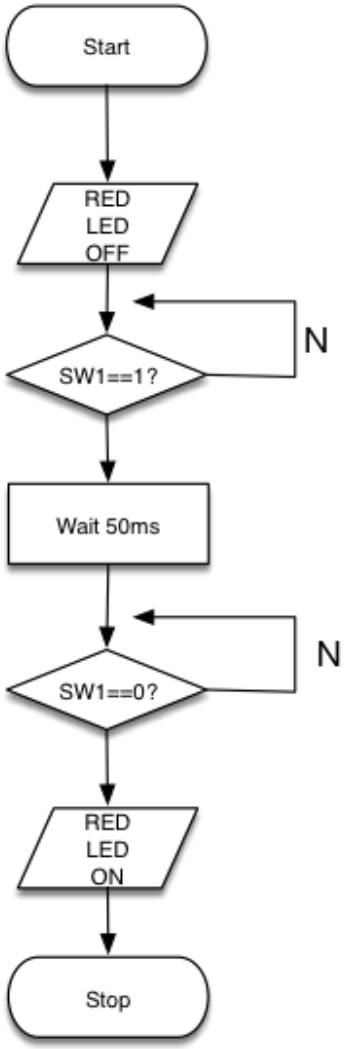
Reactive effects - if you've not covered reactance, it should suffice to say that perfect step waveforms are almost impossible - signals often rise as an exponential curve (although it might be very rapid)

This reinforces the points that electronics is ultimately analog and signals are rarely ideal.

A problem with such phenomena is that their occurrence is stochastic (random, probability based). An engineer must be mindful of such issues, and design systems to minimize the probability of such events occurring or causing malfunction, especially in safety critical systems.

In the case of switch bounce, the exact nature is highly unpredictable.

Consider the revised flow-chart opposite. This has added a delay after the first press is detected.



Adding a delay to address the problem of switch bounce

TASK 3.2.3
Modify the code to add this delay
Does it impact on the user experience? Is the delay long enough? Does it always work? Ask other students for their views. Why might different people give different accounts?
What would happen if you made the delay too long (e.g. 5s)?
hint: use the wait function that we used previously
Critically discuss (in your log book) how reliability is traded against latency. Is there a delay that will make the circuit 100% reliable?

Adding the delay makes the system less responsive. This is often referred to as **latency**. This task illustrates some key points:

- electronic signals are rarely “ideal”
- switch inputs suffer “switch bounce”
- we sometimes have to make trade-offs, such as latency for reliability.

Non-Blocking Polling

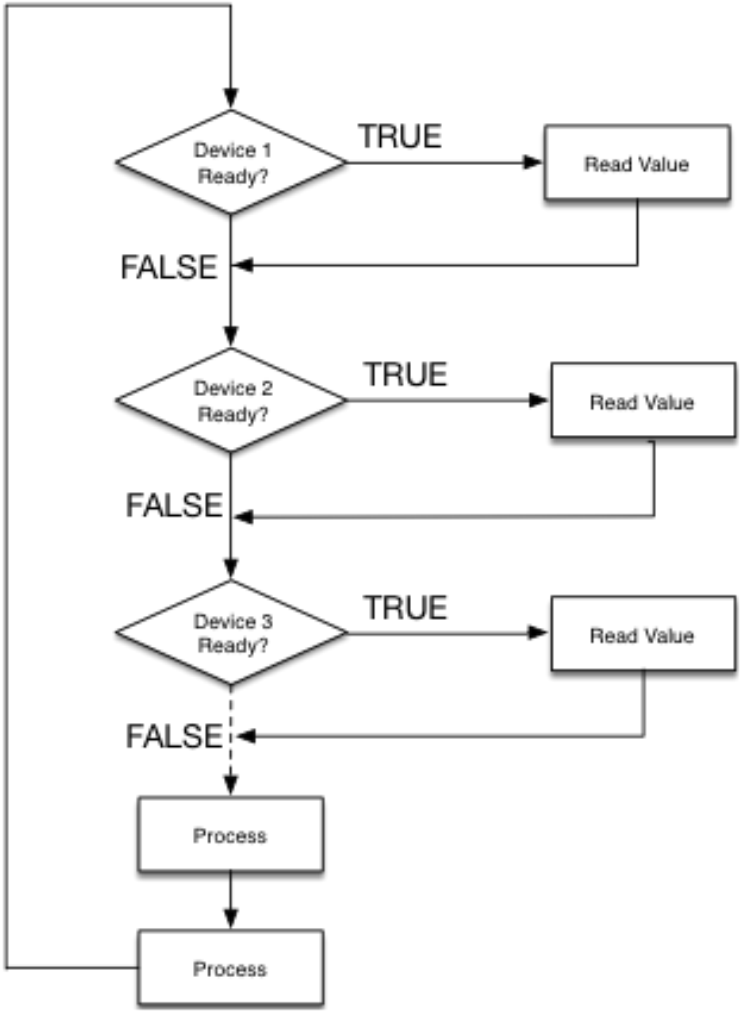
A technique to read data from multiple input sources without blocking a thread of execution.

In the figure opposite, each device is *polled* to see if it has any available data (or if there has been any change). If yes, then the value is retrieved and stored. The next device is then polled.

This method is an improvement over the busy-wait approach as it does not block the “thread” of execution, so all devices are queried at (typically) high rates.

This method does have some disadvantages however. The loop must repeat fast enough to read all devices before data is lost. This again means CPU cycles and power are being consumed even where there is no new input to process. Furthermore, the presence of conditional statements (if/while/switch) means the execution path through the code will vary, and thus the loop timing is likely to jitter. This can cause problems where data must be read at fixed intervals (as we will discover later).

In the next task we implement such a methodology where we poll two devices: a timer and a switch. You should **read** the mbed documentation for the Timer class before you attempt the next task.



TASK 3.2.4 Polling Method

A. First modify the previous task to be in accordance with the flow chart opposite. *This still uses the busy-wait approach.*

B. Add another switch and a (green) LED to your circuit.

Use D4 and D3 for the switches SW1 and SW2 (DigitalIn)

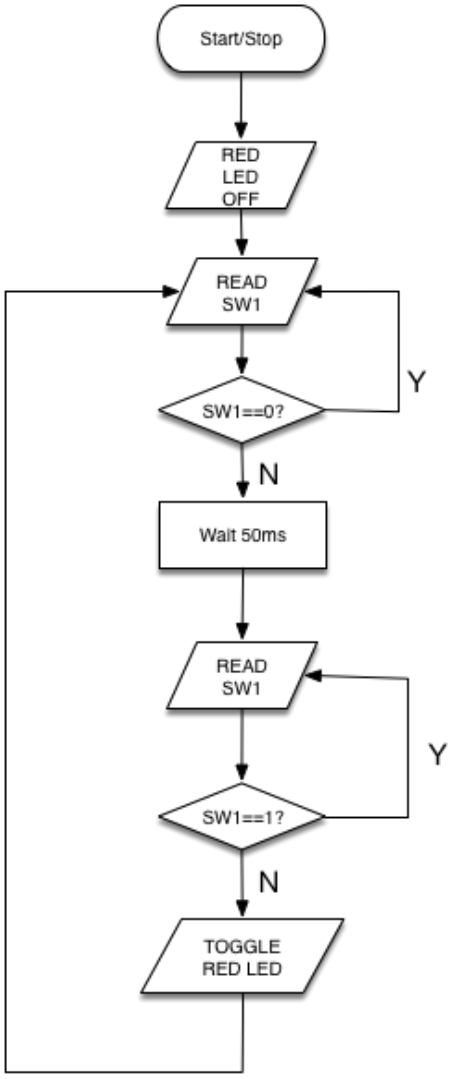
Use D7 and D5 for the RED and GREEN LEDs (DigitalOut)

Your task is to control BOTH the red LED with switch 1 ***and*** *the green LED using switch 2 independently. Again, you need to press and release the switch to* ***toggle*** *the state of the respective LED, and avoid switch bounce.* ***Poll a*** *Timer****, don't use wait().*** *Study and use Task324 sample code as a starting point. Make sure you fully understand it. This uses the polling method and follows the state diagram shown on the following page. You need to scale this to also control the green LED using SW2, without blocking.*

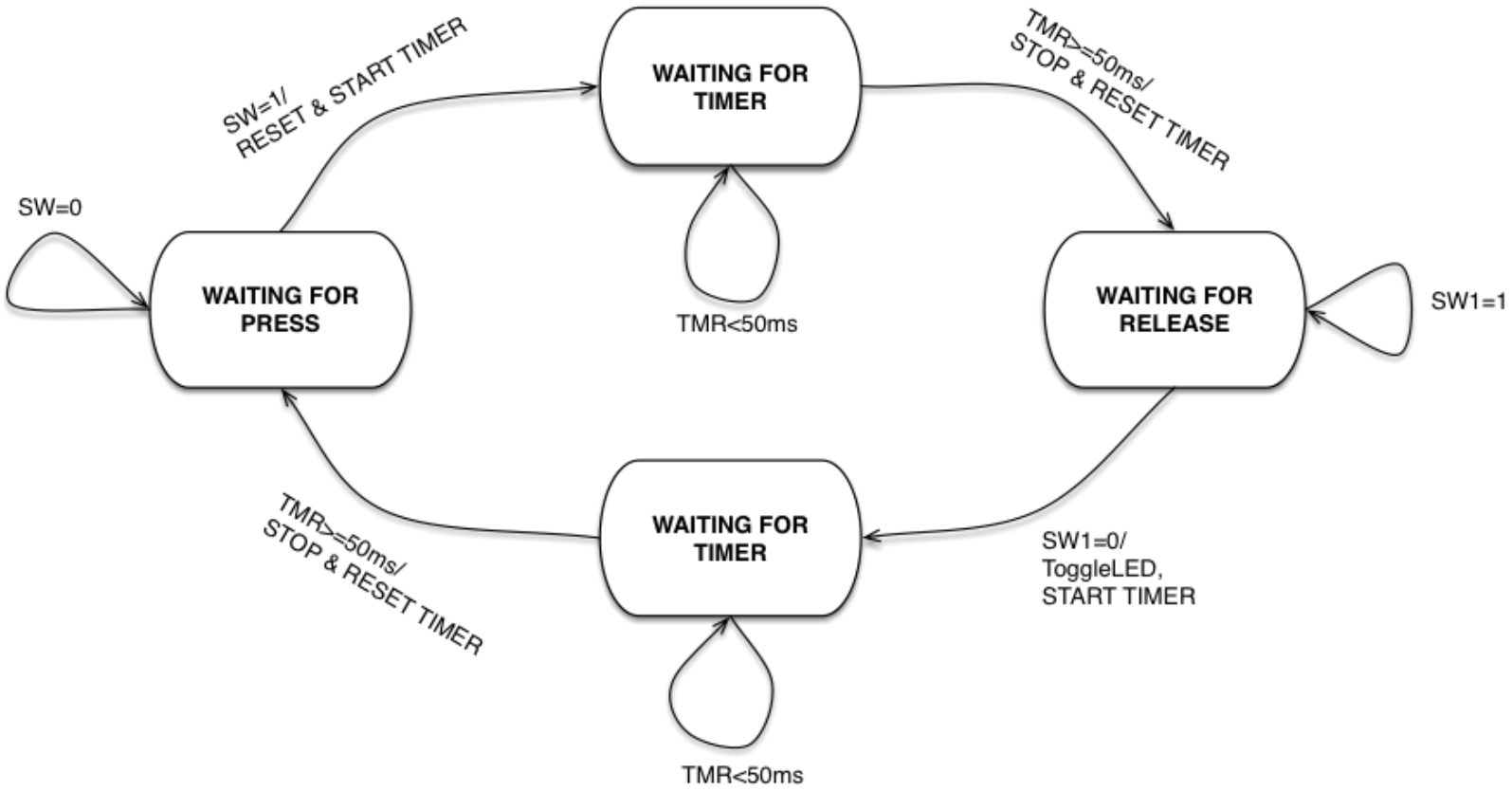
A big difference is that you now have to manage two input switches. ***Question:*** *Why can't you use the busy-wait technique?*

Question: *Are the switches polled at a constant rate? Explain.*

Question*: Do we need to poll the switches so fast? (this MCU is driven by a 180Mhz Clock)*



Modified flow chart that toggles a LED and repeats. This uses busy-wait so will only work for a single input switch



State Diagram for Task 3.2.4 - single switch SW and LED. For state transitions, the format is: {input condition / (mealy) Output}

The basic code for this can be found here https://os.mbed.com/teams/University-of-Plymouth-Stage-2-and-3/code/Task324/

The solution is here: https://os.mbed.com/teams/University-of-Plymouth-Stage-2-and-3/code/Task324Solution/. Only look at this if you are completely stuck.

Self-Study Challenge: Finite State Machines in C

Look at the code solution and observe how the switch-case is used to implement a state machine. Make notes in your log books on implementation of software state machines using a switch-case.

Self-Directed Task

Using the same hardware as above, write a new project to do the following:

- On power up, the Green LED should flash once a second (1Hz).
- Pressing SW1 should reduce the flashing rate (frequency)
- Pressing SW2 should increase the flashing rate
- Pressing SW1 and SW2 together should reset the frequency to 1Hz
- Take steps to avoid switch bounce. Poll a timer to check the time. Do not use wait()
- Use one state machine per switch / timer pair. Show the tutor your state-diagram before you write the code.

Document this in your log book. Include a state diagram. Remember that your state diagram has two inputs, a switch and a timer, although you won't necessarily poll both in each state.

Tips:

State diagrams can be sketched on paper, photographed with a smartphone or tablet and inserted into your logbook. **I recommend using Microsoft Office Lens and OneDrive to make this much more seamless**.

You are strongly advised to complete this task before the next lab session. Remember a taught module is 200Hrs. This should be approximately 16 hours / week split between VHDL and C.

4Hrs / week lectures

4Hrs / week practicals

8+hrs/week self study

Advanced Task (last 10%)

The state machines above are Mealy Machines (outputs are changed on state-transitions). Can you re-write this task as a Moore Machine? *Hint: Split the state machine into two distinct switch-case blocks, one for the next state and the next for the output.*

Interrupts - a first look

Although simple, polling has some major disadvantages:

1. It uses a lot of CPU resource even when there are no changes in the inputs. This is unlike most modern computer systems which are event driven and can idle.
2. The loop cycle time is variable (e.g. due to conditional statements). Therefore the “sampling interval” of the inputs is not constant and is said to “jitter”. This can be a problem for certain types of input signal such as audio.
3. If the loop cycle is ever too long, input changes could be missed and data lost. The delay gets longer as more code is added.
4. Any blocking in the loop would result in inputs being ignored. For example, we cannot easily read the terminal in the polling loop and the C-Standard fgets and scanf are blocking functions.

Reminder!

Don’t forget to set the platform to match the board you are using (e.g. F401RE or F429ZI)

TASK 3.2.5

the Edge TriggeRed Interrupt

Keep the circuit used in the previous exercise. The code in Task325 shows how to use an **interrupt** to detect a switch being released.
Build the code in Task325
What is name of the function that causes the led to change state (on->off or off->on)?
How is this function called? If you do not understand, ask the tutor.
What is performed in the main loop?
Does this solution address switch bounce?

Note how the main loop simply puts the MCU in a low power sleep state. This means when there is nothing to do, the CPU does not waste cycles (and hence power). When the interrupt occurs, it wakes. This is the basis of event driven computing.

TASK 3.2.6 Interrupts 2 Timer Interrupt

The code in Task326 improves the solution by using another source of interrupt - a timer.

Build the code in Task326

What is the function and purpose of the following two lines:

```
sw1.fall(NULL);

sw1TimeOut.detach();
```

How has this code an improvement over the previous?

This solution is still not robust - why?

This solution is an improvement, but still does not work perfectly.

Key Points:

This solution used two types of interrupt. One is driven from the GPIO and switch, the other from an internal hardware timer.

- When a rising edge is detected, the rising-edge detection is immediately deactivated and a “one-shot” timer is started.
- The a one-shot timer (known as a `Timeout`) is used to add a 200ms delay. When this time has elapsed, its own ISR is called in which the rising edge interrupt is re-enabled.
- The timer is an internal device that still operates even when the CPU is in sleep mode.

The remaining problem is that a switch release sometimes registers a rising edge (due to switch bounce). In the next solution we address with with a state-machine design.

TASK 3.2.7

The code in Task327 improves the solution greatly by using a state machine model as we did in the polling method.
Build the code in Task327
Can you sketch a state-diagram for this?
What fundamental advantage does this have over the polling method?
Can you now extend this code to control the green LED with SW2. Just this one, I will allow you to copy-paste-edit code (it makes a point).
Was it possible to separate the code for the red and green LEDs?
A (verbose) solution is available

You have probably found that the two switches and LEDs don't share any state (variables, hardware etc..), so don't interfere with each other.

Key Points:

- In this example, it was possible to virtually duplicate code (and change some names) to add the extra switch and LED. This is because they are completely independent and share no (mutable) state.
- In general, it is not usually so simple to extend functionality. Safe interrupt code can be hard to write.
- The main routine once again just puts the MCU into a low-power sleep state. This solution is power efficient.
- All interrupt service routines are fast and short. None have any blocking calls in them, making this solution very responsive.
- Interrupts can only be preempted by higher priority interrupts. No priorities have been assigned in this code, so blocking inside an ISR could potentially delay others.
- There are many functions that should not be be called by an interrupt (such as printf).

Race Conditions and Corruption

Interrupt service routines can be dangerous. The danger centres around "**shared mutable state**" - i.e. variables accessed from more than one interrupt.

In this section we will take a closer look at the origins of this problem.

In the previous example, the interrupt service routines (ISRs) for each switch had some global data that was shared between different ISRs However, none of the interrupts were able to preempt each other meaning this data was always accessed exclusively.

Note - the **`main()`** function can always be preempted by any of the ISRs. This can often be overlooked.

Let's now take a look under the hood of an interrupt driven application and witness data corruption. For this, we need to use Keil uVision.

TASK 3.2.8

Download the code in Task328 from the DLE and export to your desktop.

Build the project in Keil uVision and deploy to your board. Keep the three LEDs connected as before. Inspect the code to see what it does.

Experiment 1 Now press and release the BLACK switch on the Nucleo board to RESET. When the RED led lights, it is counting up. When the YELLOW led lights, it is counting back down.

The counter is equal to zero at the start. The number of up counts = the number of down counts. If the GREEN led goes out at the end, this means the value of counter = 0 (correct result).

Note the order in which the functions are called. The last function to run will check the counter and set the green LED.

Experiment 2 While holding down the BLUE switch, press and release the BLACK reset switch. Note the timing in which the up and down counts are run. What is the state of the green LED at the end?

In the second experiment, you should have found that the green light stayed on[3]. This means the final value of the counter is NOT zero!

---

[3] Note - this experiment depends on timing - If it the green light went out, find the line that reads: `t1.attach_us(&countDown, 15);` and try tweaking the delay slightly.

Using the debugger, place a breakpoint at the end of the `countDown()` function. With the BLUE button held down, press RESET. Step out of the function - in which function does it end up?
What is the final value of the counter?
Look at a single `counter++` and `counter--` in disassembly mode. Each follows a read-modify-write cycle.

The ONLY difference between the two experiments is the timing of the timer interrupt - *the function of the code has NOT changed, yet the results are different*.

Note that `counter--` requires multiple instructions and thus can be interrupted by an ISR. If an ISR interrupts this code, and itself modifies `counter`, then it's stored value will become inconsistent. **This is a key point for software safety**.

This is the assembler for `counter–`

r3 holds the address of the 64 bit variable '`counter`'	
`MOV r1,r3`	r1 = address of variable counter
`LDR r2,[r1, #0x00]`	r2 = least significant word (lsw)
`LDR r1,[r1, #0x04]`	r1 = most significant word (msw)
`SUBS r2,r2,#1`	r2 = r2 - 1, (carry/borrow set)
`SBC r1,r1,#0x00`	r1 = r1 - 0 - borrow (Sub with carry)
`STR r2, [r3, #0x00]`	Store lsw
`STR r1, [r2 #0x04]`	Store msw

Question : When a timer interrupt occurs, many registers will be pushed to the stack, *including* {r0-r3}. When it returns they will be popped off again. Given this information, *can you explain the final value of counter*? Discuss with the tutor if not sure.

Multiple Outputs

The mbed.org website contains a lot of useful reference and tutorial information. A great place to start is the online API guide for mbed.

Much of what we have used to far can be found under the section “Input and Output APIs”.

So far, we have only read from a single input pin or asserted a single output pin at a time. We often want to read groups of pins at the same time[4]. In the next task, we are going to convert decimal numbers to binary using the LEDs as an output display.

The red LED will be the **most significant bit** (BIT2) and the greed LED the **least significant bit** (BIT0)

PIN	LED COLOUR	BIT
D5	GREEN	BIT0
D6	YELLOW	BIT1
D7	RED	BIT2

Pin assignments for the LEDs

TASK 3.3.1

Create a new project

Paste in the code code below

Try setting `binaryOutput` to different values (0..7)

Do you see the binary equivalent displayed in the LEDs? If not, ask the tutor to explain (this is rather critical!)

What happens if you set binaryOutput to a value greater than 7?

```
#include "mbed.h"

//lsb first
BusOut binaryOutput(D5, D6, D7);

int main() {

    //Try different values
    binaryOutput = 3;

    while (1) { }
}
```

[4] Remember that integer values can be represented in binary as groups of bits (also known as a bus).

BinaryOut

The new software component is `BusOut` which takes a variable number of parameters. These parameters specify (lsb first) which pins to use for the binary output.

Assigning a decimal to the instance "`binaryOutput`" converts the decimal to binary, and sets the pins accordingly.

Exhaustively testing all values between 0 and 7 is fairly time consuming, especially if you needed to repeat the tests.

Read the online documentation for more information.

Important Terminology

Before we move on to analogue I/O with mbed, it's important to review some important terminology:

Blocking

Where a process or thread of code stops to wait for a resource to become available, and does not proceed.

Blocking can be performed in different ways.

- You might create a rapid polling loop that frequently polls a device for it's status. This consumes a lot of CPU cycles.
- Where a scheduler is employed, a thread might block, in which case it is simply not executed until the resource signals its availability. This consumes very few additional CPU cycles, but does require the overheads of a scheduler and the associated context switches and synchronization.
- Blocking a thread of code that is shared with other tasks will starve the other tasks of CPU time, which in some cases might result in data loss, poor responsiveness etc.
- Blocking is not always negative however. It is not uncommon to block on a resource in a separate thread, so that the remaining code and functionality can continue unimpeded. Such schemes are also power efficient.

Rapid Polling (non-blocking)

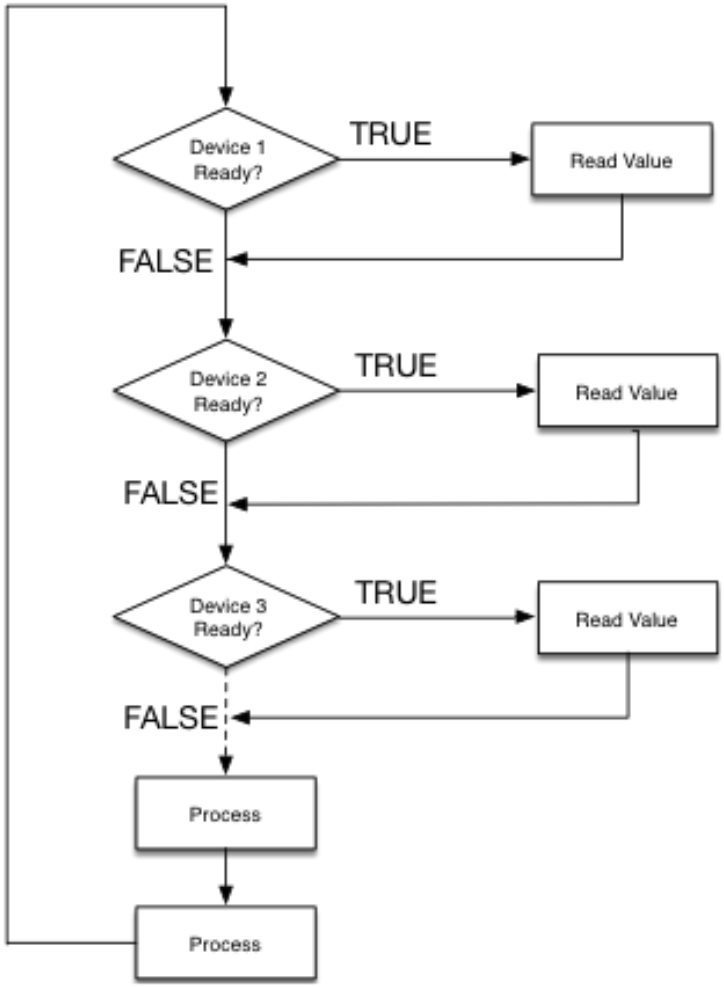
A technique to read data from multiple input sources without blocking a thread of execution.

In the figure below, each device is queried (polled) to see if it has any available data (or if there has been any change). If yes, then the value is retrieved and stored. The next device is then polled.

This method does not block the current thread of execution, so all devices can be queried often at high rates. It does not suffer from problems with race conditions as (in the absence of any other concurrent tasks) there is no preemption.

This method does have some disadvantages however. The loop must repeat fast enough to read all devices before data is lost. This again means CPU cycles and power are being consumed even where there is no new input to process. Furthermore, the presence of conditional statements means the execution path through the code will vary, and thus the loop timing is likely to jitter. This can cause problems where data must be read at fixed intervals.

```
#include "mbed.h"

//Global objects
BusOut binaryOutput(D5, D6, D7);
DigitalIn SW1(D3);
DigitalIn SW2(D4);

//Analog input
AnalogIn AIN(A0);

//Global variable
float fVin = 0.0;

//Main function
int main() {

    while(1) {

        //Read ADC
        fVin = AIN;

        //Write to terminal
        printf("Analog input = %5.3f\n", fVin);

        //Wait
        wait(0.5);

    } //end while(1)
} //end main
```



Rapid polling loop (non blocking). Note that all reads are non-blocking, so only query the device status without waiting.

Busy Wait

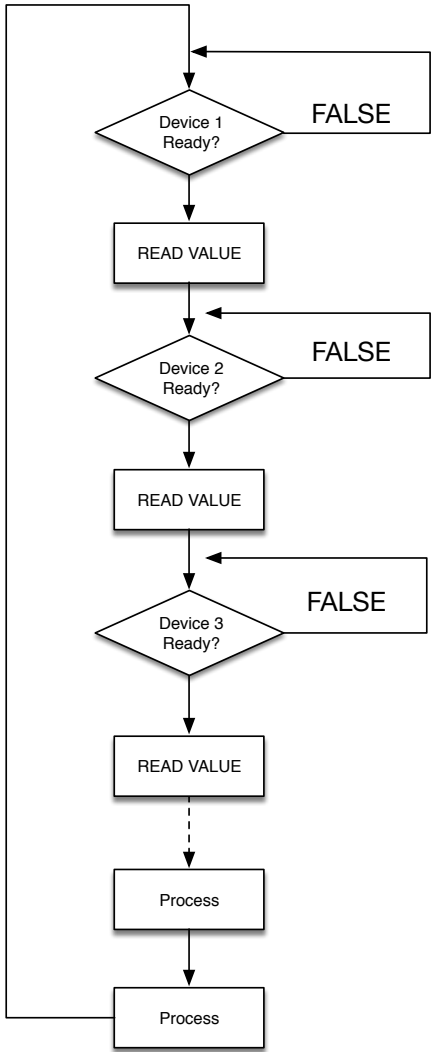
When an embedded application needs to read data from multiple sources, one method is to read each device in turn and block until data is available. Another term is spinning. This is considered an “anti-pattern” and is not generally recommended.

The approach is very simple in that it blocks on each device until it is ready to provide some data.

It is not efficient in terms of CPU usage or power consumption as it can utilize all the CPU time doing nothing useful.

However, if all the devices are fast or have a known worst case latency, then this approach might still work and still meet all the timing deadlines. One advantage is that this method (in the absence of any other concurrent task) does not risk race conditions.

When you rapidly poll a single device, this is sometimes known as “spinning”. It is usually only used when the device being waited on will respond very quickly.



Busy-wait polling, whereby the software waits for each device to complete a task.

Key Points on Interrupts

Hardware events are typically asynchronous.

In general, hardware interrupts are the most elegant mechanism for the CPU to respond to a hardware device in a timely way.

Interrupts can have different priorities, and if nested is enabled (we did not use this)[5], can preempt lower priority interrupts.

Interrupts communicate through shared mutable state (global variables typically). *This introduce the risk of race conditions and data corruption*.

A major advantage of interrupts is that a CPU can enter a low power idle / sleep state. Hardware interrupts will wake it when there is some useful work to be done. This is in contrast with polling methods where CPU cycles are consumed constantly.

Now all / many functions are interrupt safe.

Interrupts should be kept short. Later we will meet “threads” which are often considered to be a safer alternative.

[5] Even if all interrupts have the same priority, the main function can typically be pre-empted by an interrupt. This can easily be overlooked.

Self-Study Challenge: Interrupts

You are now to solve the previous self-study task, only this time with interrupts, and safely!

Self-Directed Task

Using the same hardware as above, write a new project to do the following:

- On power up, the Green LED should flash once a second (1Hz).
- Pressing (and releasing) SW1 should reduce the flashing rate (frequency)
- Pressing (and releasing) SW2 should increase the flashing rate
- Pressing SW1 and SW2 together should reset the frequency to 1Hz
- For full marks, take steps to avoid switch bounce. You may use a timer or better, a `Timeout`. Do **not** use wait()
- Use one state machine per switch / timer pair. Show the tutor your state-diagram before you write the code.

Document this in your log book. Include any state diagrams.

Tips:

You can use a Ticker to flash an LED. To change the frequency, you must detach the ticker and attach it again with the new rate.

Watch out for race conditions. Remember to temporarily turn off interrupts to protect critical sections.

Remember you can “detach” interrupt sources in mbed. A switch interrupt could detach itself and attach a Timeout. When the timeout ISR runs, it detaches itself, and reattaches the switch interrupt etc.. etc.. One approach is that each “state becomes a function”. I’ll leave you to think about that one, but I give hints when asked ;)

State diagrams can be sketched on paper, photographed with a smartphone or tablet and inserted into your logbook.

I recommend using Microsoft Office Lens and OneDrive to make this much more seamless.

You are strongly advised to complete this task before the next lab session. Remember a taught module is 200Hrs. This should be approximately 16 hours / week split between VHDL and C.

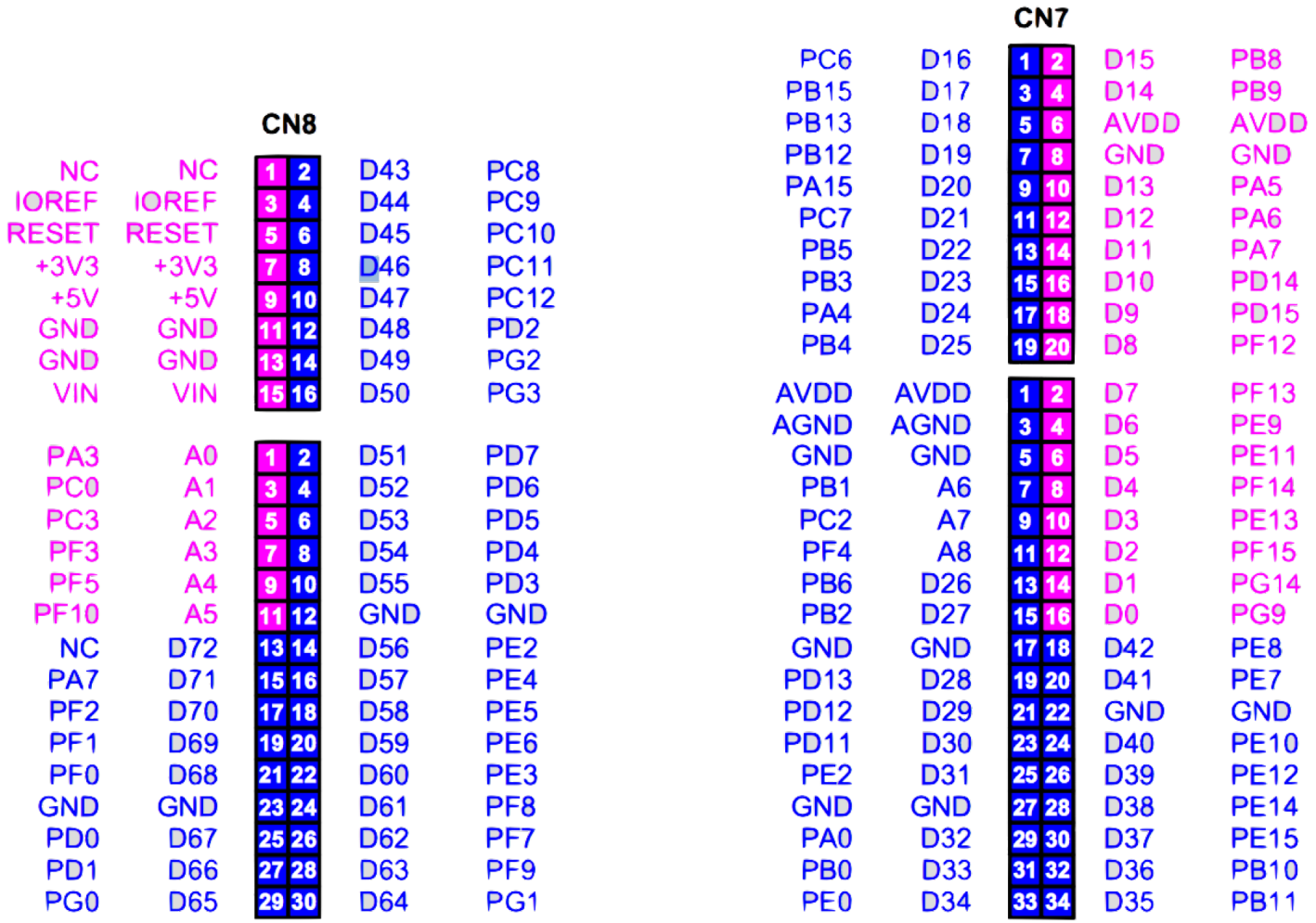
4Hrs / week lectures

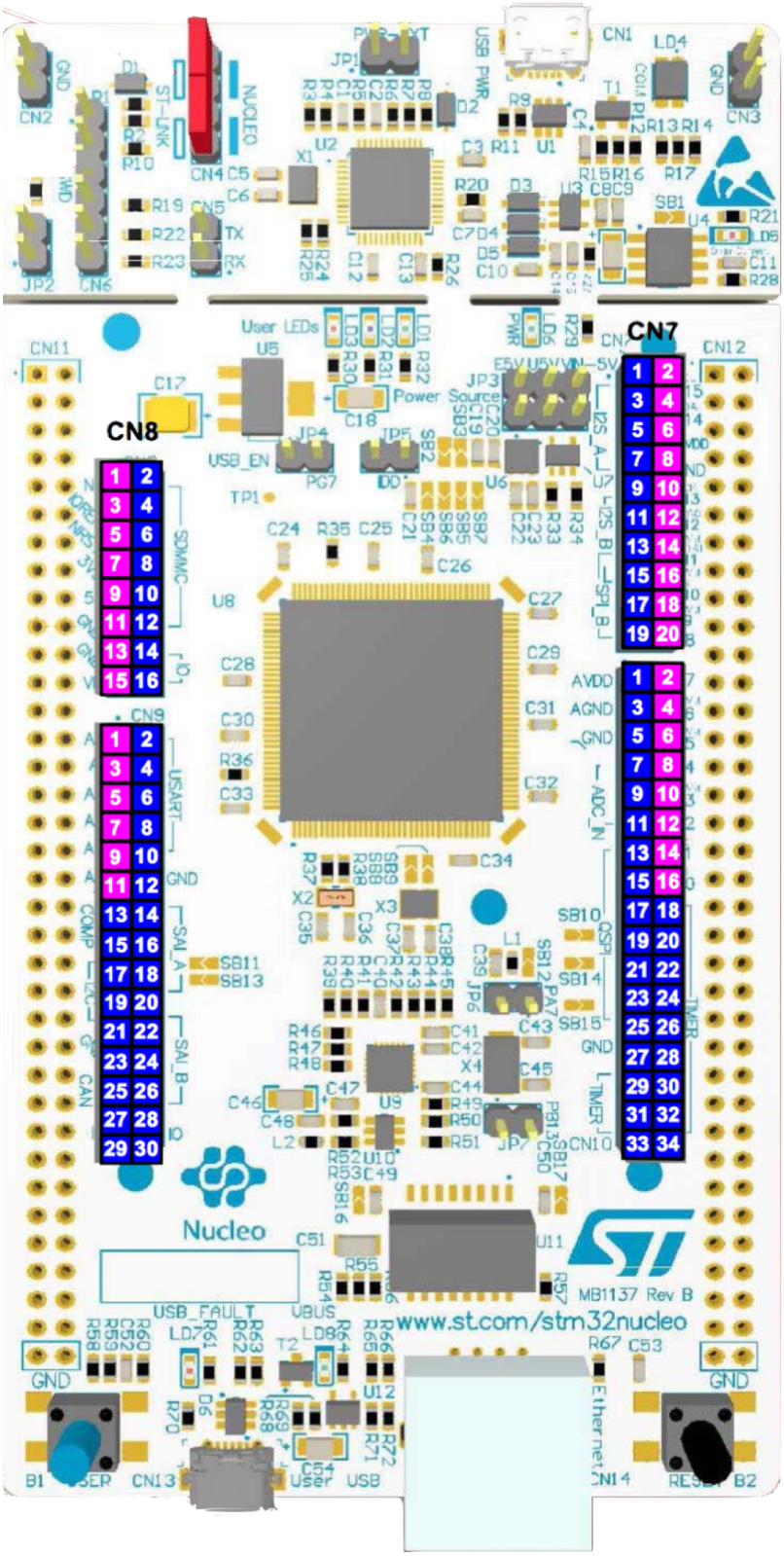
4Hrs / week practicals

8+hrs/week self study

There is no advanced task.

Appendix – NUCLEO F429ZI Connections

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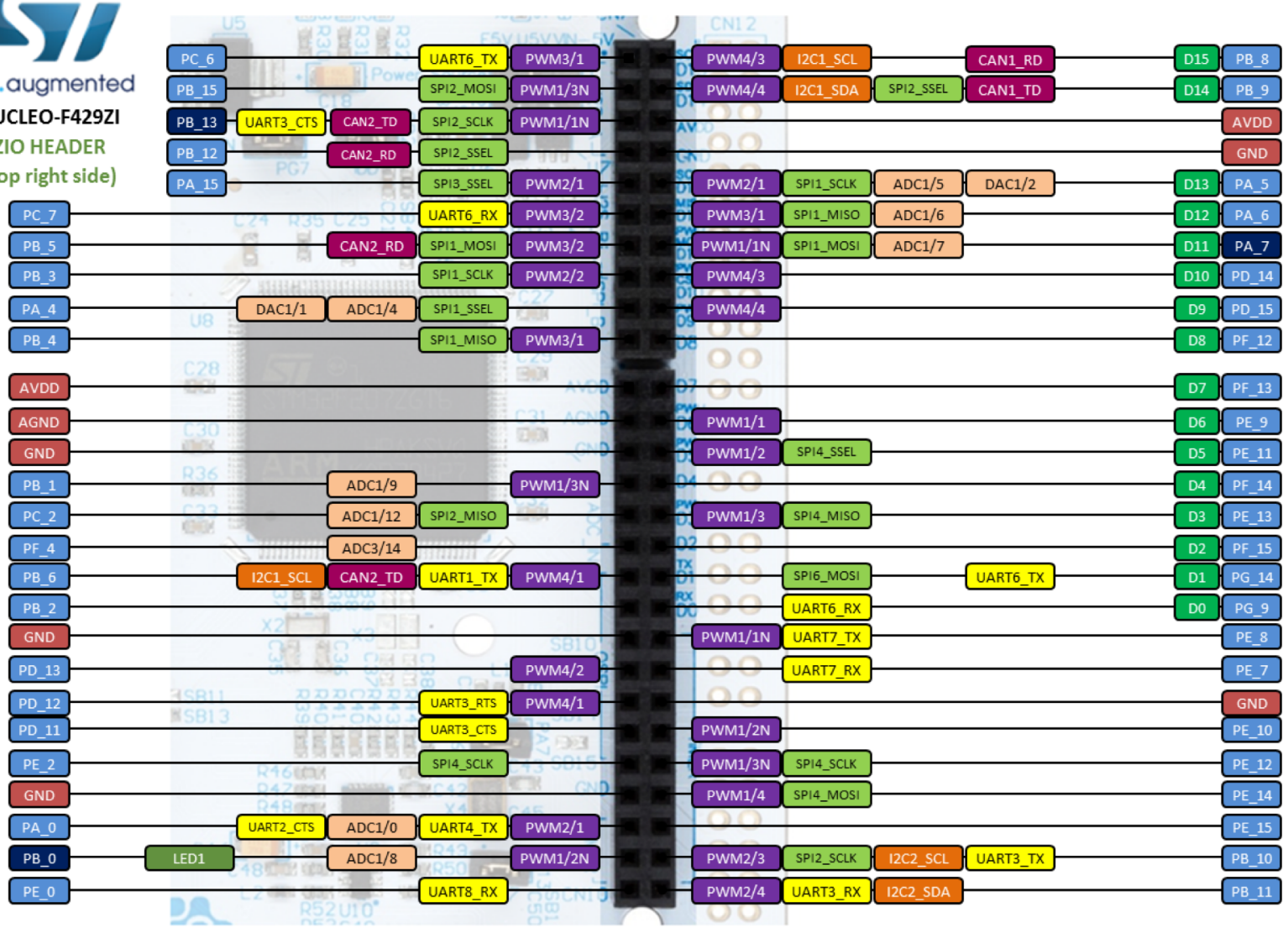

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