Cyber-Physical Systems

Basic I/O with RPi

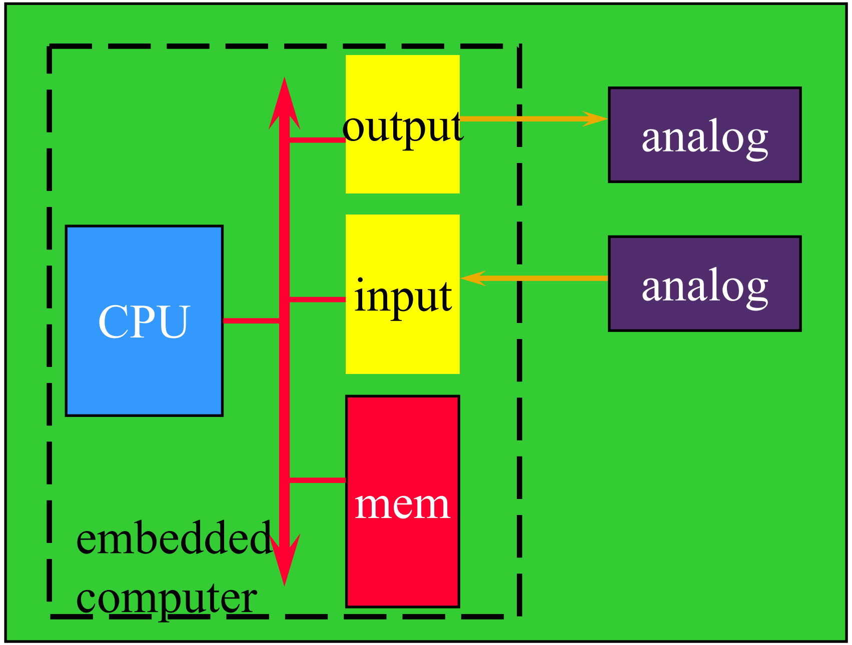
UNIVERSITY AT ALBANY
State University of New York

ICEN 553/453– Fall 2018

Prof. Dola Saha

Embedded System

- Embedded computing system: any device that includes a processing system but is NOT a general-purpose computer.
- Often application specific: takes advantage of application characteristics to optimize the design
- Might have real-time requirements
- Might be power constrained



Connecting the Analog and Digital Worlds

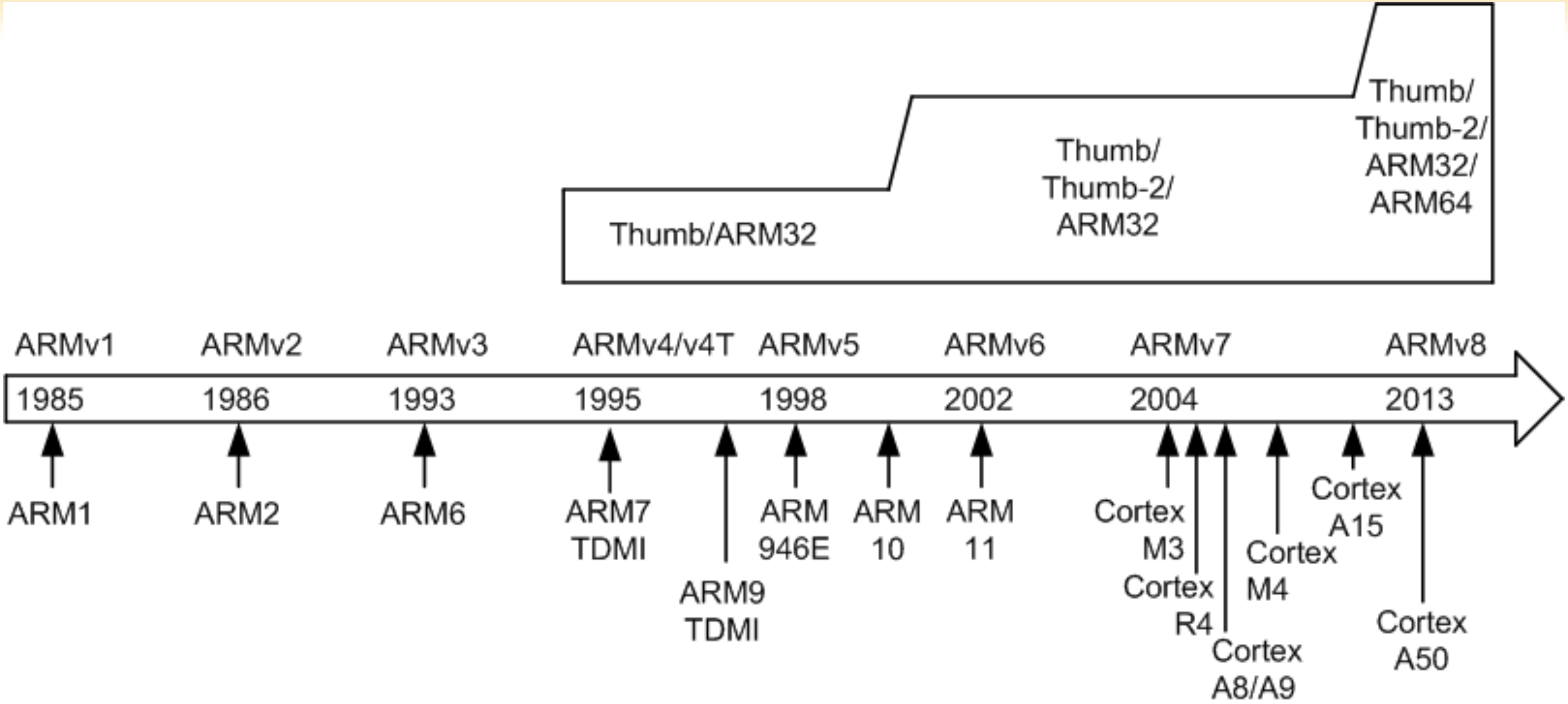
- Cyber
  - Digital
  - Discrete in Time
  - Sequential

- Physical
  - Continuum
  - Continuous in time
  - Concurrent

Practical Issues

- Analog vs. digital
- Wired vs. wireless
- Serial vs. parallel
- Sampled or event triggered
- Bit rates
- Access control, security, authentication
- Physical connectors
- Electrical requirements (voltages and currents)

History of ARM Processor



ARM Cortex Processors

ARM Cortex-A family:

Applications processors

Support OS and high-performance applications

Such as Smartphones, Smart TV

ARM Cortex-R family:

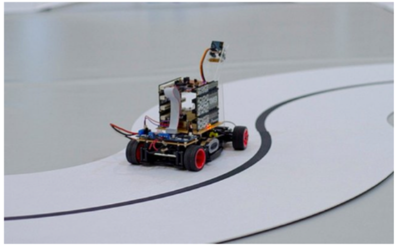
Real-time processors with high performance and high reliability

Support real-time processing and mission-critical control

ARM Cortex-M family:

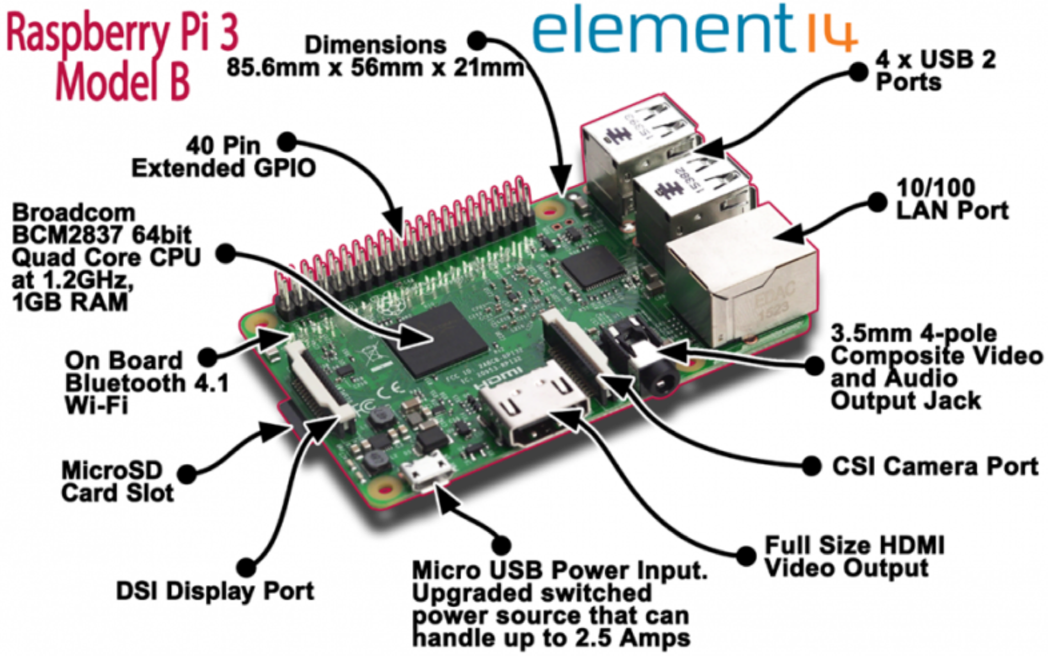
Microcontroller

Cost-sensitive, support SoC



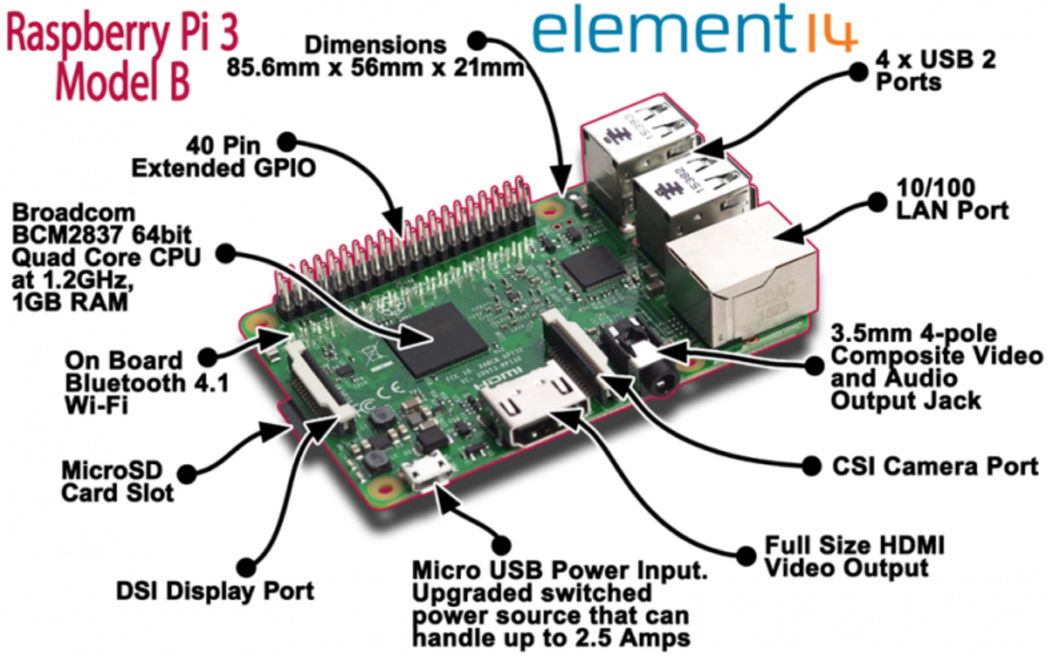
Raspberry Pi – Know your board

- The Raspberry Pi 3 Model B+ is the latest product in Raspberry Pi range.
  - Broadcom BCM2837B0, Cortex-A53 (ARMv8) 64-bit SoC @ 1.4GHz
  - 1GB LPDDR2 SDRAM
  - 2.4GHz and 5GHz IEEE 802.11.b/g/n/ac wireless LAN, Bluetooth 4.2, BLE
  - Gigabit Ethernet over USB 2.0 (maximum throughput 300 Mbps)
  - Extended 40-pin GPIO header
  - Full-size HDMI



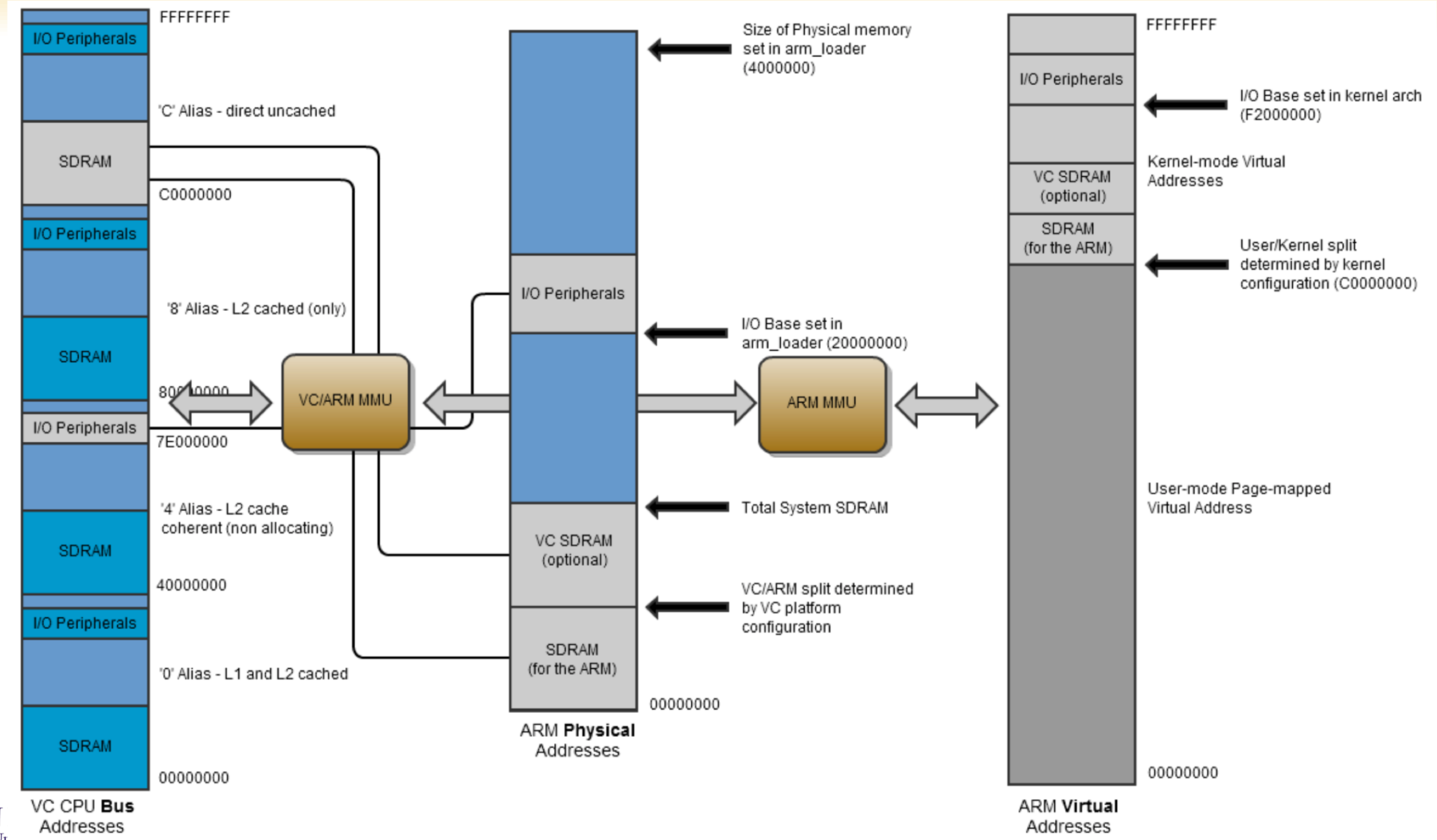
Raspberry Pi – Know your board

- The Raspberry Pi 3 Model B+ is the latest product in Raspberry Pi range.
  - CSI camera port for connecting a Raspberry Pi camera
  - DSI display port for connecting a Raspberry Pi touchscreen display
  - 4-pole stereo output and composite video port
  - Micro SD port for loading your operating system and storing data
  - 5V/2.5A DC power input
  - Power-over-Ethernet (PoE) support (requires separate PoE HAT)



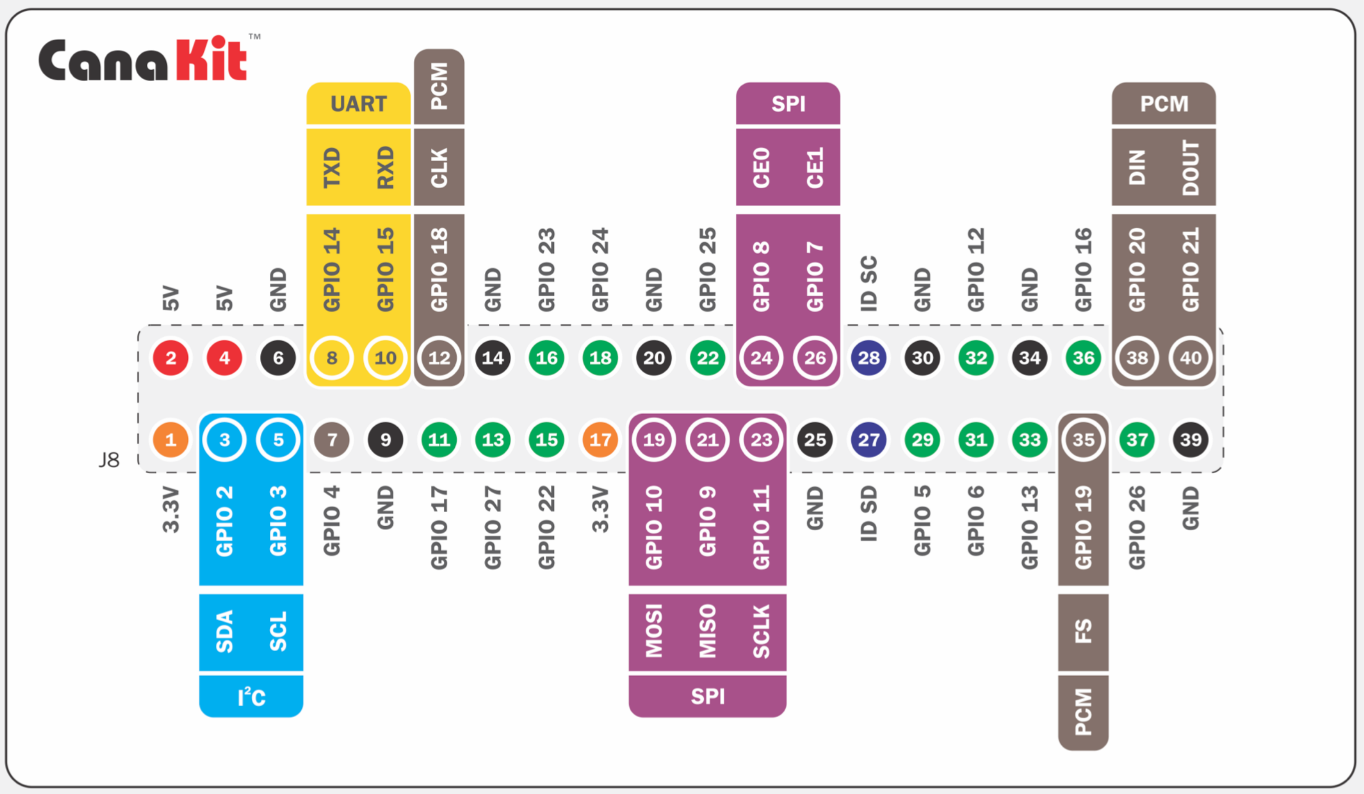
ARM Peripherals

BCM2837 Manual

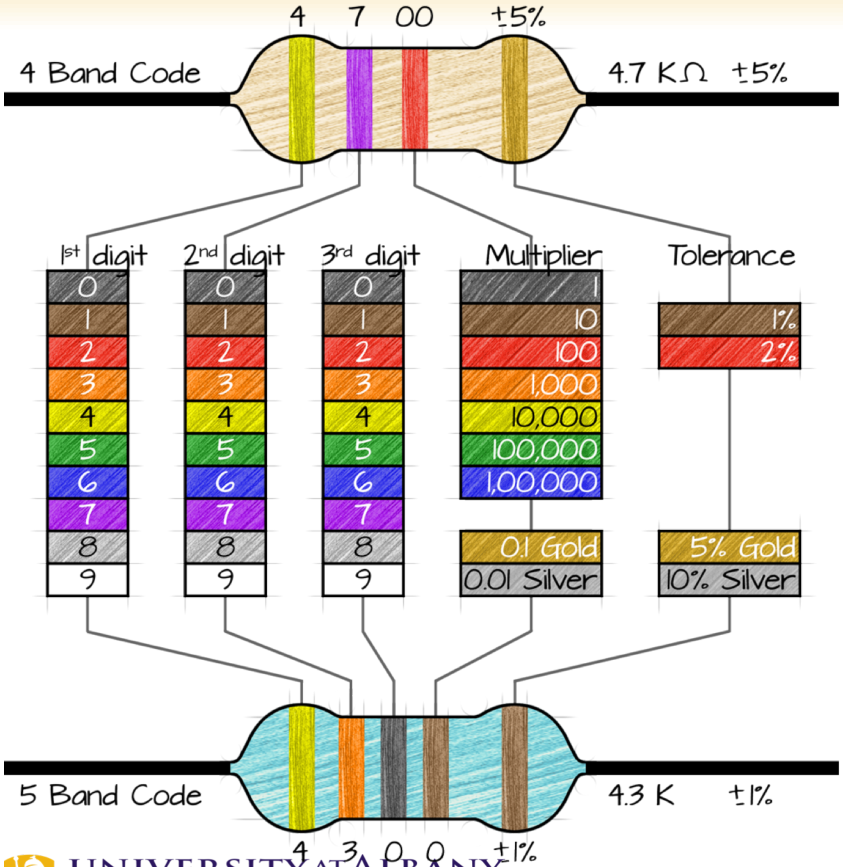


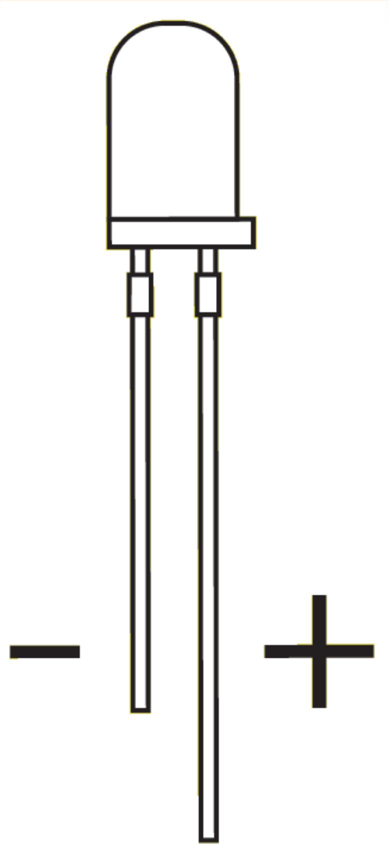
GPIO Pins

- https://pinout.xyz

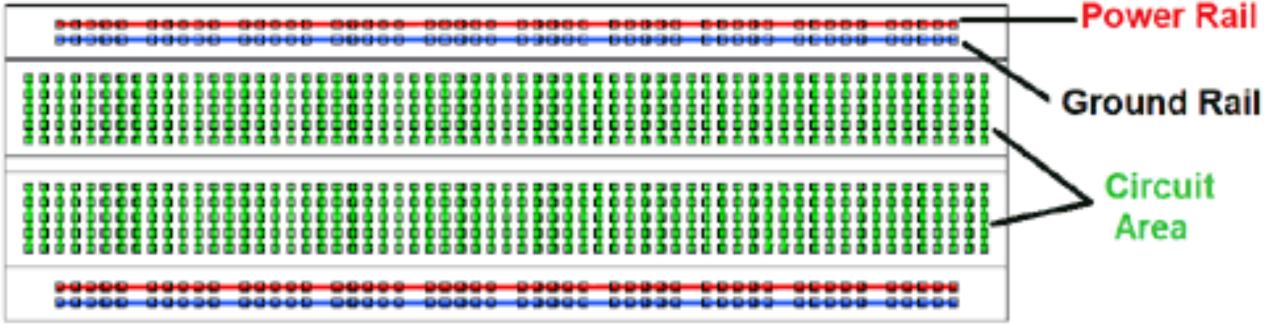


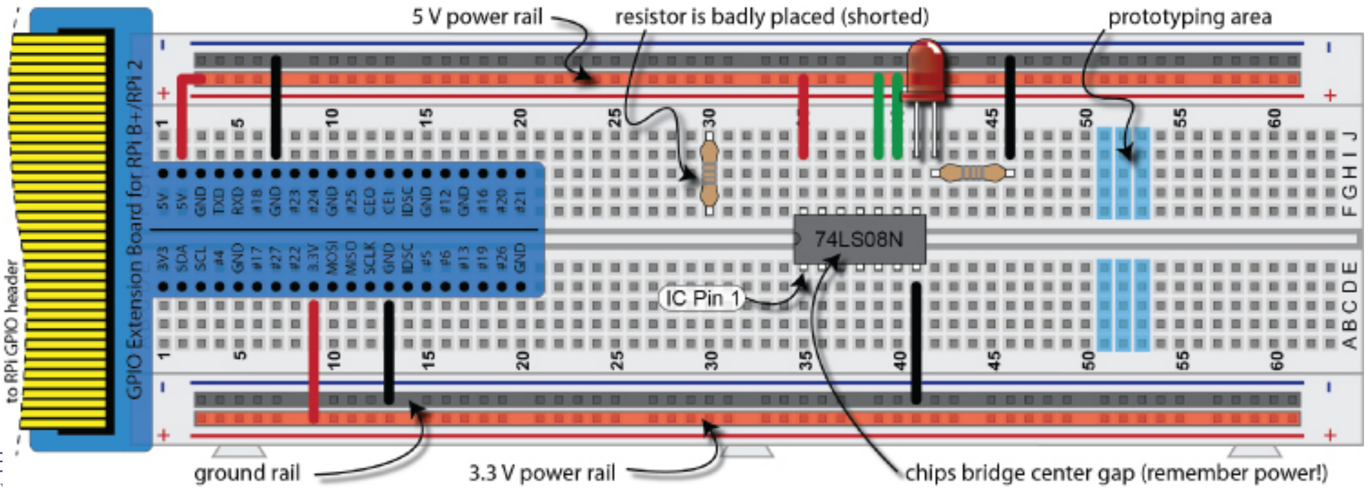
Resistors and LEDs



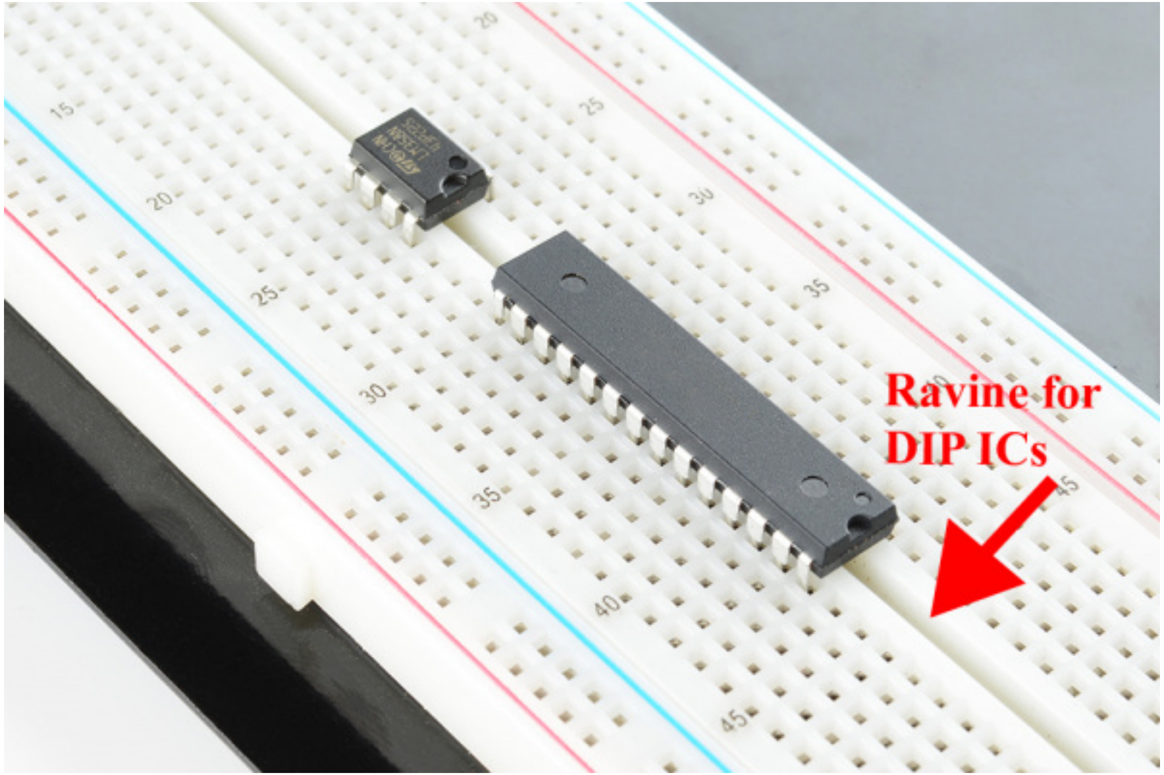


Breadboard Connections



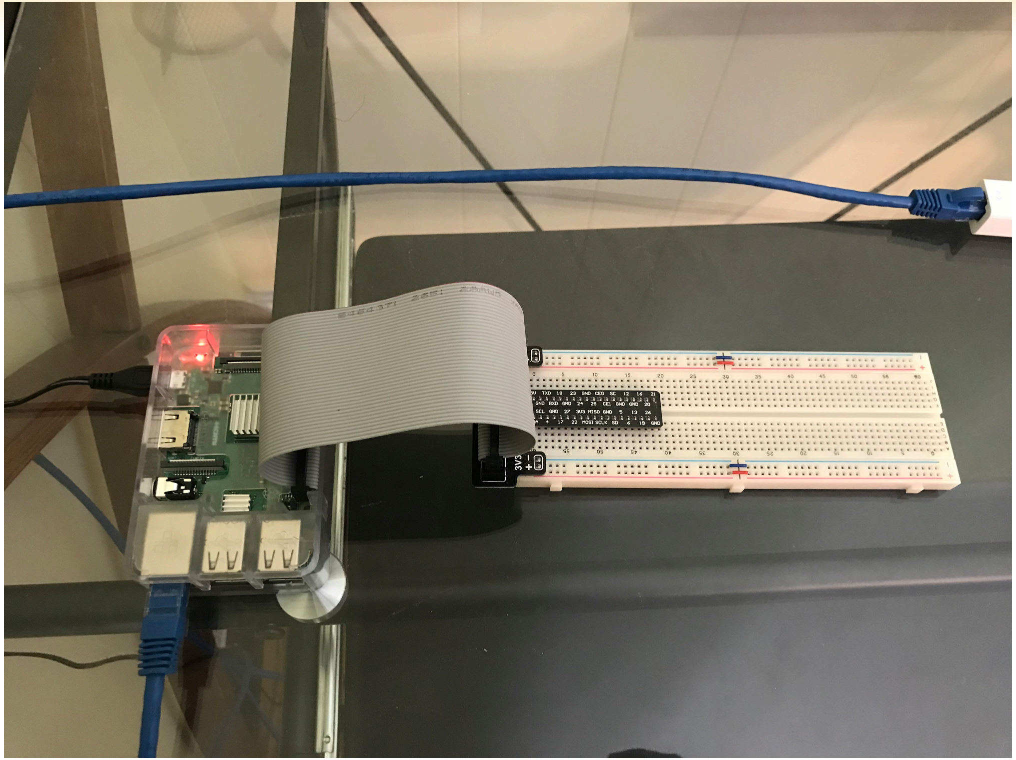


Dual In-Line Package or DIP

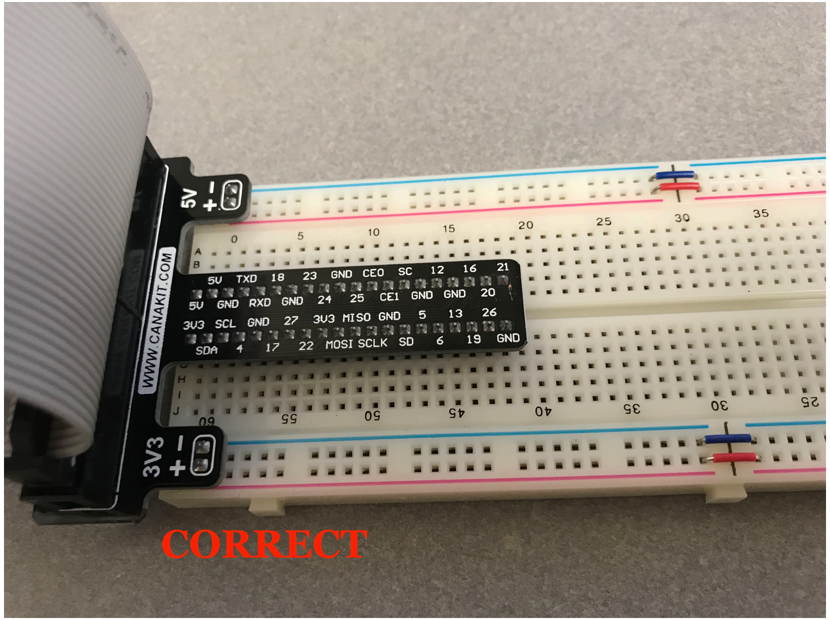


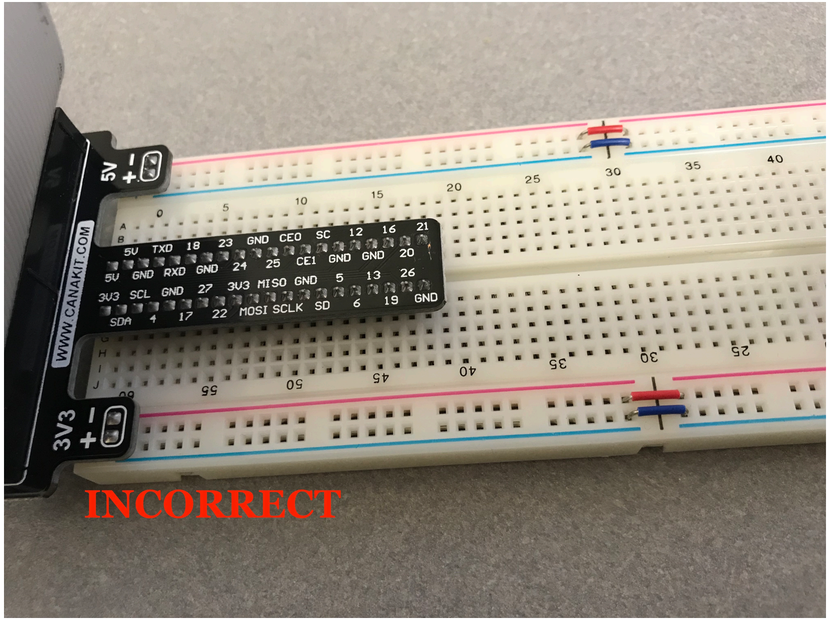
GPIO

- GPIO to Breadboard Interface Board
- GPIO Ribbon Cable
- Breadboard



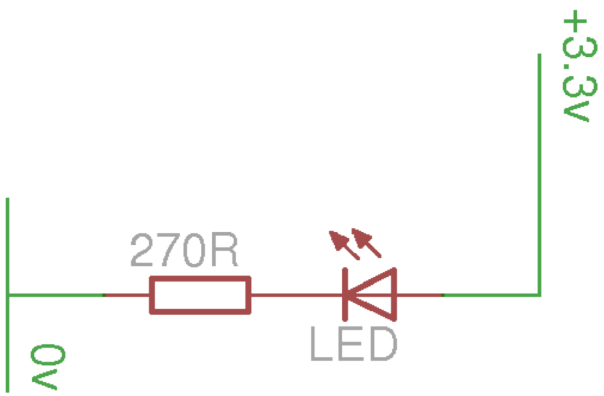
Convention

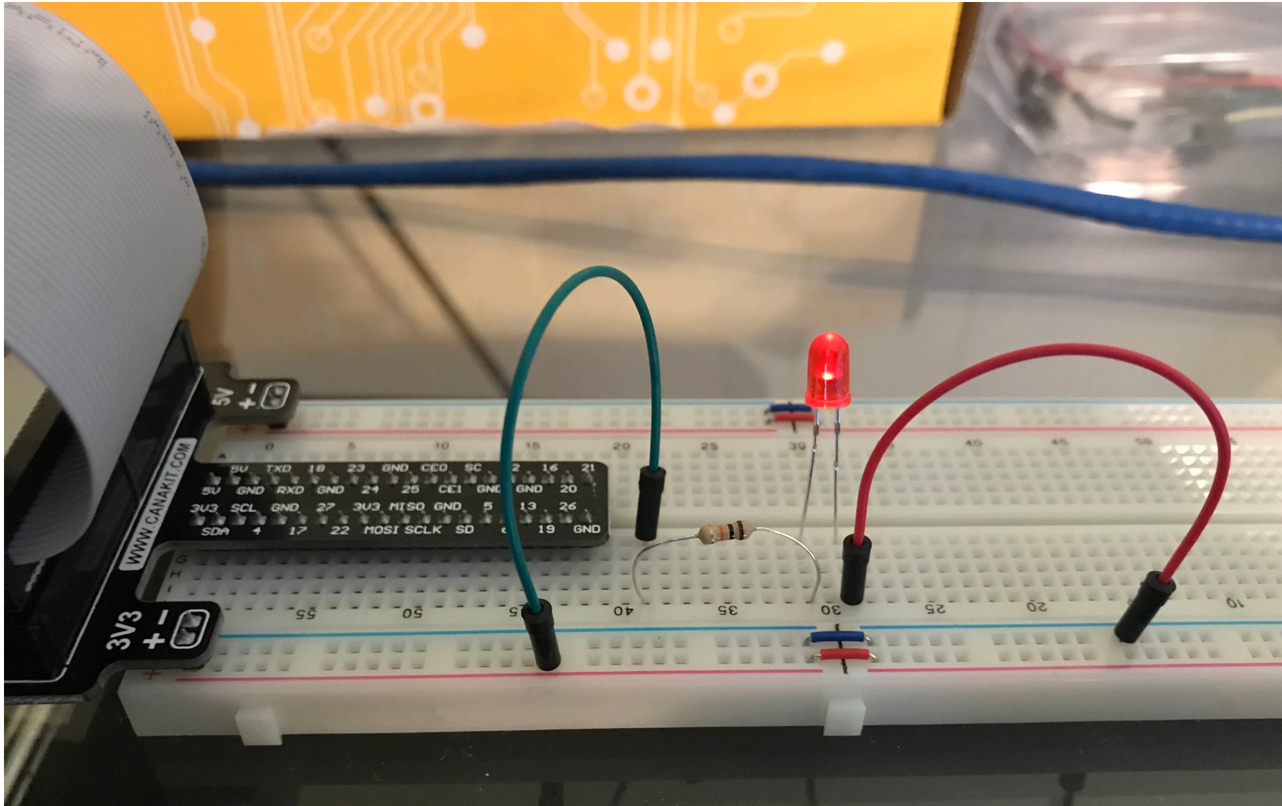

WWW.CANAKIT.COM
5V
3V3
CORRECT


WWW.CANAKIT.COM
5V
3V3
INCORRECT

Circuit to Breadboard

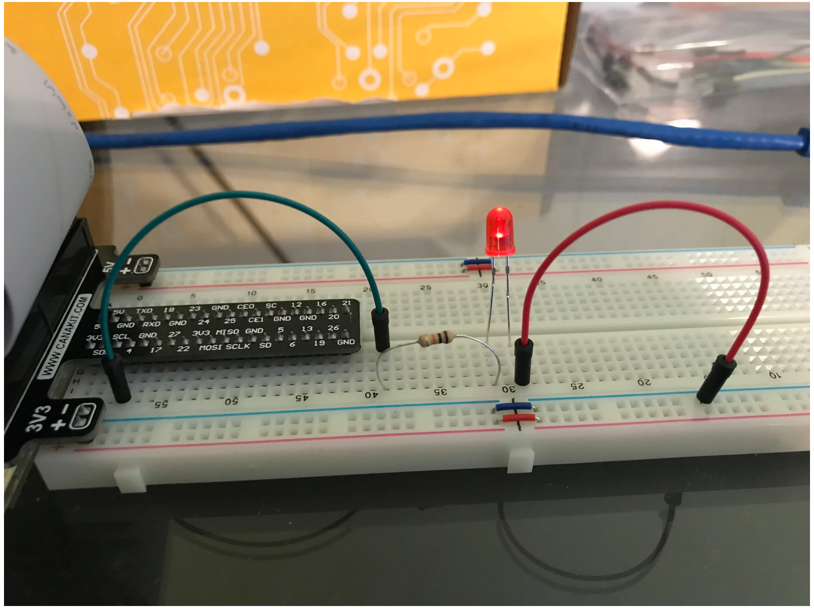
- Use 3V





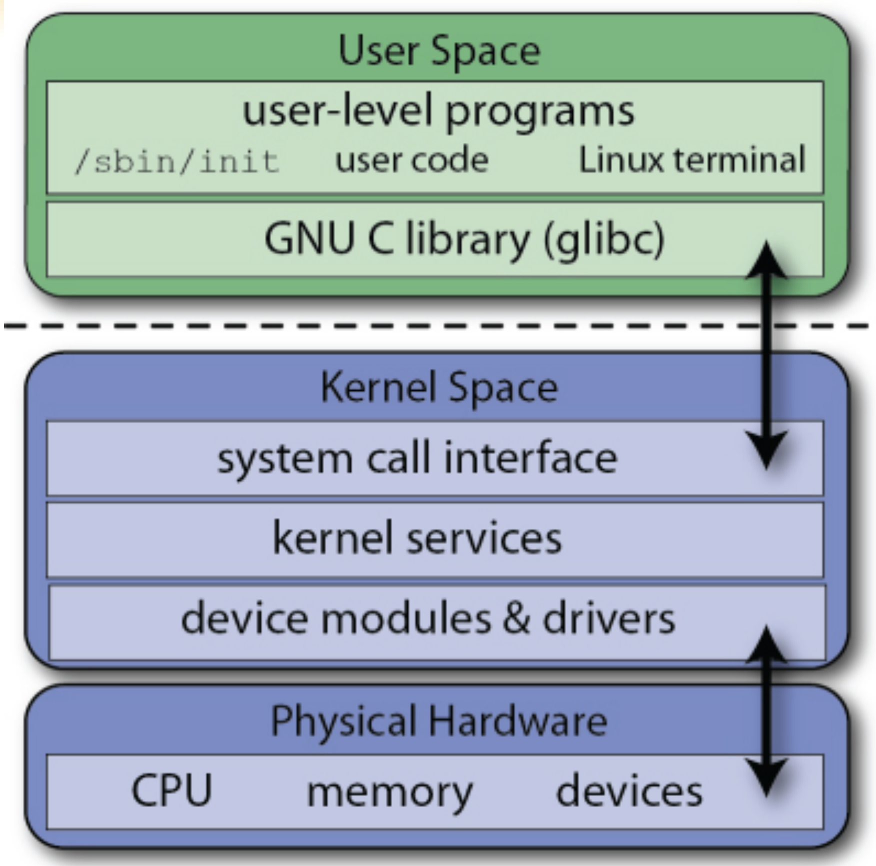
Circuit to Breadboard

- Use GPIO pin



sysfs - a filesystem for exporting kernel objects

- The **sysfs** filesystem is a pseudo-filesystem which provides an interface to kernel data structures.
- The files under **sysfs** provide information about devices, kernel modules, filesystems, and other kernel components.



Linux Kernel vs User Space

- The Linux kernel runs in an area of system memory called the *kernel space*
- Regular user applications run in an area of system memory called *user space*
- A hard boundary between these two spaces prevents
  - User applications from accessing memory and resources required by the Linux kernel
  - Linux kernel from crashing due to badly written user code
  - Interfering one user's applications with another
  - Provides a degree of security.

sysfs

- Paths in sysfs (/sys/class/gpio)
  - Control interfaces used to get userspace control over GPIOs
    - export
    - unexport
  - GPIOs themselves
  - GPIO controllers ("gpio_chip" instances)
- GPIO signals have paths like /sys/class/gpio/gpioN/
  - "direction" - reads as either "in" or "out”
  - "value" - reads as either 0 (low) or 1 (high)
  - "edge" - reads as either "none", "rising", "falling", or "both”
  - "active_low" - reads as either 0 (false) or 1 (true)

Steps to perform I/O using sysfs

- Export the pin.
- Set the pin direction (input or output).
- If an output pin, set the level to low or high.
- If an input pin, read the pin's level (low or high).
- When done, unexport the pin.

Exporting GPIO control to userspace

- "export"
  - Userspace may ask the kernel to export control of a GPIO to userspace by writing its number to this file.
  - Example: "echo 19 > export" will create a "gpio19" node for GPIO #19, if that's not requested by kernel code.
- "unexport"
  - Reverses the effect of exporting to userspace.
  - Example: "echo 19 > unexport" will remove a "gpio19" node exported using the "export" file.

Control GPIO with Linux

- Become the Sudo user
  - dsaha@sahaPi:~ $ sudo su
- Go to the GPIO folder and list the contents
  - root@sahaPi:/home/dsaha# cd /sys/class/gpio/
  - root@sahaPi:/sys/class/gpio# ls
  - export gpiochip0 gpiochip128 unexport
- Export gpio 4
  - root@sahaPi:/sys/class/gpio# echo 4 > export
  - root@sahaPi:/sys/class/gpio# ls
  - export gpio4 gpiochip0 gpiochip128 unexport

Control GPIO with Linux

- Go to the gpio4 folder and list contents
  - root@sahaPi:/sys/class/gpio# cd gpio4/
  - root@sahaPi:/sys/class/gpio/gpio4# ls
  - active_low device direction edge power subsystem uevent value
- Set direction (in or out) of pin
  - root@sahaPi:/sys/class/gpio/gpio4# echo out > direction
- Set value to be 1 to turn on the LED
  - root@sahaPi:/sys/class/gpio/gpio4# echo 1 > value

Control GPIO with Linux

- Set value to be 0 to turn off the LED
  - root@sahaPi:/sys/class/gpio/gpio4# echo 0 > value
- Check the status (direction and value) of the pin
  - root@sahaPi:/sys/class/gpio/gpio4# cat direction
  - out
  - root@sahaPi:/sys/class/gpio/gpio4# cat value
  - 0

Control GPIO with Linux

- Ready to give up the control? Get out of gpio4 folder and list contents, which shows gpio4 folder
  - root@sahaPi:/sys/class/gpio/gpio4# cd ../
  - root@sahaPi:/sys/class/gpio# ls
  - export gpio4 gpiochip0 gpiochip128 unexport
- Unexport gpio 4 and list contents showing removal of gpio4 folder
  - root@sahaPi:/sys/class/gpio# echo 4 > unexport
  - root@sahaPi:/sys/class/gpio# ls
  - export gpiochip0 gpiochip128 unexport

Program

- Bash Script
  - exploringrpi/chp05/bashLED/bashLED
- Python Code
  - exploringrpi/chp05/pythonLED/python2LED.py
- C code
  - exploringrpi/chp05/makeLED/makeLED.c

Bash and Python Script

```bash
LED_GPIO=4   # Use a variable -- easy to change GPIO number

# An example Bash functions
function setLED
{ # $1 is the first argument that is passed to this function
  echo $1 >> "/sys/class/gpio/gpio$LED_GPIO/value"
}

# Start of the program -- start reading from here
if [ $# -ne 1 ]; then   # if there is not exactly one argument
  echo "No command was passed. Usage is: bashLED command,"
  echo "where command is one of: setup, on, off, status and close"
  echo -e " e.g., bashLED setup, followed by bashLED on"
  exit 2     # error that indicates an invalid number of arguments
fi
echo "The LED command that was passed is: $1"
if [ "$1" == "setup" ]; then
  echo "Exporting GPIO number $1"
  echo $LED_GPIO >> "/sys/class/gpio/export"
  sleep 1    # to ensure gpio has been exported before next step
  echo "out" >> "/sys/class/gpio/gpio$LED_GPIO/direction"
elif [ "$1" == "on" ]; then
  echo "Turning the LED on"
  setLED 1   # 1 is received as $1 in the setLED function
elif [ "$1" == "off" ]; then
  echo "Turning the LED off"
  setLED 0   # 0 is received as $1 in the setLED function
elif [ "$1" == "status" ]; then
  state=$(cat "/sys/class/gpio/gpio$LED_GPIO/value")
  echo "The LED state is: $state"
elif [ "$1" == "close" ]; then
  echo "Unexporting GPIO number $LED_GPIO"
  echo $LED_GPIO >> "/sys/class/gpio/unexport"
fi
```

```python
import sys
from time import sleep
LED4_PATH = "/sys/class/gpio/gpio4/"
SYSFS_DIR = "/sys/class/gpio/"
LED_NUMBER = "4"

def writeLED ( filename, value, path=LED4_PATH ):
   "This function writes the value passed to the file in the path"
   fo = open( path + filename,"w")
   fo.write(value)
   fo.close()
   return

print "Starting the GPIO LED4 Python script"
if len(sys.argv)!=2:
   print "There is an incorrect number of arguments"
   print "  usage is:  pythonLED.py command"
   print "  where command is one of setup, on, off, status, or close"
   sys.exit(2)
if sys.argv[1]=="on":
   print "Turning the LED on"
   writeLED (filename="value", value="1")
elif sys.argv[1]=="off":
   print "Turning the LED off"
   writeLED (filename="value", value="0")
elif sys.argv[1]=="setup":
   print "Setting up the LED GPIO"
   writeLED (filename="export", value=LED_NUMBER, path=SYSFS_DIR)
   sleep(0.1);
   writeLED (filename="direction", value="out")
elif sys.argv[1]=="close":
   print "Closing down the LED GPIO"
   writeLED (filename="unexport", value=LED_NUMBER, path=SYSFS_DIR)
elif sys.argv[1]=="status":
   print "Getting the LED state value"
   fo = open( LED4_PATH + "value", "r")
   print fo.read()
   fo.close()
else:
   print "Invalid Command!"
print "End of Python script"
```

C Program

```c
#define GPIO_NUMBER "4"
#define GPIO4_PATH "/sys/class/gpio/gpio4/"
#define GPIO_SYSFS "/sys/class/gpio/"

void writeGPIO(char filename[], char value[]){
   FILE* fp;                             // create a file pointer fp
   fp = fopen(filename, "w+");           // open file for writing
   fprintf(fp, "%s", value);             // send the value to the file
   fclose(fp);                           // close the file using fp
}

int main(int argc, char* argv[]){
   if(argc!=2){                          // program name is argument 1
      printf("Usage is makeLEDC and one of:\n");
      printf("   setup, on, off, status, or close\n");
      printf(" e.g. makeLEDC on\n");
      return 2;                          // invalid number of arguments
   }
   printf("Starting the makeLED program\n");
   if(strcmp(argv[1],"setup")==0){
      printf("Setting up the LED on the GPIO\n");
      writeGPIO(GPIO_SYSFS "export", GPIO_NUMBER);
      usleep(100000);                    // sleep for 100ms
      writeGPIO(GPIO4_PATH "direction", "out");
   }
   else if(strcmp(argv[1],"close")==0){
      printf("Closing the LED on the GPIO\n");
      writeGPIO(GPIO_SYSFS "unexport", GPIO_NUMBER);
   }
```

```c
   else if(strcmp(argv[1],"on")==0){
      printf("Turning the LED on\n");
      writeGPIO(GPIO4_PATH "value", "1");
   }
   else if (strcmp(argv[1],"off")==0){
      printf("Turning the LED off\n");
      writeGPIO(GPIO4_PATH "value", "0");
   }
   else if (strcmp(argv[1],"status")==0){
      FILE* fp;       // see writeGPIO function above for description
      char line[80], fullFilename[100];
      sprintf(fullFilename, GPIO4_PATH "/value");
      fp = fopen(fullFilename, "rt");          // reading text this time
      while (fgets(line, 80, fp) != NULL){
         printf("The state of the LED is %s", line);
      }
      fclose(fp);
   }
   else{
      printf("Invalid command!\n");
   }
   printf("Finished the makeLED Program\n");
   return 0;
}
```

Use Rpi Library

- https://sourceforge.net/projects/raspberry-gpio-python/
- Note: Current release does not support SPI, I2C, 1-wire or serial functionality on the RPi yet

```python
import RPi.GPIO as GPIO
from time import sleep

ledPin = 4                     # GPIO Pin Number, where LED is connected

GPIO.setmode(GPIO.BCM)         # Broadcom pin-numbering scheme
GPIO.setup(ledPin, GPIO.OUT)   # LED pin set as output

GPIO.output(ledPin, GPIO.HIGH) # Turn the LED on
sleep(1)                       # Sleep for 1 sec
GPIO.output(ledPin, GPIO.LOW)  # Turn the LED off
```

Use gpiozero Library

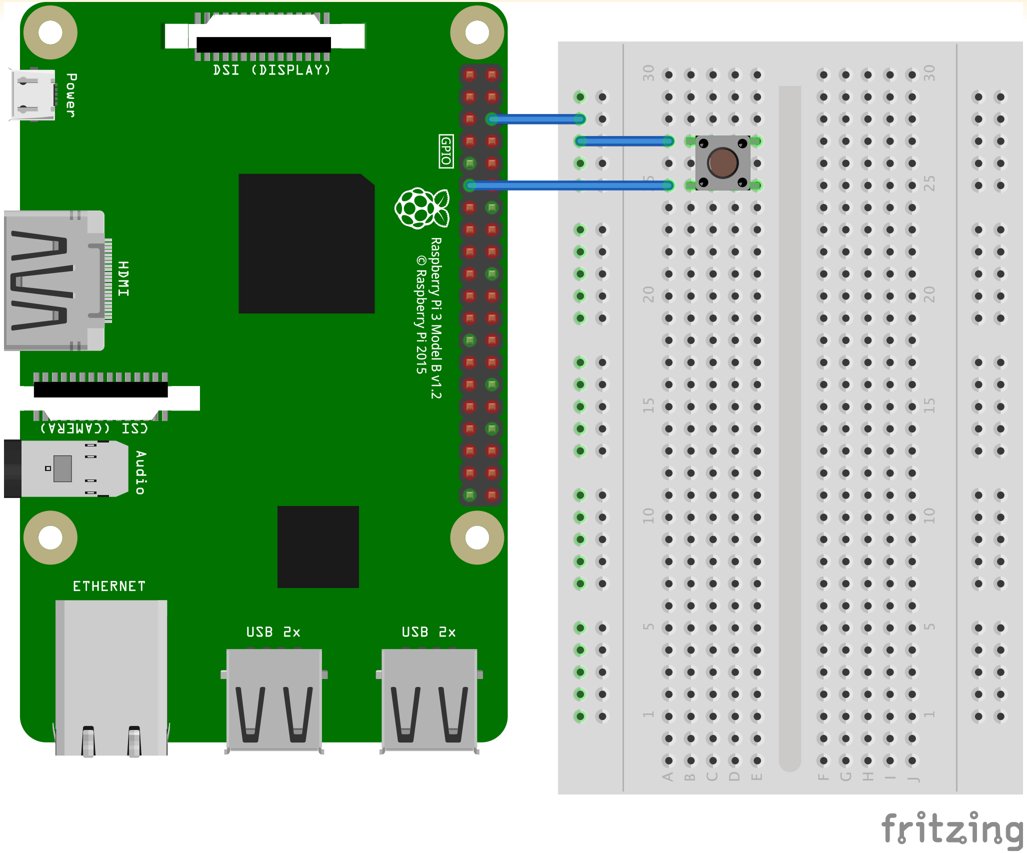
- https://gpiozero.readthedocs.io/en/stable/

```python
from gpiozero import LED
from time import sleep

led = LED(4)        # GPIO Pin Number
led.on()            # Turn on LED
sleep(1)            # Sleep for 1 sec
led.off()           # Turn off LED
```

GPIO as Input

- Push-button Switch



Reading GPIO

```
import RPi.GPIO as GPIO
import time

buttonPin=17     # GPIO Pin Number where Button Switch is connected

GPIO.setmode(GPIO.BCM)             # Broadcom pin-numbering scheme
GPIO.setup(buttonPin, GPIO.IN, pull_up_down=GPIO.PUD_UP)
# Button pin set as input

while True:                              # Monitor continuously
    input_state = GPIO.input(buttonPin)  # Get the input state
    if input_state == False:             # Check status
        print('Button Pressed')          # Print
        time.sleep(0.2)                  # Sleep before checking again
```

```
from gpiozero import Button
import time

button = Button(17) # GPIO Pin Number where Button Switch is connected

while True:                              # Monitor continuously
    if button.is_pressed:                # Check Status
        print("Button Pressed")          # Print
        time.sleep(0.2)                  # Sleep before checking again
```

GPIO Block Diagram

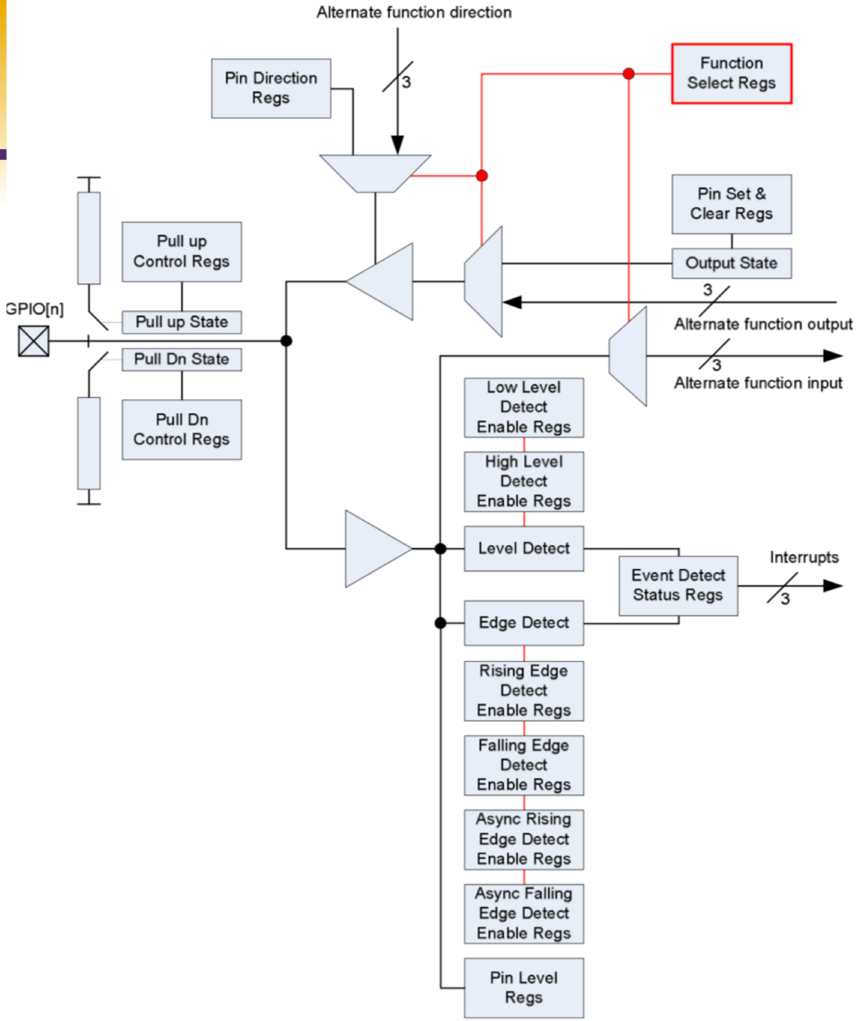
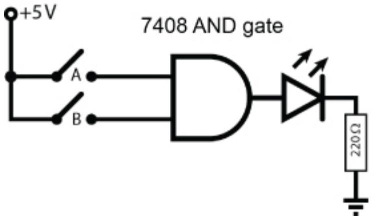


Figure 6-1 GPIO Block Diagram

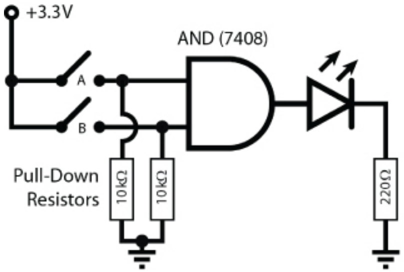
Pull-down and Pull-up Resistors

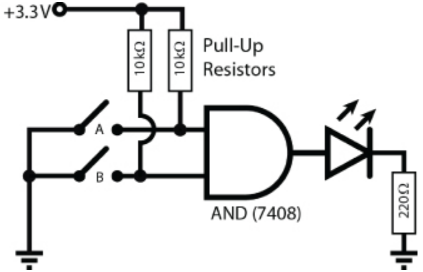
- Used to ensure that the switches do not create floating inputs
- Pull-down resistors:
  - used to guarantee that the inputs to the gate are low when the switches are open
- Pull-up resistors:
  - used to guarantee that the inputs are high when the switches are open.



7408 AND gate

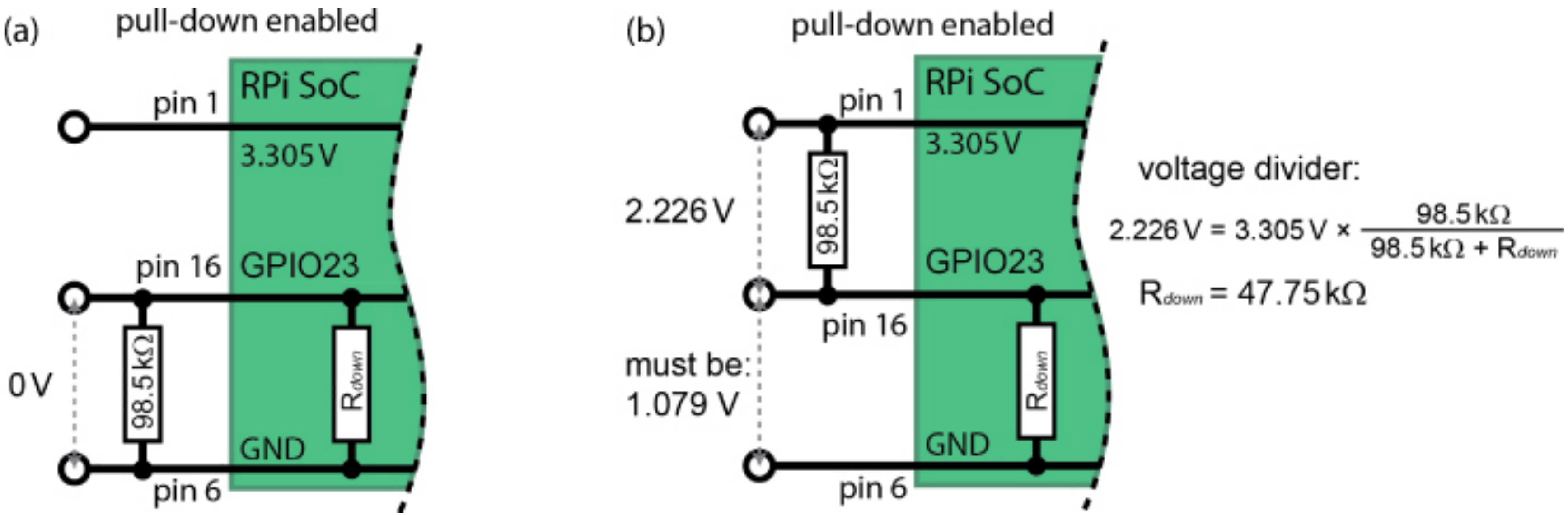
Switch A	Switch B	Required (A.B)	74LS08 TTL Output	74HC08 CMOS Output
Closed	Closed	On	On	On
Closed	Open	Off	**On**	**~Off**
Open	Closed	Off	**On**	**~Off**
Open	Open	Off	**On**	**~Off**





Calculate Internal Resistor Value

- Voltage Divider (pin 16 vs pin 7)



Internal pull-up/pull-down Resistors

- Can be configured using memory based GPIO control
- **cat /proc/iomem**
- 00000000-3b3fffff : System RAM
- ....
- 3f200000-3f2000b3 : /soc/gpio@7e200000
- ...

Address Mapped

/dev/mem

- *'/dev/mem'* is a character device file that is an image of the main memory of the computer.
- Byte addresses in */dev/mem* are interpreted as physical memory addresses.
- References to nonexistent locations cause errors to be returned.

Use /dev/mem directly

- **wget** http://www.lartmaker.nl/lartware/port/devmem2.c
- **gcc devmem2.c -o devmem2**
- **./devmem2**

Usage: ./devmem2 { address } [type [data]]

address : memory address to act upon

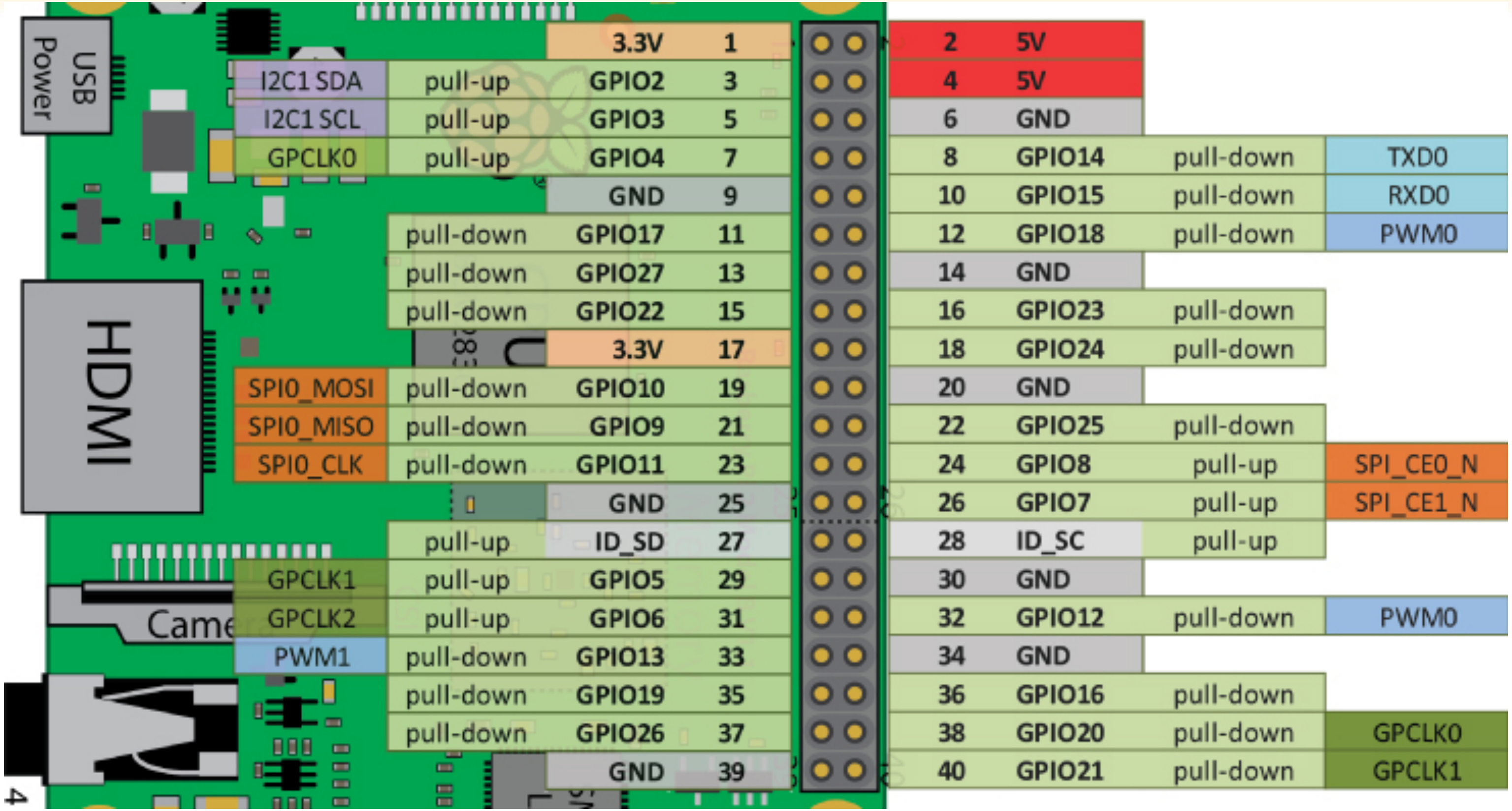
type : access operation type : [b]yte, [h]alfword, [w]ord

data : data to be written

GPIO Pull-up/down Register Control

- The **GPIO Pull-up/down Register** controls the actuation of the internal pull-up/down control line to ALL the GPIO pins. This register must be used in conjunction with the **2 GPPUDCLKn registers**.
- Note that it is **not possible to read back** the current Pull-up/down settings and so it is the users' responsibility to 'remember' which pull-up/downs are active. The reason for this is that GPIO pull-ups are maintained even in power-down mode when the core is off, when all register contents is lost.

Default Configuration of Pull-up/down Resistors



BCM 2837 Manual

- Table 6-1

0x 7E20 0094	GPPUD	GPIO Pin Pull-up/down Enable	32	R/W
0x 7E20 0098	GPPUDCLK0	GPIO Pin Pull-up/down Enable Clock 0	32	R/W
0x 7E20 009C	GPPUDCLK1	GPIO Pin Pull-up/down Enable Clock 1	32	R/W

- Table 6-28

31-2	---	Unused	R	0
1-0	PUD	PUD - GPIO Pin Pull-up/down 00 = Off – disable pull-up/down 01 = Enable Pull Down control 10 = Enable Pull Up control 11 = Reserved *Use in conjunction with GPPUDCLK0/1/2	R/W	0

BCM 2837 Manual

Bit(s)	Field Name	Description	Type	Reset
(31-0)	PUDCLKn (n=0..31)	0 = No Effect 1 = Assert Clock on line *(n)* *Must be used in conjunction with GPPUD	R/W	0

Table 6-29 – GPIO Pull-up/down Clock Register 0

Bit(s)	Field Name	Description	Type	Reset
31-22	-	Reserved	R	0
21-0	PUDCLKn (n=32..53)	0 = No Effect 1 = Assert Clock on line *(n)* *Must be used in conjunction with GPPUD	R/W	0

Table 6-30 – GPIO Pull-up/down Clock Register 1

Control Pull-up/down (from BCM2837 manual)

- Write to GPPUD to set the required control signal (i.e. Pull-up or Pull-Down or neither to remove the current Pull-up/down)
- Wait 150 cycles – this provides the required set-up time for the control signal
- Write to GPPUDCLK0/1 to clock the control signal into the GPIO pads you wish to modify – NOTE only the pads which receive a clock will be modified, all others will retain their previous state.
- Wait 150 cycles – this provides the required hold time for the control signal
- Write to GPPUD to remove the control signal
- Write to GPPUDCLK0/1 to remove the clock

Pull Down Resistor is enabled

- Set bit 4 on the GPPUDCLK0 register, clear the GPPUD register, and then remove the clock control signal from GPPUDCLK0
  - GPIO4 is bit 4, which is 10000 in binary ($0x10_{16}$)
- Get the Value in GPIO 4
  - sudo su
  - cd /sys/class/gpio/
  - echo 4 > export
  - cd gpio4
  - cat value

Pull Down Resistor is enabled

- GPPUD Enable Pull-down
  - sudo /home/dsaha/myCode/devmem2 0x3F200094 w 0x01
- GPPUDCLK0 enable GPIO 4
  - sudo /home/dsaha/myCode/devmem2 0x3F200098 w 0x10
- GPPUD Disable Pull-down
  - sudo /home/dsaha/myCode/devmem2 0x3F200094 w 0x00
- GPPUDCLK0 disable Clk signal
  - sudo /home/dsaha/myCode/devmem2 0x3F200098 w 0x00
- cat value
  - 0

Pull up Configuration

- GPPUD Enable Pull-up
  - sudo /home/dsaha/myCode/devmem2 0x3F200094 w 0x02
- GPPUDCLK0 enable GPIO 4
  - sudo /home/dsaha/myCode/devmem2 0x3F200098 w 0x10
- GPPUD Disable Pull-up
  - sudo /home/dsaha/myCode/devmem2 0x3F200094 w 0x00
- GPPUDCLK0 disable Clk signal
  - sudo /home/dsaha/myCode/devmem2 0x3F200098 w 0x00
- cat value
  - 1

WiringPi

```
[dsaha@sahaPi:~/wiringPi $ gpio readall
 +-----+-----+---------+------+---+---Pi 3+--+---+------+---------+-----+-----+
 | BCM | wPi |   Name  | Mode | V | Physical | V | Mode | Name    | wPi | BCM |
 +-----+-----+---------+------+---+----++----+---+------+---------+-----+-----+
 |     |     |    3.3v |      |   |  1 || 2  |   |      | 5v      |     |     |
 |   2 |   8 |   SDA.1 | ALT0 | 1 |  3 || 4  |   |      | 5v      |     |     |
 |   3 |   9 |   SCL.1 | ALT0 | 1 |  5 || 6  |   |      | 0v      |     |     |
 |   4 |   7 | GPIO. 7 |   IN | 1 |  7 || 8  | 0 | IN   | TxD     | 15  | 14  |
 |     |     |      0v |      |   |  9 || 10 | 1 | IN   | RxD     | 16  | 15  |
 |  17 |   0 | GPIO. 0 |   IN | 0 | 11 || 12 | 0 | IN   | GPIO. 1 | 1   | 18  |
 |  27 |   2 | GPIO. 2 |   IN | 0 | 13 || 14 |   |      | 0v      |     |     |
 |  22 |   3 | GPIO. 3 |   IN | 0 | 15 || 16 | 0 | IN   | GPIO. 4 | 4   | 23  |
 |     |     |    3.3v |      |   | 17 || 18 | 0 | IN   | GPIO. 5 | 5   | 24  |
 |  10 |  12 |    MOSI |   IN | 0 | 19 || 20 |   |      | 0v      |     |     |
 |   9 |  13 |    MISO |   IN | 0 | 21 || 22 | 0 | IN   | GPIO. 6 | 6   | 25  |
 |  11 |  14 |    SCLK |   IN | 0 | 23 || 24 | 1 | IN   | CE0     | 10  | 8   |
 |     |     |      0v |      |   | 25 || 26 | 1 | IN   | CE1     | 11  | 7   |
 |   0 |  30 |   SDA.0 |   IN | 1 | 27 || 28 | 1 | IN   | SCL.0   | 31  | 1   |
 |   5 |  21 | GPIO.21 |   IN | 1 | 29 || 30 |   |      | 0v      |     |     |
 |   6 |  22 | GPIO.22 |   IN | 1 | 31 || 32 | 0 | IN   | GPIO.26 | 26  | 12  |
 |  13 |  23 | GPIO.23 |   IN | 0 | 33 || 34 |   |      | 0v      |     |     |
 |  19 |  24 | GPIO.24 |   IN | 0 | 35 || 36 | 0 | IN   | GPIO.27 | 27  | 16  |
 |  26 |  25 | GPIO.25 |   IN | 0 | 37 || 38 | 0 | IN   | GPIO.28 | 28  | 20  |
 |     |     |      0v |      |   | 39 || 40 | 0 | IN   | GPIO.29 | 29  | 21  |
 +-----+-----+---------+------+---+----++----+---+------+---------+-----+-----+
 | BCM | wPi |   Name  | Mode | V | Physical | V | Mode | Name    | wPi | BCM |
 +-----+-----+---------+------+---+---Pi 3+--+---+------+---------+-----+-----+
```

The gpio Command (WiringPi)

Command	Example	Description
gpio read <pin>	`gpio read 2`	Read a binary value from a WPi numbered pin. Use `-g` to use GPIO numbers. Example reads button state.
gpio write <pin> <value>	`gpio write 0 1`	Set a binary value on a WPi numbered pin. Example sets the LED on. <value> is either `1` or `0`.
gpio mode <pin> <mode>	`gpio mode 1 pwm`	Example sets the h/w PWM outputs on (WPi pin 1, GPIO 18). <mode> is one of `in`, `out`, `pwm`, `up`, `down`, or `tri`.
gpio pwm <pin> <value>	`gpio pwm 1 256`	Set a PWM value on the PWM output pin.
gpio clock <pin> <freq>	`gpio mode 7 clock` `gpio clock 7 2400000`	Sets up a clock signal (i.e., 50% duty cycle) on a pin with general purpose clock capabilities. The signal is derived by dividing the 19.2 MHz clock, so integer divisors of this frequency are optimum.
gpio readall	`gpio readall`	Reads all of the pins and prints a chart of their numbers, modes, and values.
gpio unexportall	`gpio unexportall`	Unexport all GPIO sysfs entries.
gpio export <gpio> <mode>	`gpio export 4 input`	Exports a pin using the GPIO numbering. <mode> is either `in/input` or `out/output`.
gpio exports	`gpio exports`	Lists all sysfs exported pins.
gpio unexport <gpio>	`gpio unexport 4`	Unexport a pin using the GPIO numbering.
gpio edge <pin> <mode>	`gpio edge 4 rising`	Enables the GPIO pin for edge interrupt triggering. <mode> is one of `rising`, `falling`, `both`, or `none`.
gpio wfi <pin> <mode>	`gpio wfi 2 both`	Wait on a state change. <mode> is one of `rising`, `falling`, or `both`.
gpio pwm-bal	`gpio pwm-bal`	Set the PWM mode to be balanced.
gpio pwm-ms	`gpio pwm-ms`	Set the PWM mode to be mark-space.
gpio pwmr <range>	`gpio pwmr 512`	Set the PWM range. <range> is not limited - typically less than 4,095.
gpio pwmc <divider>	`gpio pwmc 10`	Set the PWM clock divider. PWM frequency = 19.2 MHz / (range × divider).

wiringPi Functions

Return	Function Call	Description
Setup		
int	`wiringPiSetup(void)`	Initializes wiringPi. Must be used with root privileges. Returns 0 if successful.
int	`wiringPiSetupGpio(void)`	Same as above. Uses GPIO rather than WPi numbers. Must use root privileges.
int	`wiringPiSetupSys(void)` ← use one	Uses sysfs. Root not required if udev rules in place (see end of chapter). You must manually export pins. Slower, as memory-mapping does not work.
int	`wiringPiSetupPhys(void)`	Uses the physical pin numbering on the RPi.
int	`piBoardRev(void)`	Returns the board version (0=n/a, 1=A, 2=B, 3=B+, 4=compute, 5= A+, 6=RPi 2)
GPIO Control		
void	`pinMode(int pin, int mode)`	Sets the pin to be one of `INPUT`, `OUTPUT`, or `PWM_OUTPUT` (on the hardware PWM pins only). Not available if `wiringPiSetupSys()` is used.
int	`getAlt(int pin)`	Get the ALT mode for a pin.
void	`pinModeAlt(int pin, int mode)`	Set the ALT mode for a pin.
void	`digitalWrite(int pin, int value)`	Sets the pin to be one of `HIGH` (1) or `LOW` (0). The pin mode must be OUTPUT.
void	`digitalWriteByte(int value)`	Fast parallel write of 8 bits to the first eight GPIO pins.
int	`digitalRead(int pin)`	Returns the input on a pin and returns either `HIGH` (1) or `LOW` (0).
void	`pullUpDnControl(int pin, int pud)`	Sets the pull-up or pull-down resistor type to be one of `PUD_OFF` (none), `PUD_UP` (pull up), or `PUD_DOWN` (pull down). Not available in sysfs mode.
PWM and Timers		
void	`pwmWrite(int pin, int value)`	Sets the PWM output for a h/w PWM pin. Not available in sysfs mode.
void	`pwmSetMode(int mode)`	RPi PWM has two modes `PWM_MODE_BAL` (balanced) or `PWM_MODE_MS` (mark-space ratio). MS mode is most commonly used. BAL affects PWM frequency.
void	`pwmSetRange(unsigned int range)`	Sets the PWM range register. Valid values 2-4,095. Range and divisor affect frequency.
void	`pwmSetClock(int divisor)`	Sets the PWM clock divisor. PWM frequency = 19.2MHz / (divisor × range)
void	`pwmToneWrite(int pin, int freq)`	Set the frequency using the hardware PWM pin.
void	`gpioClockSet(int pin, int freq)`	Sets the frequency on a GPIO clock pin.
Interrupts		
int	`waitForInterrupt(int pin,int timeout)`	Waits for an interrupt. Timeout is set in ms where -1 is none. You must initialize the pin from outside the program, or using `system()` and the `gpio` command.
int	`wiringPiISR(int pin, int edgeType, void (*function)(void));`	Set a callback function (ISR) to be called on an interrupt event, which is one of `INT_EDGE_FALLING`, `INT_EDGE_RISING`, `INT_EDGE_BOTH`, or `INT_EDGE_SETUP`.
int	`piHiPri(int priority)`	Sets the priority of the program (0 to 99) allowing for a reduction in latency. Must be run as root. Returns 0 for success and -1 otherwise.
Helper Functions		
int	`wpiPinToGpio(int wPiPin)`	Converts WPi numbers into GPIO numbers.
int	`physPinToGpio(int physPin)`	Converts physical pin numbers to GPIO numbers.
uint32_t	`millis(void)`	Returns the number of milliseconds since a setup function was called.
uint32_t	`micros(void)`	Returns the number of microseconds since a setup function was called.
void	`delay(unsigned int t_ms)`	Delays for `t_ms` milliseconds. Delay is non-blocking and will exhibit latency.
void	`delayMicroseconds(unsigned int t_us)`	Delays for a number of microseconds.

Table information gleaned from `wiringPi.h` and `wiringPi.c`, which are distributed in the `/wiringPi/` directory of the wiringPi repository

wiringPi Blink LED

```
#include <wiringPi.h>
int main (void)
{
  wiringPiSetup () ;
  pinMode (0, OUTPUT) ;
  for (;;)
  {
    digitalWrite (0, HIGH) ; delay (500) ;
    digitalWrite (0,  LOW) ; delay (500) ;
  }
  return 0 ;
}
```

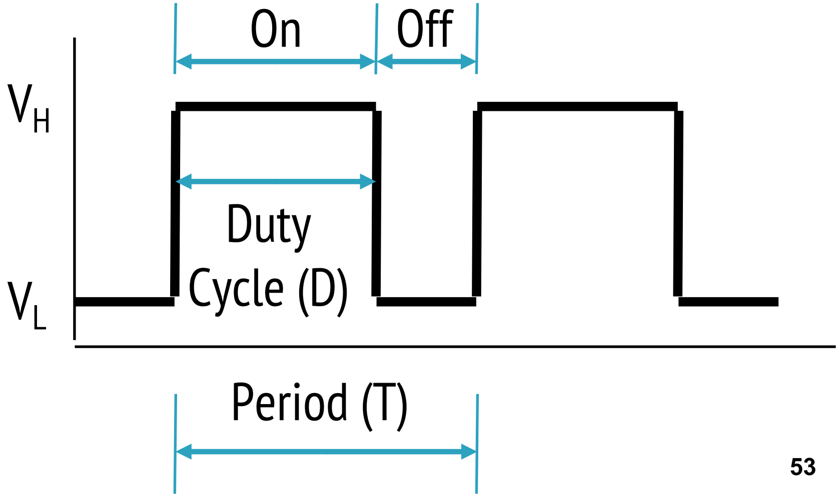
http://wiringpi.com/examples/blink/

Analog Output

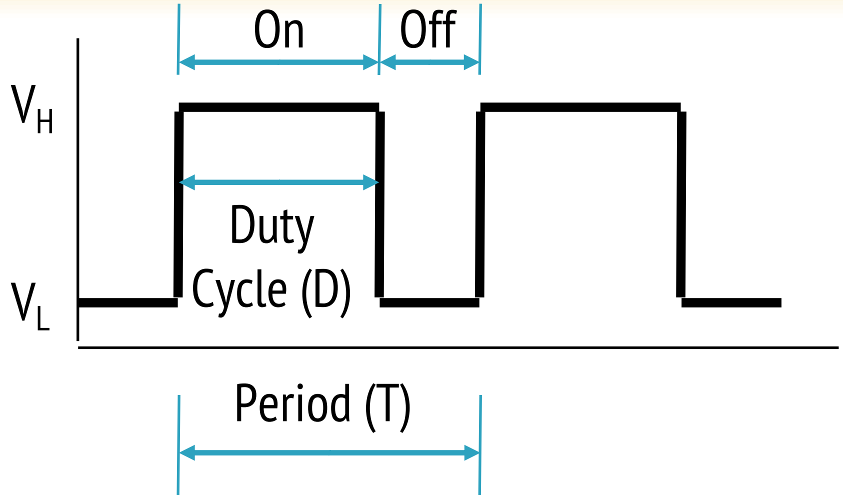
- Pulse Width Modulation (PWM)
  - Technique that conforms a signal width, generally pulses
  - The general purpose is to control power delivery
  - The on-off behavior changes the average power of signal
  - Output signal alternates between on and off within a specified period.
  - If signal toggles between on and off quicker than the load, then the load is not affected by the toggling

PWM – Duty Cycle

- A measure of the time the modulated signal is in its "high" state
- Generally recorded as the percentage of the signal period where the signal is considered on



Duty Cycle Formulation



Duty Cycle is determined by:

$$Duty\ Cycle = \frac{On\ Time}{Period} \times 100\%$$

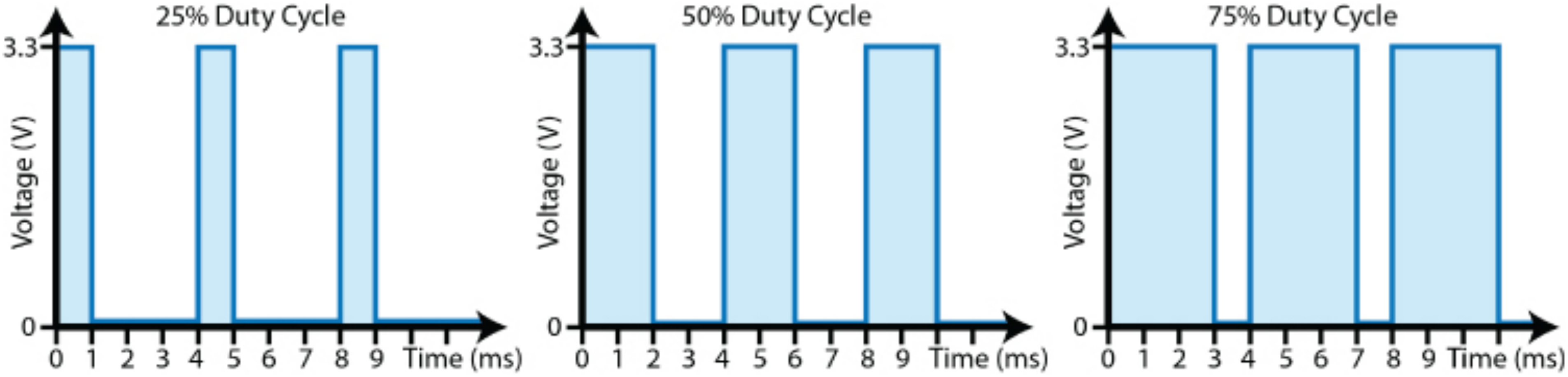
*Average value of a signal can be found as:

$$\bar{y} = \frac{1}{T}\int_0^T f(t)dt$$

$$V_{avg} = D \cdot V_H + (1 - D) \cdot V_L$$

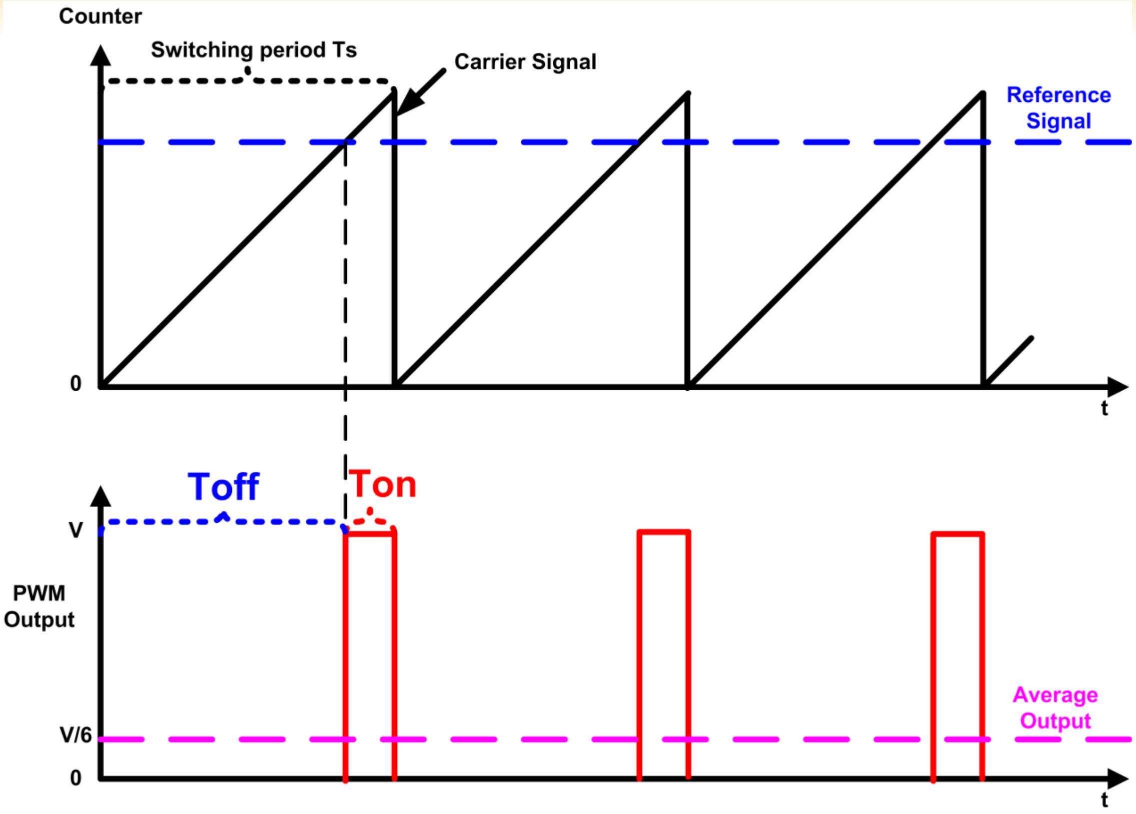
*In general analysis, V_L is taken as zero volts for simplicity.

PWM Duty Cycle



PWM Mode

- Counter counts up to the range provided
- When the counter value is higher than set value, output is high



PWM Duty Cycle Calculation

- The PWM device on the RPi is clocked at a fixed base-clock frequency of 19.2 MHz
- Integer divisor and range values are used to tailor the PWM frequency according to application requirements
- $f_{PWM} = 19.2MHz/(divisor \times range)$
- If f_{PWM} is 10KHz (0.01MHz), and range is 128,
  - $divisor = \frac{19.2MHz}{f_{PWM} \times range} = 15$

PWM0 and PWM1 Map

	PWM0	PWM1
GPIO 12	Alt Fun 0	-
GPIO 13	-	Alt Fun 0
GPIO 18	Alt Fun 5	-
GPIO 19	-	Alt Fun 5
GPIO 40	Alt Fun 0	-
GPIO 41	-	Alt Fun 0
GPIO 45	-	Alt Fun 0
GPIO 52	Alt Fun 1	-
GPIO 53	-	Alt Fun 1

9.6 Control and Status Registers

PWM Address Map			
Address Offset	**Register Name**	**Description**	**Size**
0x0	CTL	PWM Control	32
0x4	STA	PWM Status	32
0x8	DMAC	PWM DMA Configuration	32
0x10	RNG1	PWM Channel 1 Range	32
0x14	DAT1	PWM Channel 1 Data	32
0x18	FIF1	PWM FIFO Input	32
0x20	RNG2	PWM Channel 2 Range	32
0x24	DAT2	PWM Channel 2 Data	32

exploringPi/chp06/wiringPi/pwm.cpp

```
#include <iostream>
#include <wiringPi.h>
using namespace std;
#define PWM0       12                        // this is physical Pin 12
#define PWM1       33                        // only on the RPi B+/A+/2/3
int main() {                                 // must be run as root
   wiringPiSetupPhys();                      // use the physical pin numbers
   pinMode(PWM0, PWM_OUTPUT);                // use the RPi PWM output
   pinMode(PWM1, PWM_OUTPUT);                // only on recent RPis
   // Setting PWM frequency to be 10kHz with a full range of 128 steps
   // PWM frequency = 19.2 MHz / (divisor * range)
   // 10000 = 19200000 / (divisor * 128) => divisor = 15.0 = 15
   pwmSetMode(PWM_MODE_MS);                  // use a fixed frequency
   pwmSetRange(128);                         // range is 0-128
   pwmSetClock(15);                          // gives a precise 10kHz signal
   cout << "The PWM Output is enabled" << endl;
   pwmWrite(PWM0, 32);                       // duty cycle of 25% (32/128)
   pwmWrite(PWM1, 64);                       // duty cycle of 50% (64/128)
   return 0;                                 // PWM output stays on after exit
}
```