

# Mutley's Guide To The Wacky Racers, V.012E-3

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## Chapter 1

# Requirements





## Chapter 2

# Hardware

### 2.0.1 Recommendations

1. Independently fuse the buck converter and H-bridge. This allows a fuse to be removed to isolate part of the circuit when finding a fault, such as a short across the power rails.
2. Have a zener diode to protect against overvoltage input from a bench power supply.
3. Have current limiting resistors for all off-board signals.
4. Have plenty of testpoints, especially for power supplies and signals. You will never have too many!
5. Have at least one grunty ground testpoint for attaching a scope ground clip.
6. Have a dedicated PIO pin to drive a testpoint that you can use to trigger an oscilloscope for debugging.
7. Have the SAM4S erase pin connected to a test point close to a 3.3 V testpoint. This is useful to completely erase the SAM4S flash memory when nothing works.

## 2.1 SAM4S MCU

The SAM4S MCU is overkill for this assignment but is typical of ARM processors used for bare-metal applications.

### 2.1.1 Power pins

The SAM4S has four grounds. They must all be connected. There are also seven power pins. These must all be connected since they power different parts of the chip. Note, some pins require 3.3 V while others require 1.2 V. The 1.2 V is generated by an internal voltage regulator.

### 2.1.2 Peripheral pins

**Many of the peripheral pins are dedicated and cannot be reassigned in software**, e.g., SPI, TWI, and USB pins. Note, there are restrictions on the PWM pins.

By default the PB4 and PB5 pins are configured for the JTAG debugger. These can be used for general PIO after setting an internal bit. See [disabling JTAG pins](#).

The logic levels are set by the voltage on the VDDIO pin (usually 3.3 V). PA12–PA14 and PA26–PA31 can sink/source 4 mA. The USB pins (PB10–PB11) can sink/source 30 mA. The rest can only sink/source 2 mA of current

### 2.1.3 USART/UART

The SAM4S has two USARTs and two UARTs. The USARTs can emulate a UART, have hardware flow control, and have a better driver so they are recommended if you need a UART interface.

### 2.1.4 PWM

The SAM4S can generate four independent PWM signals. There are restrictions on which SAM4S pins they come out on. Note, the PWMLx and PWMHx signals are complementary.

### 2.1.5 TWI

The SAM4S has two TWI peripherals (that can act as a master and a slave) with dedicated TWD and TWCK pins. External pull-up resistors are required. TWI1 shares pins with JTAG; you will need to disable JTAG in software.

### 2.1.6 SPI

The SAM4S has a single SPI peripheral with dedicated SCK, MISO, and MOSI pins. Any PIO pin can be used for the chip select<sup>1</sup>.

### 2.1.7 ADC

The SAM4S has a single ADC with a multiplexer to select one of a number of analogue inputs. It can sample at 1 MHz.

### 2.1.8 USB

The SAM4S has a single USB peripheral connected to the DDP and DDM pins. 27 ohm series termination resistors are required, placed close to the SAM4S.

## 2.2 Other chips

### 2.2.1 DRV8833 dual H-bridge

The capacitor connected to the bootstrap pin must be rated for 16 V. The datasheet recommends an X7R dielectric.

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<sup>1</sup>For high speed operation, you should use one of the dedicated chip select pins.

If you want control over fast decay and slow decay in both forward and reverse you will need four PWM signals. The SAM4S can provide four independent PWM signals but be careful that PWMxH and PWMxL are driven with the same PWM signal but are complementary.

You can drive the H-bridge with only two PWM signals but you will have fast decay in one direction and slow decay in the other. It appears that fast decay is better at slow speeds since the motor heats less.

### 2.2.2 NRF24L01+ radio

This operates around 2.4 GHz and has 128 programmable channels, each of 1 MHz. A 5 byte address is appended to the start of each transmission and the receiver will only respond when the address matches.

The radio interfaces to the SAM4S using the SPI bus. The IRQ pin is driven low to indicate a packet has been received.

A well filtered power supply is critical otherwise the range will be limited on reception. Preferably, the device should have its own 3V3 regulator with a low-pass RC filter comprised of a series resistor and large capacitor (say 22 uF) or a low-pass LC filter made with a ferrite bead and capacitor.

### 2.2.3 MPU9250 IMU

This contains a three axis accelerometer, a three axis gyroscope, and a three axis magnetometer. It appears that the magnetometer has been bolted on to the accelerometers/gyroscopes and requires more hoop jumping in software to make it work.

It has two different I2C addresses (0X68 and 0X69) depending on the state of the AD0 pin.

### 2.2.4 Voltage regulators

There are many flavours of [voltage regulator](#). Some are better for digital applications, some are better for analogue applications, some are better for low power applications, etc.

If you are using a voltage regulator with an enable pin, do not forget to allow for the time for the output voltage to ramp up. This can be tens of milliseconds depending on the capacitive load and current draw.

Note, some regulators have pins that you must not connect. Some have multiple pins for the same purpose; these must all be connected.



## Chapter 3

# Schematic



## Chapter 4

# PCB layout

### 4.1 Introduction

Before you lay out your PCB, an hour spent checking your schematic will avoid many hours of testing and rework grief!

### 4.2 Placement

1. Keep small signal analogue components (radio) well away from digital electronics and power electronics.
2. Place local decoupling capacitors to minimise the loop area.
3. Place bulk capacitors close to where power comes from.
4. Keep the crystal close to the MCU.
5. Place switches so they can be pushed.
6. Place LEDs so they can be seen.
7. Place USB connector so it can be connected to.
8. Place connectors on edge with wires going away from the board.

### 4.3 Power supplies

1. Use planes for power distribution.
2. If cannot use power plane for power connection, make trace as wide<sup>1</sup> as possible.

### 4.4 Signal traces

1. Use microstrips for any signal above 50 kHz.

---

<sup>1</sup>To reduce inductance and resistance.

2. Keep signal traces apart to reduce crosstalk (3-W rule).
3. Avoid signal traces jumping layers (especially for signals above 50 kHz). If you do, use vias close to ends of traces.
4. Use tented<sup>2</sup> vias if under components with metal pads.

## 4.5 Check list

1. No planes under or close to the radio antenna; otherwise the radio range is limited.
2. The SPI signals for the radio are connected to the correct MCU pins.
3. The PWM signals for the motor are connected to the correct MCU pins. Note, the PWMLx and PWMHx pins are complementary and cannot be driven independently.
4. All the MCU VDD pins need to be powered.
5. All the MCU GND pins need to be powered.
6. Avoid connecting to PB4 and PB5 (say for TWI1). If you do you will need to disable JTAG in software.

---

<sup>2</sup>These have a layer of insulating solder resist.



# Chapter 5

## Software

### 5.1 Preparation

Do not underestimate the effort required to flash your first LED. You require:

- A computer with `git` installed and a useful shell program such as `bash`. UC has a [mirror](#) for a variety of Linux distributions; we recommend Ubuntu or Mint.
- A working ARM toolchain (`arm-none-eabi-gcc/g++` version 4.9.3 or newer).
- `OpenOCD` V0.8.0 or later.
- An ST-link programmer and 10-wire ribbon cable for programming. You can get the adaptor from Scott Lloyd in the SMT lab. You will need to make your own cable (For a grey ribbon cable, align the red stripe with the small arrow denoting pin 1 on the connector. For a rainbow ribbon cable, connect the brown wire to pin 1.). There are two variants of the ST-link programmer with **different pinouts** so you may need to customise your programming cable.
- Plenty of gumption.

#### 5.1.1 Toolchain

The required software is installed on computers in the ESL and CAE. It should run under both Linux and Windows. If there is a problem ask the technical staff.

If you are working from a personal Linux computer make sure to update your machine to the latest software versions. This is particularly important for the ARM toolchain (`arm-none-eabi-gcc/g++`) which should be at version 4.9.3 or newer. You can do this with the following command for an Ubuntu or Mint distribution:

```
$ sudo apt update && sudo apt upgrade}
```

For MacOS machines that have [homebrew](#) installed, you can use the following command:

```
$ brew install openocd git}
$ brew cask install gcc-arm-embedded}
```

### 5.1.2 Project forking

The example software is hosted on the eng-git **Git** server at <https://eng-git.canterbury.ac.nz/wacky-racers/wacky-racers-2021>. Your group leader should have forked this template project. This creates your own group copy of the project on the eng-git server that you can modify, add members, etc. To fork the project:

1. Go to <https://eng-git.canterbury.ac.nz/wacky-racers/wacky-racers-2021>.
2. Click the ‘Fork’ button. This will create a copy of the main repository for the project.
3. Click on the ‘Settings’ menu then click the ‘Expand’ button for ‘Sharing and permissions’. Change ‘Project Visibility’ to ‘Private’.
4. Click on the ‘Members’ menu and add group members as Developers.

### 5.1.3 Project cloning

Once your project has been forked from the template project, each group member needs to clone it. This makes a local copy of your project on your computer.

If you are using an ECE computer, it is advised that you clone the project on to a removable USB flash drive. This will make git operations and compilation a 100 times faster than using the networked file system.

There are two ways to clone the project. If you are impatient and do not mind having to enter a username and password for every git pull and push operation use:

```
$ git clone
↪ https://eng-git.canterbury.ac.nz/groupleader-userid/wacky-racers-2021.git
↪ wacky-racers
```

Otherwise, set up ssh-keys and use:

```
$ git clone git@eng-git.canterbury.ac.nz:groupleader-userid/wacky-racers-2021.git
↪ wacky-racers
```

You can several different cloned copies of your project in different directories. Sometimes if you feel that the world, and git in particular, is against you, clone a new copy, using:

```
$ git clone
↪ https://eng-git.canterbury.ac.nz/groupleader-userid/wacky-racers-2021.git
↪ wacky-racers-new
```

### 5.1.4 Configuration

Each board has different PIO definitions and requires its own configuration information. The [wacky-racers/src/boards](#) directory contains a number of configurations; one for the hat and racer boards. Each configuration directory contains three files:

- `board.mk` is a makefile fragment that specifies the MCU model, optimisation level, etc.
- `target.h` is a C header file that defines the PIO pins and clock speeds.
- `config.h` is a C header file that wraps `target.h`. It’s purpose is for porting to different compilers.

You will need to edit the `target.h` file for your board and set the definitions appropriate for your hardware. Here's an excerpt from `target.h` for a hat board:

```
/* USB */
#define USB_VBUS_PIO PA5_PIO

/* ADC */
#define ADC_BATTERY PB3_PIO
#define ADC_JOYSTICK_X PB2_PIO
#define ADC_JOYSTICK_Y PB1_PIO

/* IMU */
#define IMU_INT_PIO PA0_PIO

/* LEDs */
#define LED1_PIO PA20_PIO
#define LED2_PIO PA23_PIO
```

## 5.2 First program

Your first program to test your board should only flash an LED (the hello world equivalent for embedded systems). The key to testing new hardware is to have many programs that only do one simple task each.

### 5.2.1 OpenOCD

OpenOCD is used to program the SAM4S. For this assignment, we are using a ST-link programmer to connect to the SAM4S using serial wire debug (SWD). This connects to your board with a 10-wire ribbon cable and an IDC connector.

1. Before you start, disconnect the battery and other cables from your PCB.
2. Connect a 10-wire ribbon cable from the ST-link programmer to the programming header on your PCB. This will provide 3.3 V to your board so your green power LED should light.
3. Open a **new terminal window** and start OpenOCD.

```
$ cd wacky-racers
$ openocd -f src/mat91lib/sam4s/scripts/sam4s_stlink.cfg
```

All going well, the last line output from OpenOCD should be:

```
Info : sam4.cpu: hardware has 6 breakpoints, 4 watchpoints
```

Congrats if you get this! It means you have correctly soldered your SAM4S. If not, do not despair and do not remove your SAM4S. Instead, see [troubleshooting](#).

### 5.2.2 LED flash program

For your first program, use `wacky-racers/src/test-apps/ledflash1/ledflash1.c`. The macros `LED1_PIO` and `LED2_PIO` need to be defined in `target.h` (see [configuration](#)). If your LEDs are active

high, replace 1 with 0 in the LED config structures.

```

/* File:    ledflash1.c
   Author:  M. P. Hayes, UCECE
   Date:    15 May 2007
   Descr:   Flash an LED
*/
#include <pio.h>
#include "target.h"
#include "pacer.h"

/* Define how fast ticks occur.  This must be faster than
   TICK_RATE_MIN.  */
enum {LOOP_POLL_RATE = 200};

/* Define LED flash rate in Hz.  */
enum {LED_FLASH_RATE = 2};

/*
   This test app is the faithful blinky program. It works as follows:

   1. set the LED pin as an output low (turns on the LED if LED active low)

   2. initialize a pacer for 200 Hz

   3. wait for the next pacer tick.

   4. if this is the 50th pacer tick then toggle the LED.

   5. go to step 3.

   Suggestions:
   * Add more LEDs
   * Blink interesting patterns (S-O-S for example)
   * Make two LEDs blink at two separate frequencies.
*/

int
main (void)
{
    uint8_t flash_ticks;

    /* Configure LED PIO as output.  */
    pio_config_set (LED1_PIO, PIO_OUTPUT_LOW);

    pacer_init (LOOP_POLL_RATE);
    flash_ticks = 0;

    while (1)
    {

```

```

    /* Wait until next clock tick. */
    pacer_wait ();

    flash_ticks++;
    if (flash_ticks >= LOOP_POLL_RATE / (LED_FLASH_RATE * 2))
    {
        flash_ticks = 0;

        /* Toggle LED. */
        pio_output_toggle (LED1_PIO);
    }
}

```

### 5.2.3 Compilation

Due to the many files required, compilation is performed using makefiles.

The demo test programs are generic and you need to specify which board you are compiling them for. The board configuration file can be chosen dynamically by defining the environment variable `BOARD`. For example:

```

$ cd src/test-apps/ledflash1
$ BOARD=racer make

```

If all goes well, you should see at the end:

text	data	bss	dec	hex	filename
19432	2420	2732	24584	6008	ledflash1.bin

To avoid having to specify the environment variable `BOARD`, you can define it for the rest of your session using:

```

$ export BOARD=racer

```

and then just use:

```

$ make

```

Note, if you compile with the `BOARD` environment variable set incorrectly, use:

```

$ make clean
$ make

```

to delete all the object files and rebuild.

### 5.2.4 Booting from flash memory

By default the SAM4S runs a bootloader program stored in ROM. The SAM4S needs to be configured to run your application in flash memory.

If OpenOCD is running you can do this with:

```

$ make bootflash

```

Unless you force a complete erasure of the SAM4S flash memory by connecting the ERASE pin to 3.3 V, you will not need to repeat this command.

### 5.2.5 Programming

If OpenOCD is running you can store your program in the flash memory of the SAM4S using:

```
$ make program
```

When this finishes, one of your LEDs should flash. If so, congrats! If not, see [troubleshooting](#).

To reset your SAM4S, you can use:

```
$ make reset
```

## 5.3 USB interfacing

To help debug your programs, it is wise to use [USB CDC](#). This is a serial protocol for USB. With some magic, the stdin, stdout, and stderr streams can sent over USB. For example, here's an example program [wacky-racers/src/test-apps/usb\\_serial\\_test1/usb\\_serial\\_test1.c](#).

```
#include <stdio.h>
#include "usb_serial.h"
#include "pio.h"
#include "sys.h"
#include "pacer.h"
#include "delay.h"
#include <fcntl.h>

#define HELLO_DELAY 500

static usb_serial_cfg_t usb_serial_cfg =
{
    .read_timeout_us = 1,
    .write_timeout_us = 1,
};

int main (void)
{
    usb_cdc_t usb_cdc;
    int i = 0;

    pio_config_set (LED1_PIO, PIO_OUTPUT_LOW);
    pio_config_set (LED2_PIO, PIO_OUTPUT_HIGH);

    // Create non-blocking tty device for USB CDC connection.
    usb_serial_init (&usb_serial_cfg, "/dev/usb_tty");

    freopen ("/dev/usb_tty", "a", stdout);
```

```

    freopen ("/dev/usb_tty", "r", stdin);

    while (1)
    {
        printf ("Hello world %d\n", i++);
        fflush (stdout);

        pio_output_toggle(LED1_PIO);
        pio_output_toggle(LED2_PIO);

        delay_ms (HELLO_DELAY);
    }
}

```

Note, the string `"/dev/usb_tty"` is used to name the USB serial device on the SAM4S so that it can be used by the C stdio function `freopen`<sup>1</sup>.

To get this programme to work you need to compile it and program the SAM4S using:

```

$ cd wacky-racers/src/test-apps/usb_serial_test1
$ make program

```

You then need to connect your computer to the USB connector on your PCB. If you are running Linux, run:

```
$ dmesg
```

This should say something like:

```

Apr 30 11:03:50 thing4 kernel: [52704.481352] usb 2-3.3: New USB device found, idVendor=03eb
Apr 30 11:03:50 thing4 kernel: [52704.481357] usb 2-3.3: New USB device strings: Mfr=1, Product=1,
Apr 30 11:03:50 thing4 kernel: [52704.482060] cdc_acm 2-3.3:1.0: ttyACM0: USB ACM device

```

Congrats if you see `ttyACM0: USB ACM device`! If not, see [USB debugging](#).

You can now run a [serial terminal program](#). For example, on Linux:

```
$ gtkterm -p /dev/ttyACM0
```

All going well, this will repeatedly print 'Hello world'.

If you get an error 'device is busy', it is likely that the ModemManager program has automatically connected to your device on the sly. This program should be disabled on the ECE computers. For more about this and using other operating systems, see [USB CDC](#).

## 5.4 Test programs

There are a number of test programs in the directory `wacky-racers/src/test-apps`. Where possible these are written to be independent of the target board using configuration files (see [configuration](#)).

---

<sup>1</sup>When running a program with an operating system, this is all set up before `main` is called.

### 5.4.1 PWM test

The program [wacky-racers/src/test-apps/pwm\\_test2/pwm\\_test2.c](#) provides an example of driving PWM signals.

```

/* File:    pwm_test2.c
   Author:  M. P. Hayes, UCECE
   Date:    15 April 2013
   Descr:   This example starts two channels simultaneously; one inverted
            with respect to the other.
*/
#include "pwm.h"
#include "pio.h"

#define PWM1_PIO PA1_PIO
#define PWM2_PIO PA2_PIO

#define PWM_FREQ_HZ 100e3

static const pwm_cfg_t pwm1_cfg =
{
    .pio = PWM1_PIO,
    .period = PWM_PERIOD_DIVISOR (PWM_FREQ_HZ),
    .duty = PWM_DUTY_DIVISOR (PWM_FREQ_HZ, 50),
    .align = PWM_ALIGN_LEFT,
    .polarity = PWM_POLARITY_LOW,
    .stop_state = PIO_OUTPUT_LOW
};

static const pwm_cfg_t pwm2_cfg =
{
    .pio = PWM2_PIO,
    .period = PWM_PERIOD_DIVISOR (PWM_FREQ_HZ),
    .duty = PWM_DUTY_DIVISOR (PWM_FREQ_HZ, 50),
    .align = PWM_ALIGN_LEFT,
    .polarity = PWM_POLARITY_HIGH,
    .stop_state = PIO_OUTPUT_LOW
};

int
main (void)
{
    pwm_t pwm1;
    pwm_t pwm2;

    pwm1 = pwm_init (&pwm1_cfg);
    pwm2 = pwm_init (&pwm2_cfg);

```



```

    pwm_channels_start (pwm_channel_mask (pwm1) | pwm_channel_mask (pwm2));

    while (1)
        continue;

    return 0;
}

```

Notes:

1. This is for a different H-bridge module that requires two PWM signals and forward/reverse signals. You will need to generate four PWM signals or be clever with two PWM signals.
2. The `pwm_cfg_t` structure configures the frequency, duty cycle and alignment of the output PWM.
3. The frequency is likely to be too high for your motor.
4. `pwm_channels_start` is used to start the PWM channels simultaneously.

The most likely problem is that you have not used a PIO pin that can be driven as a PWM output. The SAM4S can generate four independent hardware PWM signals. See [wacky-racers/src/mat91lib/pwm/pwm.c](#) for a list of supported PIO pins. Note, PA16, PA30, and PB13 are different options for PWM2.

To drive the motors you will need to use a bench power supply. Start with the current limit set at 100 mA maximum in case there are any board shorts. When all is well, you can increase the current limit; you will need at least 1 A.

### 5.4.2 IMU test

The MPU9250 IMU connects to the SAM4S using the I2C bus (aka TWI bus). The program [wacky-racers/src/test-apps/imu\\_test1/imu\\_test1.c](#) provides an example of using the MPU9250 IMU. All going well, this prints three 16-bit acceleration values per line to USB CDC. Tip your board over, and the the third (z-axis) value should go negative since this measures the effect of gravity on a little mass inside the IMU pulling on a spring.

If you get ‘ERROR: can’t find MPU9250!’, the main reasons are:

1. You have specified the incorrect address. Use 0x68 for `MPU_ADDRESS` in `target.h` if the AD0 pin is connected to ground otherwise use 0x69.
2. You are using TWI1. The PB4 and PB5 pins used by TWI1 default to JTAG pins. See [disabling JTAG pins](#).

See also [IMU checking](#).

Other problems:

1. If you reset the SAM4S in the middle of a transaction with the IMU, the IMU gets confused and holds the TWD/SDA line low. This requires recycling of the power or sending out some dummy clocks on the TWCK/SCL signal.

### 5.4.3 Radio test

The program `wacky-racers/src/test-apps/radio_tx_test1/radio_tx_test1.c` provides an example of using the radio as a transmitter.

The companion program `wacky-racers/src/test-apps/radio_rx_test1/radio_rx_test1.c` provides an example of using the radio as a receiver.

Notes:

1. Both programs must use the same RF channel and the same address. Some RF channels are better than others since some overlap with WiFi and Bluetooth. The address is used to distinguish devices operating on the same channel. Note, the transmitter expects an acknowledge from a receiver on the same address and channel.
2. The radio ‘write’ method blocks waiting for an auto-acknowledgement from the receiver device. This acknowledgement is performed in hardware. If no acknowledgement is received, it retries for up to 15 times. The auto-acknowledgement and number of retries can be configured in software.
3. If the program hangs in the `panic` loop, there is no response from the radio module, check SPI connections and see SPI debugging.

If you cannot communicate between your hat and racer boards, try communicating with the radio test modules Scott Lloyd has in the SMT lab.

## 5.5 Your hat/racer program

We recommend that build your programs incrementally and that you poll your devices with a paced loop and not use interrupts. It is a good idea to disable the `watchdog timer` until you have robust code.

## 5.6 Howtos

### 5.6.1 PIO pins

`mat91lib` provides efficient PIO abstraction routines in `wacky-racers/src/mat91lib/sam4s/pio.h`. Each pin can be configured as follows:

```
PIO_INPUT,           /* Configure as input pin. */
PIO_PULLUP,          /* Configure as input pin with pullup. */
PIO_PULLDOWN,        /* Configure as input pin with pulldown. */
PIO_OUTPUT_LOW,       /* Configure as output, initially low. */
PIO_OUTPUT_HIGH,      /* Configure as output, initially high. */
PIO_PERIPH_A,         /* Configure as peripheral A. */
PIO_PERIPH_A_PULLUP,  /* Configure as peripheral A with pullup. */
PIO_PERIPH_B,         /* Configure as peripheral B. */
PIO_PERIPH_B_PULLUP,  /* Configure as peripheral B with pullup. */
PIO_PERIPH_C,         /* Configure as peripheral C. */
PIO_PERIPH_C_PULLUP   /* Configure as peripheral C with pullup. */
```

Here's an example:

```
#include "pio.h"

// Configure PA0 as an output and set default state to low.
pio_config_set (PIO_PA0, PIO_OUTPUT_LOW);

// Set PA0 high.
pio_output_high (PIO_PA0);

// Set PA0 low.
pio_output_low (PIO_PA0);

// Set PA0 to value.
pio_output_set (PIO_PA0, value);

// Toggle PA0.
pio_output_toggle (PIO_PA0);

// Reconfigure PA0 as an output connected to peripheral A.
pio_config_set (PIO_PA0, PIO_PERIPH_A);

// Reconfigure PA0 as an input with pullup enabled.
pio_config_set (PIO_PA0, PIO_INPUT_PULLUP);

// Read state of PIO pin.
result = pio_input_get (PIO_PA0);
```

### 5.6.2 Delaying

mat91lib provides a macro `DELAY_US` in [wacky-racers/src/mat91lib/delay.h](#) for a busy-wait delay in microseconds (this can be a floating point value). The CPU just spins for a precomputed number of clock cycles. The argument should be a constant so the compiler can compute the number of clock cycles. This function needs to be compiled with optimisation.

mat91lib also provides a function `delay_ms` for a busy-wait delay in milliseconds (this must be an integer). All this function does is call `DELAY_US (1000)` the required number of times.

An example program is [wacky-racers/src/test-apps/delay\\_test1/delay\\_test1.c](#).

### 5.6.3 Reading from ADC

[wacky-racers/src/test-apps/adc\\_usb\\_serial\\_test1/adc\\_usb\\_serial\\_test1.c](#) shows how to read a single ADC channel. **Note, this is not tested!** For more details see [wacky-racers/src/mat91lib/adc/adc.h](#).

[wacky-racers/src/test-apps/adc\\_usb\\_serial\\_test2/adc\\_usb\\_serial\\_test2.c](#) shows how to read from two multiplexed ADC channels. **Note, this is not tested!**

The ADC can be also set up to stream data continuously; this is a lot more complicated.

### 5.6.4 Reading from pushbutton

[wacky-racers/src/test-apps/button\\_test2/button\\_test2.c](#) shows the use of a simple button driver to read a pushbutton. This driver does button debouncing and state-transition detection. For more details see [wacky-racers/src/mmcilib/button/button.h](#).

### 5.6.5 Disabling JTAG pins

By default PB4 and PB5 are configured as JTAG pins. You can turn them into PIO pins or use them for TWI1 using:

```
#include "mcu.h"

void main (void)
{
    mcu_jtag_disable ();
}
```

### 5.6.6 Watchdog timer

The watchdog timer is useful for resetting the SAM4S if it hangs in a loop. It is disabled by default but can be enabled using:

```
#include "mcu.h"

void main (void)
{
    mcu_watchdog_enable ();

    while (1)
    {
        /* Do your stuff here. */

        mcu_watchdog_reset ();
    }
}
```

## 5.7 Under the bonnet

`mmcilib` is a library of C drivers, mostly for performing high-level I/O. It is written to be microcontroller neutral.

`mat91lib` is a library of C drivers specifically for interfacing with the peripherals of Atmel AT91 microcontrollers such as the Atmel SAM4S. It provides the hardware abstraction layer.

The building is controlled by [wacky-racers/src/mat91lib/mat91lib.mk](#). This is a makefile fragment loaded by [wacky-racers/src/mmcilib/mmcilib.mk](#). [wacky-racers/src/mat91lib/mat91lib.mk](#) loads other makefile fragments for each peripheral or driver required. It also automatically generates dependency files for the gazillions of other files that are required to make things work.

**Please do not edit the files in the `mat91lib`, `mmculib`, and `wackylib` directories** since this can lead to merge problems in the future. If you find a bug or would like additional functionality let MPH or one of the TAs know.



## Chapter 6

# Troubleshooting

Troubleshooting can be frustrating when you are tired. You need plenty of gumption and an open mind. Difficult problems are usually a combination of two or more problems. So **do not attempt if you are tired or in a hurry**.

### 6.1 Oscilloscope

The best tool for debugging an embedded system is an oscilloscope.

1. Use x10 probes to reduce loading on the circuit.
2. Use the correct probes for the scope so that they can be automatically detected.
3. Compensate the probes by clipping to the probe test signal on the scope and adjusting the variable capacitor in the probe to ensure a square wave without undershoot or overshoot. This is one of the few times you are allowed to use the autoscale button!

#### 6.1.1 Normal mode

This mode is for measuring transient or non-repetitive signals. It will only refresh the display if a trigger event is detected.

It is useful to increase the *trigger holdoff* to prevent triggering on multiple edges of a waveform. By default, it is set to a ridiculously small value.

#### 6.1.2 Auto mode

This mode is for measuring AC or DC signals. It is like normal mode but if it does not detect a trigger it will automatically refresh the display.

### 6.2 SAM4S not detected by OpenOCD

If a program has not been loaded:

1. Check orientation of the SAM4S (the large circle does **not** mark pin 1).

2. Check soldering of the SAM4S pins under a microscope. Giving each pin a push with a sharp spike can reveal a poorly soldered joint.
3. Check 3.3 V and 1.2 V power rails.
4. Check the serial wire debug (SWD) signals, see [debugging serial wire debug \(SWD\)](#).

If a program has been loaded:

1. [Check the crystal oscillator](#).
2. [Erase flash memory](#).
3. Re-enable [booting from flash memory](#).
4. Reprogram the SAM4S with an LED flash program.

### Erasing flash memory

1. Connect the ERASE pin to 3.3 V.
2. Re-start OpenOCD.
3. Re-enable [booting from flash memory](#).

### Debugging serial wire debug (SWD)

OpenOCD periodically polls to see if the SAM4S is alive. These occur every 100 ms.

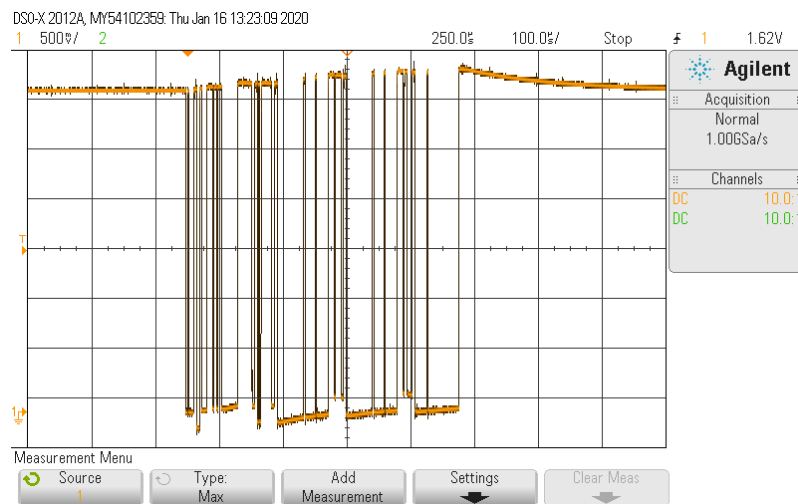


Figure 6.1: OpenOCD periodic poll when it gets a response from the SAM4S.

OpenOCD polls less often when it does not get a response. The period increases to 6.3 s.

#### 6.2.1 Checking the crystal oscillator

When the SAM4S is first powered up it uses an internal RC oscillator. However, when a program is loaded, the code before main is called switches the SAM4S to use the main oscillator that uses the



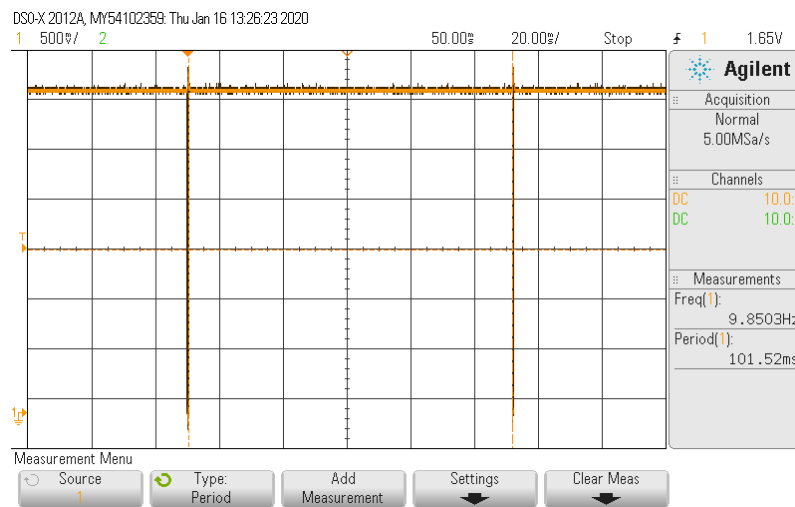


Figure 6.2: OpenOCD polls every 100 ms while connected.

external crystal. If there is a problem with the crystal oscillator the SAM4S will not run since it has no clock. Moreover, **OpenOCD** will then fail to communicate with the SAM4S.

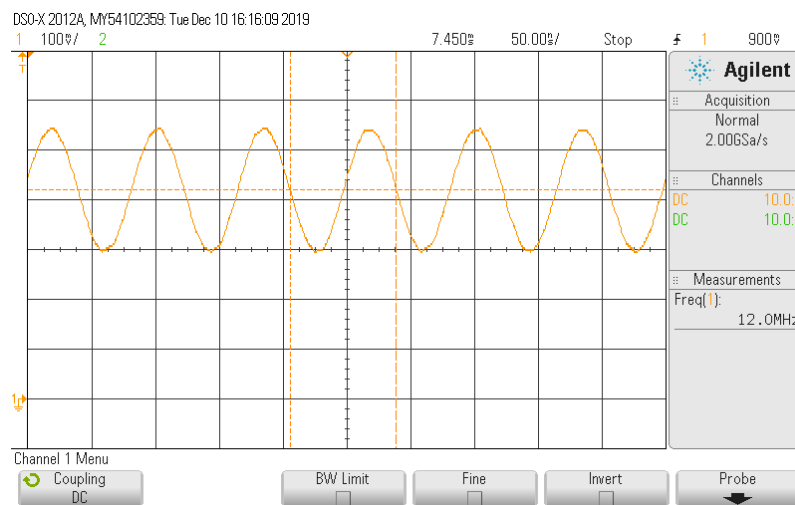


Figure 6.3: 12 MHz clock sine wave.

Add scope picture of CPU clock signals when not working

1. Connect a scope pin to the XOUT pin. A 12 MHz sinewave should be visible.
2. If there is no sinewave:
  - (a) Measure the voltage on the VDDPLL pin of the MCU with a scope. This should be 1.2 V to power the oscillator.
  - (b) Check the bypass capacitors across the crystal. These should be approx. 20 pF.

### 6.2.2 Checking the clock

The SAM4s has multiple clock sources:

1. Internal fast RC oscillator (this is selected when the SAM4S is first ever used).
2. Internal slow RC oscillator (this can be selected to save power).
3. Main oscillator using external crystal.

The SAM4S uses a phase-locked-loop (PLL) to multiply the frequency of the clock source to provide the CPU clock. Sometimes the PLL will run without a clock source and thus will generate an unexpected frequency.

The clock frequency can be checked by connecting a scope to a peripheral pin that generates a clock, e.g., PWM, SCK, TXD, and programming the peripheral.

## 6.3 USB serial

USB is a complicated protocol and there are many possibilities why it does not work.

- Check that the termination resistors are 27 ohms.
- Check the SAM4S is running at the correct frequency of 96 MHz<sup>1</sup>. Check the SAM4S XIN pin with an oscilloscope for a 12 MHz sinusoid. Note, the oscillator is not enabled unless a program has been loaded and running. If a 12 MHz signal is not found, check the MCU solder connections under a microscope. Also check that the VDDPLL pin has 3.3 V.

If the USB serial connection drops characters:

- Add a delay before sending data. This is because the driver takes a while to set up the connection after the USB cable is plugged in. If you try to send some data in this time, the data gets stored into a ring buffer for later transmission. However, the ring buffer is not large and once it is filled, the USB serial driver will drop characters.

## 6.4 Testing peripherals

### 6.4.1 Motors

### 6.4.2 Debugging PWM

If PWM does not work:

1. Check the SAM4S pin since not every pin can be a PWM signal
2. Check the definition in the configuration file `target.h`

If the PWM frequency is wrong:

1. Check the clock frequency, see [checking the clock](#).
2. Check your program.

If the PWM duty is wrong:

1. Check your program. The duty is specified as an integer in parts per thousand. (e.g. 1000 = 100% duty cycle; 50 = 5% duty cycle)

---

<sup>1</sup>The SAM4S has two PLLs so it is possible to clock the CPU at other frequencies.

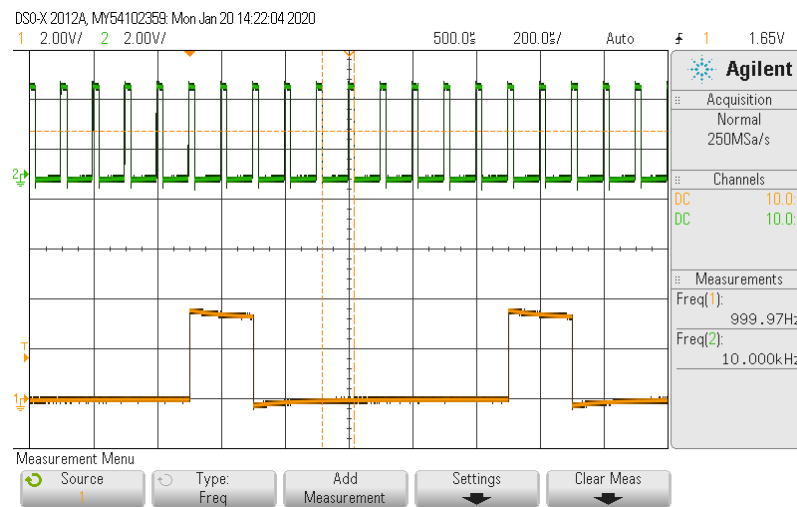


Figure 6.4: Two PWM signals at 1 kHz and 10 kHz.

### Testing the H-bridge

1. The `nFAULT` pin should be high. Note, this is an open-drain pin and requires a pullup resistor to 3V3 to make it work. Without this resistor, this pin will always read low, fault or no fault. If this is connected to the SAM4S, it will be pulled up by default.
2. The `nSLEEP` pin needs to be high to enable the chip.
3. Check that the capacitor connected to the `INT` pin is  $2.2\mu\text{F}$  and not  $2.2\text{nF}$ .
4. Check the `AIN1`, `AIN2`, `BIN1`, `BIN2` pins. If you see DC 2 V, this is due to the signal not being configured as an output on the SAM4S; the internal pullup of the SAM4S forms a voltage divider with the internal pulldown of the H-bridge chip.
5. Check that `AINSENSE` and `BINSENSE` are connected directly to ground or to ground via a small resistor if you want current limiting.

#### 6.4.3 IMU

1. Check the I2C bus (see [debugging I2C](#)).
2. Check the auxiliary I2C bus signals are not connected on the IMU (otherwise the magnetometer will not respond).
3. Check `nCS` on the IMU is pulled high.
4. Check `FSYNC` on the IMU is pulled low.
5. Try pressing on a side of the IMU with a fingernail to see if it starts working; you might have a dry joint. Otherwise look under the microscope at the pins of the IMU and touch them up with a soldering iron if necessary.

#### 6.4.4 Debugging I2C

1. I2C/TWI requires external pull-up resistors for the clock (TCK) and data (TDA) signals. Use a scope to look at the signals TWCK/SCL and TWD/SDA. If the rise times are too slow so that the high voltage level is not 3.3 V, the resistors are too large.
2. TWI channel 1 (TWI1) uses PB4 and PB5. However, these are configured on boot as JTAG pins. You can disable this, see [disabling JTAG pins](#).

Add scope picture of I2C signals

Add scope picture of I2C signals with no acknowledge

#### 6.4.5 NRF24L01+ radio

For the radio to work you need:

1. No ground planes near the antenna<sup>2</sup>.
2. A working SPI interface.
3. The correct channel and address.
4. A well filtered power supply for the radio.
5. A channel with little interference (note, some channels are shared with WiFi and Bluetooth and may be less reliable).

If nothing works, check:

1. For transmission the CE pin should be low; for reception the CE pin should be high.
2. Check that the SPI clock SCK, MOSI, and MISO signals are driven when the radio is configured (note, the MISO signal is tristate when CS is high).
3. Check that the SPI CS signal is driven low for each transmitted byte.

If the radio transmits but not receives, check:

1. The IRQ pin is driven low (this indicates that a packet has been received).
2. The power supply. The radio requires a well filtered power supply otherwise the range will be limited on reception. Preferably, the device should have its own 3V3 regulator with a low-pass RC filter comprised of a series resistor and large capacitor (say 22  $\mu$ F) or a low-pass LC filter made with a ferrite bead and capacitor.

**Note**, by default the radio waits for an auto-acknowledgement from the receiver device. This acknowledgement is performed in hardware. If no acknowledgement is received, it retries for up to 15 times. The auto-acknowledgement and number of retries can be configured in software.

#### Checking the radio power supply

Add scope picture of expected radio power supply voltage

<sup>2</sup>You might have to mount the radio vertically.

## Debugging SPI

Check:

1. The device chip select signal is driven low.
2. The SCK signal toggles while the chip select is low.
3. The MOSI signal does something while the chip select is low.

The MISO signal is usually tri-state and is driven by the device when the chip select is low.

The SPI standard is rather loose and there are four modes to confuse the unwary; these are due to two clock polarity modes and two clock phase modes. When using the wrong mode, the read data can be bit-shifted or unreliable.

Add scope picture of SPI signals

## 6.5 Other problems

1. *OpenOCD does not run.* The most common problem is that the USB permissions are not correct.
2. *A program does not correctly build after a file has been changed.* Every now and then the file timestamps are incorrect (this is a common problem with network drives due to a skew in the clocks) and make will not correctly rebuild a file. Running **make clean** will remove the existing dependency and object files so you can start afresh.
3. *A program hangs.* This can be observed by an LED no longer flashing. There are a number of reasons:
  - (a) The program is stuck in an infinite loop. Note, an embedded system should only have an infinite loop for the main loop; all other loops should have a timeout condition.
  - (b) The program has crashed trying to access invalid memory. Usually this is due to buffer overflow or dereferencing uninitialised pointers (say by not calling `radio_init`). Try running **make debug**. This will start the [debugger](#) and attach to your MCU. If the debugger says that your program has stopped in `_hardfault_handler`, then your program is likely to have accessed invalid memory. Use the `bt` command to print a stack trace to see how your program went astray.
  - (c) You are printing output using USB but a terminal program is not running.
4. *The output of the 3V3 regulator works fine when powered from USB but gives 6 V when powered from a 7.2 V battery.* Check that the 7.2 V is not connected directly to a SAM4S pin (say for battery monitoring) since this will cause an ESD protection diode inside the SAM4S to conduct.
5. *The ADC works fine for one channel but hangs for multiple channels.* Check the configuration structure. If using a single channel, its channel number is specified in the `.channel` field. For example:

```
static const adc_cfg_t adc_cfg =
{
    .bits = 12,
    .channel = ADC_CHANNEL_0,
    .trigger = ADC_TRIGGER_SW,
```

```
    .clock_speed_kHz = ADC_CLOCK_FREQ / 1000  
};
```

However, multiple channels are encoded as a bitmask as specified in the `.channels` field, for example:

```
static const adc_cfg_t adc_cfg =  
{  
    .bits = 12,  
    .channels = BIT(ADC_CHANNEL_4) | BIT(ADC_CHANNEL_2),  
    .trigger = ADC_TRIGGER_SW,  
    .clock_speed_kHz = ADC_CLOCK_FREQ / 1000  
};
```

# Chapter 7

## Rework

### 7.1 Removing resistors and capacitors

1. Apply flux from syringe to pads.
2. Use tweezer soldering iron.

### 7.2 Removing larger parts

1. Apply flux from syringe to pads.
2. Use a grunty soldering iron. **Do not push hard with a small soldering iron since this will bend the tips.**

### 7.3 Removing MCU

1. Apply flux from syringe to all pins.
2. Get Scott to show you how to use the hot-air gun. The key is to choose a head that matches the size of the MCU.

### 7.4 Adding a wire

1. For a signal trace, choose the very fine wire.
2. Cut to length and strip insulation from both ends. The second end is a lot harder!
3. Bend wire to shape and tape down to the PCB. Note, you can run this wire through vias.
4. Apply flux from syringe to both pads.
5. Use small soldering iron.





## Chapter 8

# Debugging

Your SAM4S can be debugged using OpenOCD in conjunction with GDB. However, debugging embedded systems is difficult due to asynchronous behaviour. Moreover, when optimising, a compiler will rearrange (and even remove) code and hold variables in registers.

### 8.1 Command-line debugging with GDB

If OpenOCD is running, a running program can be debugged using:

```
$ make debug
```

This starts GDB and attaches to the SAM4S. GDB is a command line debugger but there are many GUI programs that will control it, for example, **vscode** and **geany** have plugins.

GDB allows you to inspect the CPU registers, memory, set breakpoints, set watchpoints, and much more.

You can reset your program using the GDB **jump reset** command. However, this does not reset the peripherals as with a power-on reset.

The backtrace, **bt**, command is useful to show the function call stack.



# Appendix A

## OpenOCD

The Open On-Chip Debugger (OpenOCD) is an open-source on-chip debugging, in-system programming, and boundary-scan testing tool. It is able to communicate with various ARM and MIPS microprocessors via [JTAG](#) or [SWD](#). It works with a number of different [JTAG](#) or [SWD](#) interfaces/programmers. User interaction can be achieved via telnet or the GNU debugger (GDB).

### A.1 Configuration files

OpenOCD needs a [configuration file](#) to specify the interface (USB or parallel port) and the target system. Unfortunately, these change with every new release of OpenOCD.

### A.2 Running OpenOCD

OpenOCD runs as a daemon program in the background and can be controlled from other programs using TCP/IP sockets. This means that you can remotely debug from another computer. The socket ports it uses are specified in the [OpenOCD configuration](#) file supplied when it starts. By default, OpenOCD uses port 3333 for [GDB](#) and port 4444 for general interaction using Telnet.

#### A.2.1 Communicating with OpenOCD using telnet

If OpenOCD is running, commands can be sent to it using telnet. For example,

```
$ telnet localhost:4444
> monitor flash info 0
```

#### A.2.2 Communicating with OpenOCD using GDB

If OpenOCD is running, commands can be set to it with [GDB](#). There are two steps: connecting to OpenOCD with the target remote command, and then sending a command with the GDB monitor command. For example,

```
$ gdb
(gdb) target remote localhost:3333
(gdb) monitor flash info 0
```

## A.3 OpenOCD commands

All the gory OpenOCD details can be found in the [OpenOCD manual](#). If you are getting strange errors see [OpenOCD errors](#).

## A.4 Flash programming

OpenOCD can program the flash program memory from a binary file.

## A.5 FTDI support

Many [JTAG interfaces](#) use chips made by Future Technology Devices International (FTDI) to translate between the USB and JTAG protocols. FTDI provide a library to communicate with these devices; however, this is not open-source and hence cannot be distributed. There is an open-source equivalent, [libftdi](#), which in turn uses the open-source libusb. This can be temperamental to get working on a Windows system.

## A.6 Getting OpenOCD

The developers of OpenOCD release source packages (and provide subversion access) but do not provide official builds for any operating system. However, there are various sites which provide prebuilt versions of OpenOCD.

### A.6.1 Windows

Windows installers for release versions of OpenOCD can be found [here](#). Some development versions can be found [here](#). Unless you need a feature not present in the release version, avoid getting the development versions as they can be less stable.

Alternatively, the [WinARM](#) toolchain contains a version of OpenOCD, albeit one that appears (from the description on the project page) to be out of date. It is also possible to build your own copy of OpenOCD using either [MinGW](#) or [Cygwin](#); instructions for this are posted in various places online.

Realistically, it's probably easier to set up a virtual machine with Linux and use that instead.

### A.6.2 Linux

Many recent distributions of Linux have OpenOCD in their software repositories. However, this is often out of date and (in some cases) buggy. In this case it is straightforward to [build the latest version](#).

### A.6.3 Mac OSX

The easiest way to install OpenOCD on Mac OSX is to use [Homebrew](#). If you wish to use JTAG with an adaptor based on a FTDI chip (for example, the UCECE USB to JTAG adaptor or a Bus Blaster), make sure you include libftdi support by installing with the command:

```
$ brew install openocd --enable-ft2232_libftdi
```

## A.7 Errors

See [OpenOCD errors](#).



# Appendix B

## Git

To properly use git you should commit and push often. The smaller the changes and the more often you make per commit, the smaller the chance of the dreaded merge conflict.

### B.1 Typical workflow

1. Edit file
2. Save changes
3. Check differences

```
$ git diff .
```

4. Commit changes

```
$ git commit -m "Commit message"
```

Note, you should commit at least every 15 min, preferably when you have made a single functional change. Ideally each commit should be self-contained.

5. Push changes to server

```
$ git push
```

The more often you push, the lower the chance that you will get a merge conflict.

### B.2 Diff, status, blame, log

The diff command is useful to determine what changes you made.

The status command says which files have been modified and what you should do, say when you get a merge conflict.

The blame command is useful to determine who authored each line of code.

The log command shows all the previous commit messages.

## B.3 Pulling from upstream

To be able to get updates if the template project is modified you will need to:

```
$ cd wacky-racers
$ git remote add upstream https://eng-git.canterbury.ac.nz/wacky-racers/wacky-racers-2021.git
```

Again if you do not want to manually enter your password (and have ssh-keys uploaded) you can use:

```
$ cd wacky-racers
$ git remote add upstream
  ↪ git@eng-git.canterbury.ac.nz:wacky-racers/wacky-racers-2021.git
```

Once you have defined the upstream source, to get the updates from the main repository use:

```
$ git pull upstream master
```

If you enter the wrong URL make a mistake, you can list the remote servers and delete the dodgy entry using:

```
$ git remote -v
$ git remote rm upstream
```

Note, **origin** refers to your group project and **upstream** refers to the template project that origin was forked from.

## B.4 Merging

The bane of all version control programs is dealing with a merge conflict. You can reduce the chance of this happening by committing and pushing faster than other people in your group.

If you get a message such as:

```
From https://eng-git.canterbury.ac.nz/wacky-racers/wacky-racers-2021
 * branch          master      -> FETCH_HEAD
error: Your local changes to the following files would be overwritten by merge:
    src/test-apps/imu_test1/imu_test1.c
Please, commit your changes or stash them before you can merge.
```

what you should do is:

```
$ git stash
$ git pull
$ git stash pop
# You may now have a merge error.  You will now have to edit the offending file, in this case imu_
# Once the file has been fixed
$ git add src/test-apps/imu_test1/imu_test1.c
$ git commit -m "Fix merge"
```

Sometimes when you do a git pull you will be thrown into a text editor to type a merge comment. The choice of editor is controlled by an environment variable **EDITOR**. On the ECE computers this defaults to emacs. You can change this by adding a line such as the following to the **.bash\_profile** file in your home directory.

```
$ export EDITOR=geany
```



By the way, to exit emacs type `ctrl-x ctrl-c`, to exit vi or vim type `:q!`



## Appendix C

## Assessment