Laboratory Exercise Manual
CSCE 462: Microcomputer Systems
Texas A&M University

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0 Lab 0: Lab Setup

0.1 Learning Objective

The purpose of this lab is to explain technical and operational issues important to this class. It is essential that you become familiar with these issues to avoid significant consequences to your safety or grade. This lab also provides helpful links and a step by step guide to help you get started with your lab activities.

0.2 Components Needed

Raspberry Pi 3, Micro SD card, power adapter, breadboard and Cobbler

0.3 Lab rules

1. Do your lab assignment at home or at lab. Come back for grading during your lab session hours. You may be subject to significant grade loss for missing the lab time submission. Failing (Get a grade that is below than 5) two labs will lead to all 5-lab grade to zero.
2. The lab is an open, (student) self-managed space. Your attitude in caring for the equipment and space will directly translate to our costs and future students' privilege in enjoying this freedom.
3. Lab partner dispute: It is your responsibility to report to the instructor or TAs any partnership concerns. Team members will share the grade responsibility if such issue is not reported in time.
4. All tools and kits are expected to be returned in original conditions, except for normal wear and tear. Report damages of parts ASAP.
5. The is no restriction of which table you use during the lab assignment phase

0.4 Safety

Electrocution and fire hazards can happen even at low voltages. Please also observe the safety tips related to electronics benches in lab. Always have a partner, and let people know that you are in lab when you come to lab after the regular hours.

0.5 Raspberry Pi Basics

CPU	-Quad Core 1.2GHz Broadcom BCM 2837 -Not compatible with traditional PC software -Low power draw
RAM	-1 GB
Display & Audio	-full size HDMI -3.5mm jack -4 USB 2 ports -CSI camera port for connecting a

	Raspberry Pi camera -DSI display port for connecting a Raspberry Pi touchscreen -Micro SD port -wireless LAN and Bluetooth on board
GPIO	40-pin extended GPIO

0.6 Lab Activities

0.6.1 Storage & installation: Micro-SD card

1. Insert your Micro-SD card we provided into your computer.
2. You need to format your SD card (even if it is a brand new micro SD card, formatting is recommended). Format the disk FAT32. Overwriting the disk is recommended (this will take a while). Most computers have built-in disk formatting tools. If not, software can be found here: https://www.sdcard.org/downloads/formatter_4/
3. Download Noobs: https://www.raspberrypi.org/downloads/noobs/ (You need to download the full version which contain **Raspbian**).
4. Unzip the Noobs file into your micro-SD card.
5. Take the micro-SD card and insert it back into your Raspberry Pi 3.
6. Power on your Raspberry Pi 3, the installation process will start automatically.Select **Raspbian** to start installation. It will take a while.
7. Finish your installation and Raspberry Pi 3 will auto-restart and you are done!

0.6.2 Install and Setup SSH (optional, if you do not have a monitor to be used)

You can use SSH to execute command line actions to Raspberry Pi. To setup SSH you will need to connect your Raspberry Pi 3 to the internet. (Raspberry Pi 3 cannot to connect to TAMU Wi-Fi by default)

1. Update apt-get package index files
   a. sudo apt-get update
2. Install SSH
   a. sudo apt-get install ssh
3. Install an SSH client on your machine (if you don't have one)
   a. For Windows:
      i. Putty: www.putty.org
4. Then on Raspberry side you do:
   a. Open a command line window
   b. sudo raspi-config
   c. Under interfacing option select SSH and enable it
   d. Reboot
   e. Check your hostname by: hostname –I
   f. Use the command "passwd" to set your own password (original password is "raspberry")
5. On your computer

a. Plug in an Ethernet cable to your computer and the Raspberry Pi (so you will not need a Wi-Fi connection)
b. Ping 127.0.0.1
c. Ping hostname address (this may have changed after you plugged in your Ethernet cable, if there is more than one hostname see which in works)
d. If both succeed, open Putty, input hostname and login.

0.6.3 Python Setup

We will use Python for some of programming in this class. We will also have 1 or 2 lab to help you get familiar with ARM assembly on Raspberry Pi 3.

1. sudo apt-get install python-dev
2. sudo apt-get install python-rpi.gpio
3. Python programming guide: https://wiki.python.org/moin/BeginnersGuide
4. Python GPIO guide: https://pypi.python.org/pypi/RPi.GPIO
5. Raspbian should have Python installed as default. There is a folder called "python game" you can play with to get started with python programming.

0.6.4 Keyboard Configuration

The Raspberry Pi 3 will have UK keyboard input as default, for your convenience you will need to switch the keyboard style into US keyboard input. (This not be a problem if the correct settings were chosen when installing)

These instructions should help:
http://www.dummies.com/computers/raspberry-pi/raspberry-pi-for-kids-setting-the-keyboard-layout/

1 Lab 1: Intro to ARM Assembly on Raspberry Pi 3

1.1 Learning Objective

In this lab, you will learn how to programming Raspberry Pi 3 by ARM assembly and then programing GPIO pin as the output to control a LED.

Learning Reference: "ARM assembler in Raspberry Pi" Roger Ferrer Ibáñez: http://thinkingeek.com/2013/01/09/arm-assembler-raspberry-pi-chapter-1/

1.2 Components Needed

Raspberry Pi 3, LEDs, resistors, and appropriate wires

1.3 Lab Activities

1.3.1 Your First Program

In this section, you will follow step-by-step instructions to create your first assembly program to perform a simple arithmetic with integer variables, you do not need to demo this to your TA. If you have not installed the OS yet, please refer to **Lab 0** document to finish all pre-installation on Raspberry Pi 3.

Create a file named **helloworld.s** and edit the file with text editor or command line window. First we need to create data types for adding and the output string.

```
.data

.balign 4

string:     .asciz  "a + b = %d\n"

a:          .word 33

b:          .word 44

c:          .word 0
```

We start the program with a main function:

```
    .text
    .global main
    .extern printf
    main:
            push    {ip, lr} @ push return address + dummy register
```

Then we put the address of **a** into register **r1**, and then put the value stored in that address into **r1**. We do the same thing for **b:**

```
    ldr     r1, =a
    ldr     r1, [r1]
    ldr     r2, =b
    ldr     r2, [r2]
```

Then we add **r1** to **r2** and store the result into **r1**.

```
    add      r1, r1, r2
```

In the next step, we get the address of **c** into **r2**, and we copy the value in **r1** into **c**

```
   ldr      r2, =c
   str      r1, [r2]
```

Then we print out the result, and return the address into pc

```
   ldr      r0, =string
   ldr      r1, [r2]
   bl       printf       @ print string
   pop      {ip, pc}
```

1.3.2 Compile and Run

- Assemble the code into an object file:

  ```
  as -o helloworld.o helloworld.s
  ```

- Compile the object file by a C compiler, it will be transformed into a executable:

  ```
  gcc -o helloworld helloworld.o
  ```

- Run your first program!

  ```
  /helloworld
  ```

1.3.3 LED Blinking

In this section you are going to write a program using ARM assembly that will blink an external LED on the breadboard. Demo your final code to your TA in the lab.

1. A C equivalent program is provided here (main code):

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <sys/mman.h>
#include <stdint.h>

#define PERI_BASE 0x3F000000
#define GPIO_BASE (PERI_BASE + 0x200000)
#define FUN_SEL_OFFSET 0x0
#define SET_OFFSET 0x1C
#define CLEAR_OFFSET 0x28
#define OUTPUT 1

int main(void){
  int pin = 18; //bcm numbering (RPi standard)
```

```
    int fd;
    void *gpioBase;

    if(-1 == (fd = open("/dev/mem", O_RDWR))){
      fprintf(stderr, "open() failed.\n");
      return 254;
    }
    if(MAP_FAILED == (gpioBase = mmap(NULL,4096, PROT_READ|PROT_WRITE,
    MAP_SHARED, fd, GPIO_BASE))){
           fprintf(stderr, "mmap() failed\n");
           return 254;
    }

    setPinMode(gpioBase, pin, OUTPUT);

    int i;
    for(i=0; i<10; i++){
      setPinOn(gpioBase, pin);
      sleep(1);
      setPinOff(gpioBase, pin);
      sleep(1);
    }
    close(fd);
  }
```

This program blinks an LED using GPIO pins. The GPIO pins are manipulated via registers. These registers are memory mapped on the Raspberry Pi. The different memory locations of the registers and how to use them can be found here (http://www.cl.cam.ac.uk/projects/raspberrypi/tutorials/os/downloads/SoC-Peripherals.pdf). That guide was written for the Raspberry Pi 1, so the addresses are slightly different. Wherever it says 0x7E****** we will use 0x3F****** on the Raspberry Pi 3. You may notice that there is some additional code in the above code that seems to be mapping a file to memory. This is a result of the fact that we are using a Linux-based OS. Linux does not allow the user to have direct access to the memory. This prevents us from getting directly to our memory-mapped IO. Luckily, Linux allows access to the memory by using the "file" /dev/mem (as long as the user has root privileges). In the above code, we are opening that file and mapping the corresponding section into our program's memory. This allows us to manipulate the registers as we would if we had direct access to the memory. After we have access to the registers, the GPIO pin that we are using is set to output mode. The pin is then turned on and off multiple times. These last parts are done using the functions below.

2. Additional functions for the C program

```
void setPinMode(uint32_t* gpioBase, int pin, int mode){
  uint32_t* gpioFunSel = (uint32_t*)((char*)gpioBase+FUN_SEL_OFFSET);
  int funSelIndex = pin/10;
  int funSelShift = 3*(pin%10);
  gpioFunSel[funSelIndex] = (gpioFunSel[funSelIndex] | (mode<<funSelShift));
}

void setPinOn(uint32_t* gpioBase, int pin){
  uint32_t *gpioSet = (uint32_t*)((char*)gpioBase + SET_OFFSET);
  int gpioSCIndex = pin/32;
  int gpioSCShift = pin%32;
  gpioSet[gpioSCIndex] = (1<<gpioSCShift);
}

void setPinOff(uint32_t* gpioBase, int pin){
  uint32_t *gpioClear = (uint32_t*)((char*)gpioBase + CLEAR_OFFSET);
  int gpioSCIndex = pin/32;
  int gpioSCShift = pin%32;
  gpioClear[gpioSCIndex] = (1<<gpioSCShift);
}
```

The first function sets the pin mode. Each GPIO pin has 3 bits that control its mode. Mode 0 is input and mode 1 is output. Some pins also have other modes but these are not important right now. Each register controls 10 pins (3*10 is 30 with the 2 highest bits not used). That is why the register index and shift are computed using 10 and 3. When a pin is in output mode, whether they are on or off is controlled by the Set and Clear registers. If you want to turn the pin on, set the corresponding bit in the Set register. If you want to turn the pin off, set the corresponding bit in the Clear register. Each pin gets 1 bit in the registers. That is why the register index and shift are computed using 32.

3. Setup the memory map in assembly:

```
main:
       push {ip, lr} @stores information needed when the program exits
       ldr r1, =O_RDWR
       ldr r1, [r1]
       ldr r0, =fileName
       bl open
       mov r11, r0 @save the file discriptor
       subs r0, r0, #-1 @will set flags based on the subtraction
       beq openError @if r0 == -1 go to openError
       sub sp, sp, #8
       ldr r0, =GPIO_BASE
       ldr r0, [r0]
       str r0, [sp, #4]
       str r11, [sp]
       ldr r3, =MAP_SHARED
       ldr r3, [r3]
       ldr r2, =PROT_READ
       ldr r2, [r2]
```

```
        ldr r0, =PROT_WRITE
        ldr r0, [r0]
        orr r2, r2, r0
        mov r1, #4096
        mov r0, #0
        bl mmap
        add sp, sp, #8
        ldr r1, =MAP_FAILED
        ldr r1, [r1]
        subs r1, r0, r1 @will set flags based on the subtraction
        beq mapError @if r0 == MAP_FAILED go to mapError
        mov r10, r0 @keep gpioBase
...
openError:
        ldr r0, =openFailed
        bl printf
        mov r0, #1 @puts 1 as the return value
        pop {ip, pc}
mapError:
        mov r0, r11
        bl close
        ldr r0, =mapFailed
        bl printf
        mov r0, #1 @puts 1 as the return value
        pop {ip, pc}
```

Here is the start of the main function. It opens the file and sets up the memory map. Only r0-r3 are used for parameters for functions, so the last 2 parameters of mmap are placed on the stack. The later parts of the code that are called when open or mmap fail are included here as well.

4. Data values used in this assembly program

```
.data
pin: .int 18
delay_time: .int 1
output: .int 1
GPIO_BASE: .long 0x3F200000
FUN_SEL_OFFSET: .int 0x0
SET_OFFSET: .int 0x1C
CLEAR_OFFSET: .int 0x28
fileName: .asciz "/dev/mem"
MAP_SHARED: .int 1
MAP_FAILED: .word -1
PROT_READ: .int 1
PROT_WRITE: .int 2
O_RDWR: .int 2
openFailed: .asciz "open() failed\n"
mapFailed: .asciz "mmap() failed\n"
```

5. Modulus function used in other functions

```
modulus:
        push {lr}
        udiv r2, r0, r1
        mls r0, r1, r2, r0
        pop {pc}
```

6. setPinMode function

```
setPinMode:
        push {r4-r7, lr}
        ldr r3, =FUN_SEL_OFFSET
        ldr r3, [r3]
        add r4, r0, r3 @r4= gpioBase + FUN_SEL_OFFSET (ie gpioFunSel)
        mov r5, #10
        udiv r6, r1, r5 @r6=pin/10 (ie funSelIndex)
        mov r7, r2 @r7 = mode
        mov r0, r1
        mov r1, r5
        bl modulus @r0 = pin%10
        mov r1, #3
        mul r0, r1, r0 @r0=3*(pin%10) (ie funSelShift)
        ldr r1, [r4, r6, lsl #2] @r1=gpioFunSel[funSelIndex]
        orr r1, r1, r7, lsl r0 @r1= gpioFunSel[funSelIndex] | (mode<<funSelShift)
        str r1, [r4, r6, lsl #2] @write data back to register
        pop {r4-r7, pc}
```

This function is shows how to build a function in assembly and how to write to the registers. The functions for setPinOn and setPinOff are similar to this one. For the parameters, r0 is gpioBase, r1 is pin, and r2 is mode. Something important to notice about this function is that any registers in the range r4-r11 that are used in the function must be stored on the stack. These registers should be preserved between function calls. Another thing to notice is that the index is left shifted by 2 when loading and storing. This is because the registers are a full word long (4 bytes), so a shift in one index is a 4 byte shift.

7. Running the program

Remember that to access the file "/dev/mem" you must have root privileges. That means you should run your program using "sudo ./yourProgram".

8. How to connect a LED(Pin is different, refer to 3.6):

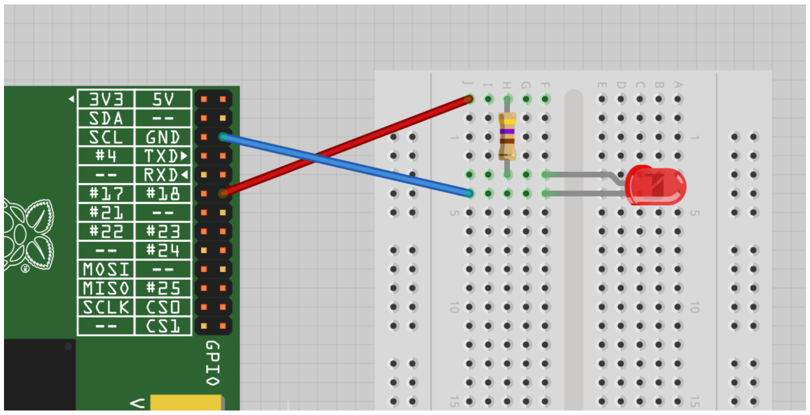


Image source: http://razzpisampler.oreilly.com/ch03.html

9. Raspberry Pi GPIO:

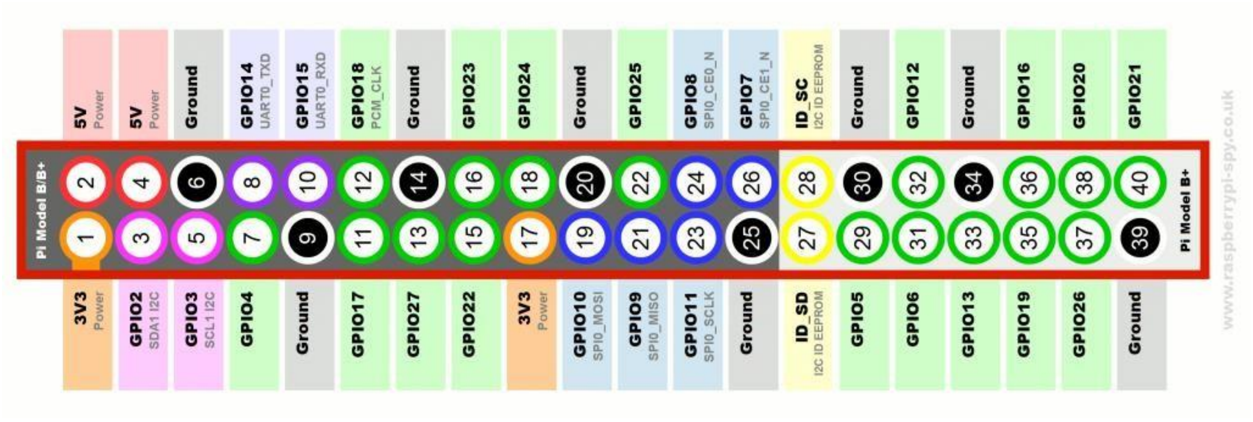


Image Source:http://www.raspberrypi-spy.co.uk/2012/06/simple-guide-to-the-rpi-gpio-header-and-pins/

1.4 Questions to Explore

We've prepared three question for you to think and explore about Raspberry Pi. Please write down your thought on the questions in the report:

1. In this lab, we used assembly language to control the output to the GPIO pin on the Raspberry Pi in order to blink the LED. Do you have an alternative way to blink this external LED? If so, write down your answer.
2. What can you add to or change in the code in section 3.2 – 3.3 if you want to control the LED on/off time to different numbers? (For example LED on for 3 second and off for 4 second, repeat.) Can we replace function delay in our code?
3. Now, if we replace the external LED in this lab by a buzzer. Can we still produce music by this buzzer using the same way we do to the LED? If yes, provide your solution. If no, what needs to be changed in order to produce music?

1.5 What to Turn In

- Source code for the assembly program to blink the LED with **inline comments** explaining the code. You do not need to comment line by line, just present your understanding of your own work.
- Answers to the exploration questions, and demo the blinking LED to TA in lab.

2 Lab 2: Using GPIO as Input and Output

2.1 Learning Objectives

In this lab, you are going to learn how to involve user's control of some actuation, read some digital data, and output digital data for actuation through Raspberry Pi's GPIO interface. Input data can be manipulated inside the Raspberry Pi before writing the outputs.

2.2 Components Needed

Raspberry Pi 3, RGB LEDs, Press button switch for user control, 8-bit DIP switches, LED Matrix Display, resistors, and appropriate wires

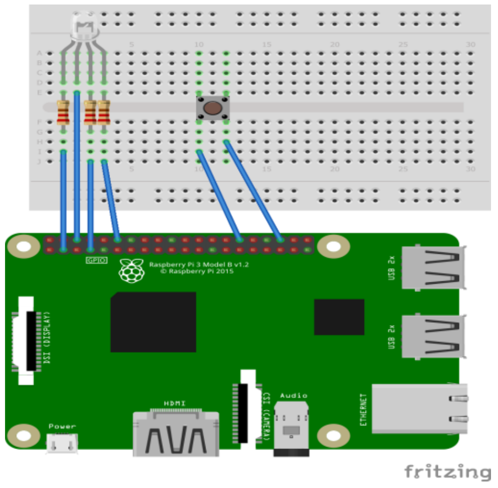
2.3 Lab Activities

2.3.1 Button-Activated LED

Interface a 3-input RGB LED as output device and 4-pin single press button switch to control LED activation. The switch and LED are to be interfaced through GPIO like the last lab. The switch will wait for user inputs to make the LED glow. The input to the GPIO pin can be read using the level registers, which start at the offset of 0x34 (from the GPIO address of 0x3F200000). There is one bit for each pin. Refer to http://www.elinux.org/RPi_GPIO_Interface_Circuits to make sure you know how to interface switch/resistor/diode etc.

lab activity: Write an C language program to enable the LED to blink (1 sec on/off) with user input. Display a particular color light in LED when user presses the button once. The cycle of blinking colors repeats. The LED starts out off. When the button is pressed the first time, the LED will blink with a certain color. The next time the button is pressed, the LED will blink with a different color. Each time the button is pressed the color will change. **You do not have to demonstrate this part.**

Circuit Design: A tentative schematic is shown below. You will determine appropriate pins, resistors, power supplies for your design.



2.3.2 DIP Switch-Controlled LED Matrix

Now consider three push buttons as the input source and an LED matrix as the output source interfaced through GPIO. You will choose a digit binary number by setting a combination of bits by push down the buttons. This is the data input.

To do this, you will connect the input pins to either VCC (1 or high) or GND (0 or low) through appropriate resistors. The Raspberry Pi 3 shall be programmed in Python to read an input value (between 000-111(binary)) and display that number by decimal (0-8) on the LED matrix. Note that the Raspberry Pi and LED should be protected using resistors.

When using GPIO in Python, you should use the library RPi.GPIO. To set up the GPIO pins, you need to choose the pin numbering mode using the setmode(mode) function. It takes a parameter that can be either RPi.GPIO.BCM, which uses the same pin numbering as the registers, or RPi.GPIO.BOARD, which uses the pin numbers based off of the physical location of the pins. Setting the pin to either input or output mode uses the setup(pin, mode) function. The mode can be either RPi.GPIO.INPUT or RPi.GPIO.OUTPUT. The library also has output(pin, value) and input(pin) functions. Lastly, when you are done using the GPIO in the program, use the cleanup() function to set the pins back to the default.

Write a python/C program that takes input from the buttons and displays the correct character on the LED matrix. **Demonstrate the working system to the TA.**

2.4 Questions to Explore

In your report, write down the discussion of the following questions:

1. Discuss the advantages and disadvantages of using assembly over C/Python.
2. In activities 1 and 2 of this lab, we might have used a loop to continuously check the signal from the input source(s). Is there a way to read input from an external button or switch other than simply polling the signal?
3. We used GPIO pins to read input from the DIP switch. If you replace the input switch by a temperature sensor (model: **TMP36**), can you read temperature value from the sensor same way as you did from the switch? If yes, explain. If no, provide a solution to correctly reading data from a temperature sensor TMP36.

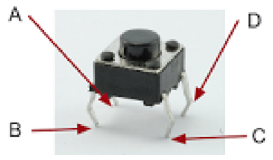
2.5 What to Turn In

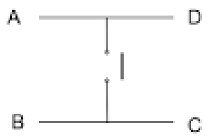
- Schematic of final working circuit for the button-activated LED
- C program for the button-activated LED
- Schematic of final working circuit for the DIP button-activated LED matrix
- Python program for the DIP switch-activated LED matrix
- Answers to the exploration questions

2.6 HELPFUL HINTS

1. Press Button

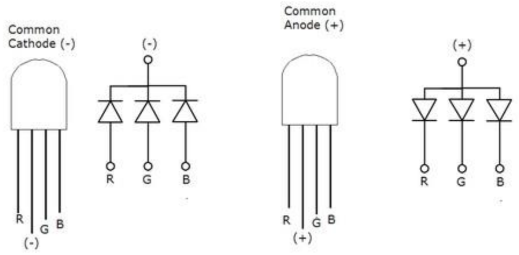
   A press button is a very common component we used to control electronic devices. We usually use them as a switch to connect/disconnect circuits. First of all, you will need to understand the four pins on the press button:





   When you're pressing the button, AD will be connected BC, which will connect the circuit. **To protect your raspberry Pi, a resistor is suggested to be placed in the circuit.** Also, the input pin on the Pi will be floating when the button is not pressed (because there are no complete circuits attached to that pin). To deal with the pin's voltage floating, it may be beneficial to put a pull-down resistor attached to the input pin if the other side of the button is attached to positive voltage. If the button is attached to ground, then a pull-up resistor should be used. **Make sure the resistance is high enough that the input pin can go to the correct voltage when the button is pressed (preferably significantly higher than the resistor you placed in series with the switch).**

2. RGB LED: A RGB (Red, Green, Blue) LED produces three different colors of light when you connect the power source to the different pins. We provide a RGB LED that have the same hardware schema as the image below. We have a common Cathode (-), which means, the second node should connect to the ground while the rest of them connect to the output pins on the Raspberry Pi. A positive voltage on the output pin will cause the corresponding LED to light up.

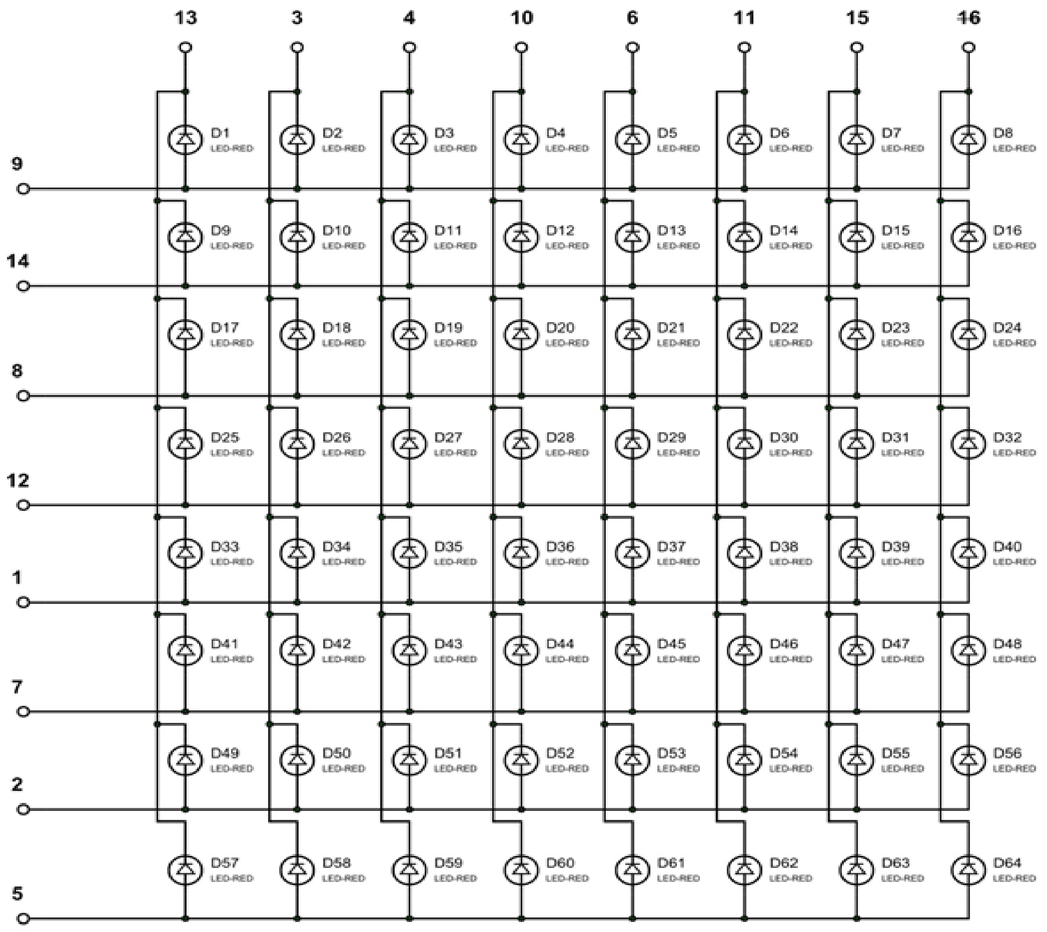


   Always remember to connect a resistor to each node! The voltage for each pin is around 2-3.2 V. The red pin will get burned immediately if you connect it directly into a pin. The blue and green pins can both stay on for several second before they will generate lots of heat and get burned (if connected directly to the pins).

3. LED Matrix

   Suggest reading: https://circuitdigest.com/microcontroller-projects/control-8x8-led-matrix-with-raspberry-pi

   An 8 by 8 LED matrix is a group of 64 LEDs in the form of matrix. There are 8 positive pins and 8 negative pins. A design schema for the matrix looks like this:



However, the pin on the real Matrix **is very confusing**. Please read the suggest reading to figure out the correct pin order. In order to light LED D1, we need to provide positive voltage on pin 9 and ground pin 13. The maximum voltage that each LED can tolerant is no more than 3.3 V. **Always connect a Resistor to protect your device and LED Matrix.**

Another thing to note that is impossible to light up 2 LEDs at the same exact time that are in different rows and columns without also lighting up the other LEDs that share those rows and columns. For instance D1 and D10 cannot be lit at the same time without D2 and D9 also being lit. The solution to this problem is to cycle the LEDs quickly. Turning D1 on and off and then turning D10 on and off continuously will make it appear as if D1 and D10 are on at the same time, even though in reality they are not.

3 LAB 3: MINI TRAFFIC LIGHT SYSTEM

3.1 LEARNING OBJECTIVE

In this lab, you are going to design and implement a finite state machine controller for a mini traffic light system. You are going to create a software system that will read some digital data, switch state by condition, and display correct traffic signal.

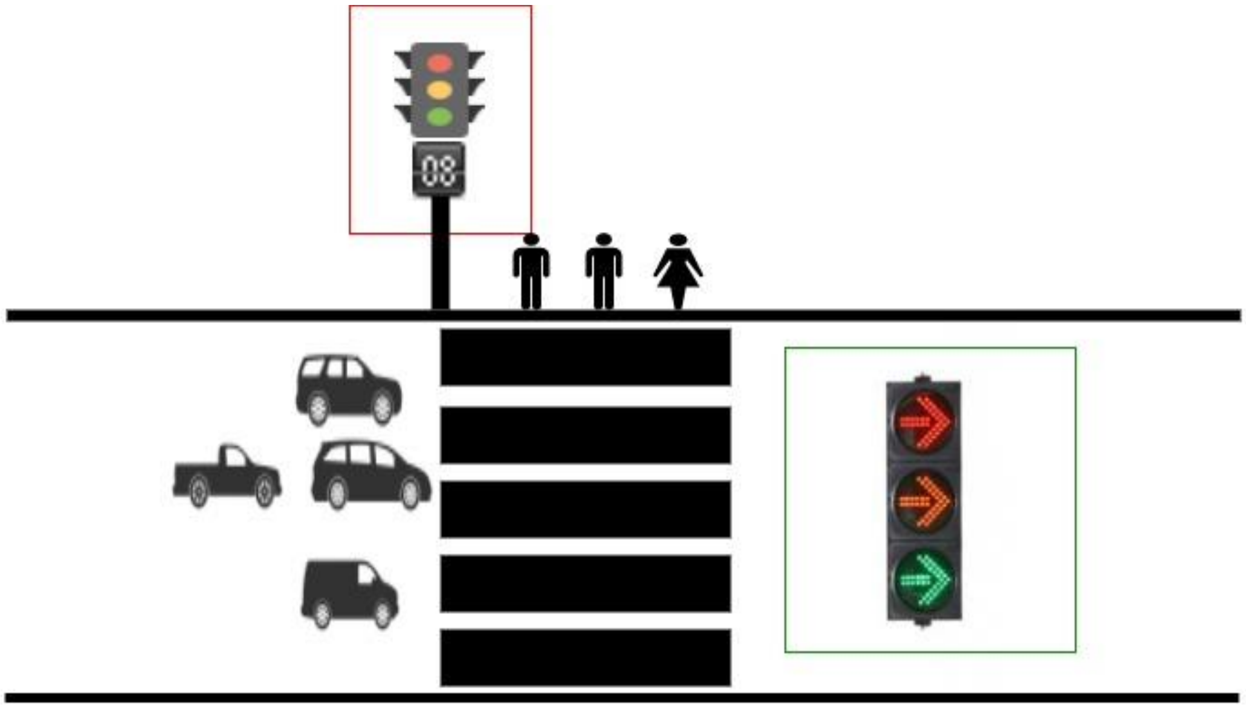
3.2 COMPONENTS NEEDED

Raspberry Pi 3, RGB LEDS (We will use blue instead of yellow for traffic signal), press button switch for control, 7-segment display for time count down, resistors, and appropriate wires

3.3 LAB ACTIVITIES

3.3.1 Stoplight Description

1. **Introduction:** Imagine a scenario like the image below. You have a heavy traffic street where random people are walking across the street while cars are driving. In this case, an appropriate traffic light system is needed for this street to ensure everyone's safety. Your goal is to design a control system for **traffic light 1 (in the red box)** & **traffic light 2 (in green box)**



2. **Components for traffic light 1:** RGB LED, countdown panel (7 segment display) and a press button (not shown in the figure). One RGB LED should work as it changes color and only one of the three colors is needed at any time.
3. **Components for traffic light 2:** RGB LED.
4. **Requirements:**

a. When button has not been pressed, traffic light 2 stay green
b. When button is pressed, traffic light 2 turn to blue and blue light flash 10 times then turn into Red.
c. When Traffic light 2 turn into red, traffic light 1 become green and countdown panel begin to count down from 20 to 0, in seconds. (In the real world it would be longer)
d. When Countdown reach 10, the traffic light 1 flash with blue light.
e. When Countdown reach 0, the traffic light 1 become red, traffic light 2 become green.
f. When button is pressed once there will be a 30 seconds cooldown to be able to make another valid press.

3.3.2 Finite State Machine
Design a finite state machine that implements the above description.

3.3.3 Simulation
From the finite state machine, implement a simulation in C that does not run on the Raspberry Pi. In this simulation, you do not need to have the timing exactly correct. It can run faster than the actual system would run for testing purposes. This simulation can just print out the state of the traffic lights because it is not actually attached to hardware. **You do not have to demonstrate this part.**

3.3.4 Final Stoplight System
Implement the stoplight system described above using hardware and the Raspberry Pi. This system will be demonstrated to the TA. The software controlling the stoplight should be written in C. This system should make use of the Raspberry Pi's built in timer.
Raspberry Pi 3 has multiple different types of timers. Most of these timers are either inconsistent, slow, or already used by the OS. The Local Arm Timer is not used by the OS and run consistently at a speed of 38.4 MHz because it ticks on every edge (rising and falling) of a crystal clock with frequency of 19.2 MHz. The description of how to control this timer can be found here (https://www.raspberrypi.org/documentation/hardware/raspberrypi/bcm2836/QA7_rev3.4.pdf). The timer works by loading a value into the timer and decrementing that value by one every tick of the timer. Once the timer reaches 0, it reloads the initial value and sets the interrupt bit (and actually does an interrupt if the interrupt was enabled). The timer is mainly controlled by a register at 0x40000034. The lower 28 bits (0-27) are the value that is loaded into the timer. The 29th bit (28) is set to 1 when you want the timer to be enabled and 0 when you don't. The 30th bit (29) bit is set when you want timer interrupts to be enabled and 0 when you don't. The 32nd bit (31) is the interrupt bit. This bit is set by the hardware when the timer reaches 0. This bit will stay set until it is cleared. To clear the interrupt bit and reset the timer without triggering an interrupt, a resister a 0x40000038 is used. The highest bit (31) clears the interrupt bit when a 1 is written to it. The second highest bit (30) will reset the timer to the load value without triggering an interrupt if a 1 is written to it.

3.4 Questions to Explore
1. Share your experience on differences between a simulator and the actual implementation in 75-100 words.

2. In the future, can we possibly have street-crossings for cars without traffic-signals like what we have now? If yes, how can we implement that?
3. Consider you want to have similar waiting countdown display arrangement across the zebra crossing. How is your design going to change?

3.5 What to Turn In

- Image of the finite state machine
- Simulation code
- Final stoplight implementation C code
- Answers to the exploration questions

4 Lab 4: Use of Digital to Analog Converter along with a Microcontroller.

4.1 Learning Objective:

In this lab, you are going to

1. Learn about generating basic waveforms and measuring them using an oscilloscope.
2. Explore generating low frequencies for various sounds and music.
3. Use DAC chip to create different waveforms.

4.2 Components Needed

Raspberry Pi 3, resistors, buzzer, and DAC chip

We will use a DAC chip MCP4725 for the lab activities below. You are allowed to use the Adafruit open source library, whose detail can be found here: https://learn.adafruit.com/mcp4725-12-bit-dac-with-raspberry-pi .

4.3 Lab Activities

4.3.1 Generating a Square Wave

A square wave is a waveform in which the amplitude strictly alternates between a fixed minimum and maximum. A square wave can be created by programming your Raspberry Pi to turn an output pin on and off.

In lab 1, when you blink your LED, you are sending a square wave out from the pin to the LED. Here is a simple C solution to generate a square wave with frequency 100 kHz (1/(5+5 µs)):

```
void squareWave(){
    while(1){
        setPinOn(gpioBase, pin)
        delayMicroseconds(5)
        setPinOff(gpioBase, pin)
        delayMicroseconds(5)
    }
}
```

By changing the delay period we can change the frequency of the square wave. In the above program the setPinOn and setPinOff functions are the same ones used in previous labs. The delayMicroseconds function should be implemented via the timer used in the last lab.

Write a C program or modify the code above to generate digital signal waveforms (square waves) with frequencies 200 kHz, 600 kHz & 800 kHz.

4.3.2 Measuring Waveforms using an Oscilloscope

Waveforms are specified by their frequency and amplitude. While a regular voltmeter can measure point values of a signal at a time, an oscilloscope can show the continuous values over a period of time of a signal. An oscilloscope can be used to display and analyze waveform of electronic signals. In other words, it draws a graph of a signal voltage as a function of time.

To view the waveform on the oscilloscope, connect the probe test cable to the signal source (red to output pin, black to ground pin). Most scopes will produce a two-dimensional graph with time on the x-axis and voltage on the y-axis.

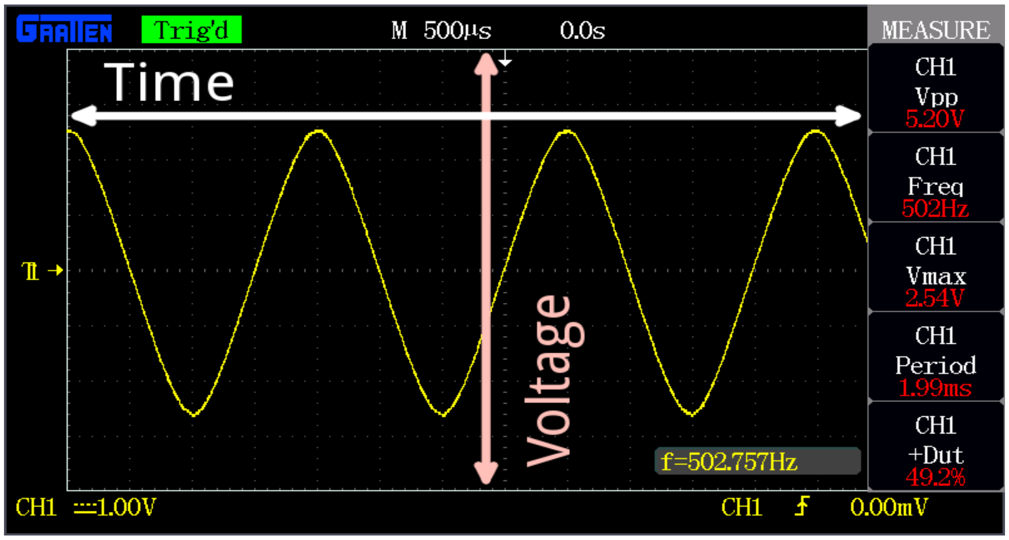


Figure a. A sample oscilloscope output provided by Sparkfun

On the x-axis, you can find out the timing characteristics, such as frequency, period, duty cycle, & rising/falling time, using a horizontal control to adjust time scale.

On the y-axis, you can find out the voltage characteristics, such as amplitude and maximum/minimum voltage, using a vertical control to adjust voltage scale.

In Lab 5, you will be asked to build an oscilloscope to read and visualize the waves you generated in Lab 4. We will discuss the detailed specification about oscilloscope in the next lab.

Read the square wave you generated in the part 1 with an oscilloscope to ensure that you have generated a wave with the desired frequency. Use control knobs on the oscilloscope panels to measure the highest voltage and the lowest voltage. Observe whether the highest reading is steady or if there is noise. Also, determine the fastest frequency that the digital output can create (by changing the frequency in the program). Record this frequency.

4.3.3 Generating Music using Raspberry Pi and a buzzer

We will learn how to use a buzzer to output music and write a program to adjust the frequency of a square wave based on user input.

Generally speaking, a tone is a particular frequency of sound. When we apply an audible signal (voltage, frequency) to the small buzzer, it makes continuous sound. A buzzer is an actuator that converts frequency into sound. Please note that a voltage does not make a tone but frequency is the cause of tone. Let’s make a buzzer produce a C4 (middle C) tone. “Middle C” has a frequency 261.6 Hz (see helpful hints for more detail).

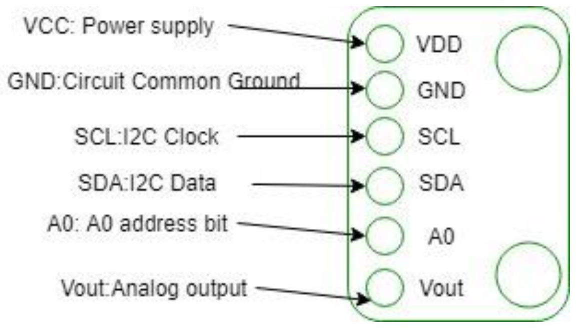
Then we need to generate a square wave that has a frequency equal to 261.6 Hz. This means the every 1 second contains 261.6 cycles of the waveform (1 Hz = 1 cycle per second). The following function will produce a 261.6 Hz square wave for 1 second:

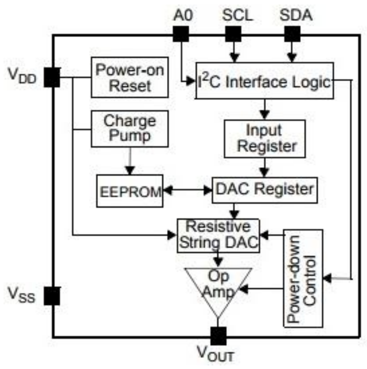
```
#include <wiringPi.h>
#include <stdio.h>

#define outputPin 0
#define C4 261.6 //Hz
#define period 1 //second
void tone(){
        long half_cycle = (long)(1000000/(2*C4))
        long numberOfLoops = (long)(freq*period);
        for(int i = 0; i < numberOfLoops; i++){
                setPinOn(gpioBase, outputPin);
                delayMicroseconds(half_cycle);
                setPinOff(gpioBase, outputPin);
                delayMicroseconds(half_cycle);
        }
}
void run(){
        tone();
        delay(20);
}
int main(){
    //set up gpio. Timer, etc. here
    while(1){
        run();
    }
}
```

Modify the code above to let the small buzzer produce a piece of music. The **tone()** function should be modified into **tone(unsigned int frequency, unsigned int period)**, which will take a frequency input and a tone period. This tone function will be used multiple times to create the piece of music. Some sample music notes can be found at the end of the lab manual. Music notes can be hard coded in your main function. **Demonstrate your musical buzzer to the TA.**

4.3.4 From Digital Output to Analog Output

Now you are familiar with generating a digital output wave and how to adjust it to a frequency. In this section you will learn about how to convert a digital signal into an analog signal and how to create waves other than a square wave.

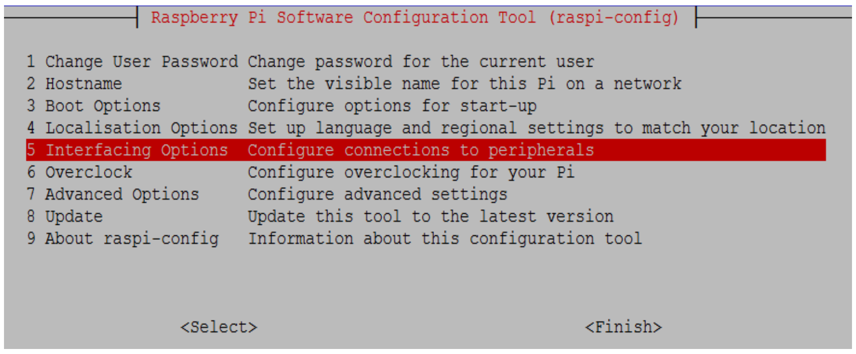




We provided you a DAC MCP4725 12-bit chip (shown in the diagram above), which will help you convert digital signals into analog. 12 bit means that it will accept up to 4096 possible inputs to provide an analog input, where 0 is 0V and 4095 is the full scale voltage (which determined by the voltage you supply to the VCC pin). According to the data sheet the VCC voltage can be in the range 2.7V to 5.5V.

There are six pin on the chip package. SDA will send data from Raspberry pi to the chip (0-4095), and the SCL (clock) will control the output rate.

You will need to enable your Raspberry Pi I2C functions in order to send signals via I2C ports. This can be done via the command "sudo raspi-config". In the menu that appears, choose option 5, "Interfacing Options". Then choose option P5, "I2C". To control the I2C output to the DAC, you can install Adafruit Python Library found Here.



```
┤ Raspberry Pi Software Configuration Tool (raspi-config) ├

1 Change User Password Change password for the current user
2 Hostname             Set the visible name for this Pi on a network
3 Boot Options         Configure options for start-up
4 Localisation Options Set up language and regional settings to match your location
5 Interfacing Options  Configure connections to peripherals
6 Overclock            Configure overclocking for your Pi
7 Advanced Options     Configure advanced settings
8 Update               Update this tool to the latest version
9 About raspi-config   Information about this configuration tool


                 <Select>                                  <Finish>
```

Use the code (Python) frame we provided below to generate a sine wave. Check that it is being generated as expected by displaying it on an oscilloscope.

```
sin_wave():
    t = 0.0
    tStep = 0.05
    while True:
        voltage = 2048*(1.0+0.5*math.sin(6.2832*t))
     dac.set_voltage(int(voltage))
     t += tStep
     time.sleep(0.0005)
```

4.3.5 Building a Function generator using Raspberry Pi

In this section, you are going to build a function generator using what you learned from sections 1- 4. The command window should display nothing until an external button is pressed. Then the system should ask for 3 input:

i. Shape of the waveform (square, triangle, or sin)
ii. Frequency
iii. Maximum output voltage

When the inputs are confirmed, the Raspberry Pi should output the correct wave with correct characteristic continuously until the button is pressed again. Then the system should ask for 3 inputs again (continuing the cycle). **Demonstrate your finished function generator to the TA.**

4.4 Questions to Explore

1. What is the highest frequency that your Raspberry Pi can generate using digital output? Why is this the case?
2. Does the highest reading stay steady or fluctuate? If not and there are noise, where does the noise come from?
3. How can you convert a digital PWM (Pulse width modulation) signal into analog signal. (e.g. possible circuit design, software conversion)
4. What is the maximum frequency you can produce with your Raspberry Pi functional generator?
5. Explain your design for the functional generator (you can use diagram to visualize your system state machine, what function you implemented, etc.)

4.5 What to Turn In

- Square wave code
- Musical buzzer code
- Functional generator code
- Answers to the exploration questions

4.6 Helpful Hints

1. Sample Music notes can be used in part 3: format: tone(time (second)) (all 4th octave):
   G(0.75) A(0.25) G(0.5) F(0.5) E(0.5) F(0.5) G(1) D(0.5) E(0.5) F(1) E(0.5) F(0.5) G(1) G(0.75) A(0.25) G(0.5) F(0.5) E(0.5) F(0.5) G(1) D(1) G(1) E(1) C(1)
2. Note frequencies can be found here:
   (https://www.seventhstring.com/resources/notefrequencies.html)

5 Lab 5: Interfacing Analog to Digital Converter (ADC) with a Microcontroller.

5.1 Learning Objective

In this lab, you are going to

1. Learn about interfacing analog sensors with microcontrollers using A/D converters.
2. Use an ADC chip to analyze analog signals.
3. Examine the characteristics of a signal using an oscilloscope.

5.2 Components Needed

Raspberry Pi 3, resistors, temperature sensor, ADC chip MCP3008, and light sensor

5.3 Lab Activities

5.3.1 Introduction to Raspberry Pi's SPI port

SPI, or Serial Peripheral interface is a communication bus that is used to interface one or more slave IC (integrated circuits) to a single master device (Raspberry Pi is the master in this lab). In lab 4, you used the I2C port as output. However, the SPI port could have been used instead. Please note that SPI is a faster bus than I2C. On the other hand, I2C can connect many devices with only a 2 wire bus, while each slave device for SPI requires an additional wire bus. There are three SPI wires shared by all slave devices on the bus:

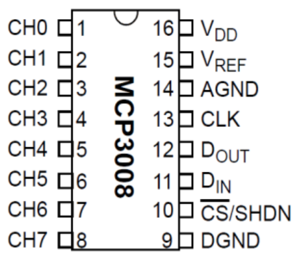
a. Master in slave out (MISO), data from slave to master on this port
b. Slave in master out (MOSI), data from master to slave on this port
c. Device clock (CLK), clock for synchronizing communications

Each slave device will have one additional port connected to the master device. This port is for selecting a device to communicate with. For Raspberry Pi, there are two available ports for you to connect with your slave devices. Once you connect devices, data transmission can happen. During each clock cycle, the master sends data on the MOSI line and the slave reads it. At the same time, the slave sends data on the MISO line, and the master reads it. This behavior is maintained even if only one line has data to transmit.

To be able to use SPI, you must enable it on the Raspberry Pi. To do this, follow the instructions from Lab 4 for enabling I2C, except instead of selecting I2C select SPI.

5.3.2 Introduction to MCP3008 ADC

Your Raspberry Pi has no built-in analog inputs. This means it cannot read any data from analog sensors. The MCP3008 is a 10-bit, 8-channel, SPI-based ADC (analog to digital converter). It communicates with the Raspberry Pi using the SPI bus on the Raspberry Pi's GPIO header.



The following table shows how you can connect your Raspberry Pi to the chip:

```
VDD          3.3V
VREF         3.3V
AGND         Ground
CLK          GPIO11(SPI_SCLK)/Phys23
DOUT         GPIO9(SPI_MISO)/Phys21
DIN          GPIO10(SPI_MOSI)/Phys19
CS           GPIO8(SPI_CE0)/Phys24
DGND         Ground

CH0-CH7    Analog Input(8 channel)
```

When connected to the Raspberry Pi, the ADC chip will take analog input from Ch0-Ch7 and provide 1/0 digital signal to the Dout pin. The following communication happens when the Raspberry Pi tries to read from the ADC chip:

1. The Raspberry Pi will first send a byte containing the digital value 1. The MCP3008 will send back its first byte, which is not important, as a response.
2. Then the Raspberry Pi will send a second byte to indicate which channel on the MCP3008 chip should receive the analog signal.
3. As the result will be a 10 bit data, which cannot be held by a single byte. MCP3008 will send back the second byte, which contains two bits of the conversion result (which is the 8th and 9th bit).
4. The Raspberry Pi then sends a response byte to indicate that the previous byte was received, and then MCP3008 sends back the last byte containing the rest of the bits (bits 0 to 7) of the converted digital value of the analog signal.
5. Finally, the Raspberry Pi merges bits 8 & 9 with bits 0 through 7 to create the 10 bit digital value from the conversion.

5.3.3 Reading Data from Sensors

We will use a photocell (CdS photoresistor) as an example to demonstrate how to read data from sensor through MCP3008. Under the normal light condition, the resistance of the photocell is about 5-10KΩ, and in the dark it goes up to 200KΩ. We can use it just like we use a normal resistor.

We can connect one side of a 10k resistor to the power of 3.3V. (To protect the chip, make sure you connect to the 3.3V pin) Then connect the other side of the 10K resistor to two wires, one connected to the photoresistor and then to the ground, the other connected to the input pin of MCP3008. With bright light in the room, the resistance will drop to a low value. This will cause higher current to flow through the photoresistor, resulting in a voltage drop across it. The input voltage will drop to almost 0V. In the dark, the voltage will go up near 3.3V due to the high resistance in the photocell relative to the resistance in the resistor.

To read the data, following Python script can be used:

```python
import spidev

# Open SPI bus
spi = spidev.SpiDev()
spi.open(0,0) #1st param is channel

def readChannel(chan):
    adc = spi.xfer2([1,(8+chan)<<4,0]) #sends 3 bytes: 1,(8+channel)<<4, 0
    #adc will contain 3 bytes (as many as sent)
    data = ((adc[1]&3) << 8) + adc[2]
    return data
```

Use your Raspberry Pi to read data from a light sensor and a temperature sensor **(Two sensors should connect to different channels and then use software to read data one by one from the correct channel).** Display the current readings in the command window.

For the temperature sensor, the temperature range is approximately -50°F-280°F corresponding to 0-3.3V. For the lighting sensor, we will use a scale of 0 to 100 which corresponds to 0-3.3V. You can find the temperature sensor datasheet here.

5.3.4 Building an Oscilloscope with Raspberry Pi and the MCP3008 Chip

In the previous activity, you accomplished reading data from the MCP3008 and processing that input data with the Raspberry Pi. In this activity, you are going to build a more complex system, a simple oscilloscope using your Raspberry Pi with the MCP3008. The simple oscilloscope will have two functions:

1. **Recognize a wave**: This is a very basic feature that all oscilloscopes should have. In this lab assignment, you can pick one of the two options to implement:
    a. **Visualize the waveform on a window using python GUI**: You will have to continuously sample the input wave, and project the data onto a plot just like the oscilloscope you used in the Lab 4. The system should keep sampling and plotting, and input should be allowed to switch between the square, sine and triangle waves while the system is running. The plotting should be paused when system is processing the received data.
    b. Display the name of the input wave on a command window: You should implement an algorithm to distinguish square, sine, and triangle waves based on the data sampled. Every time your algorithm detects a shape change, print out the name of the shape to the command window. Be aware that there will be noise when sampling the data
2. **Characterizing a wave:** The mini-oscilloscope should be able to find out the frequency for the input waveform and display it to a command window or with your visualized wave.

Build a simple oscilloscope that will meet the requirements as above. You can use Lab 4's output as input in this activity. Two team can work each other (one team generate waveform and the other recognize it). Make sure not to have the same Raspberry Pi generating and reading the wave. You can also use a functional generator in the lab; the oscilloscopes can also generate waveforms. Each team should provide their own solution by the end of deadline and demonstrate it to the TA. Make sure to note the sampling rate of your oscilloscope.

5.4 Questions to Explore

1. Summarize the difference between SPI and I2C ports. Explain in what situation using the SPI ports is better than the I2C ports, and vice versa.
2. What are the various types of ADCs in use? Which type of ADC is MCP3008 and what are its advantages/disadvantages?
3. What is the sampling rate for your oscilloscope?
4. It is important never use the same Raspberry Pi to do waveform generation and waveform recognition at the same time. Otherwise, you will generate a waveform that frequency keeps changing or get random readings from the MCP3008. Explain why this is the case.
5. It is highly likely that your sampled data contains lots of noise. How you can filter the noise? Explain your method.

5.5 What to Turn In

- Light and temperature sensor reading code
- Oscilloscope code