OSU Mechanical Engineering

Smart Products Laboratory

Digital Communication | Four Prelab

ME Course Number
Spring 2019

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1 Overview

In lab four, the fundamentals of digital communications are demonstrated through implementing the commonly used I2C protocol. In the part one of this lab you will investigate the signal properties of the protocol.

2 Background

The information below should provide a basic introduction to the concepts.

2.1 Overview

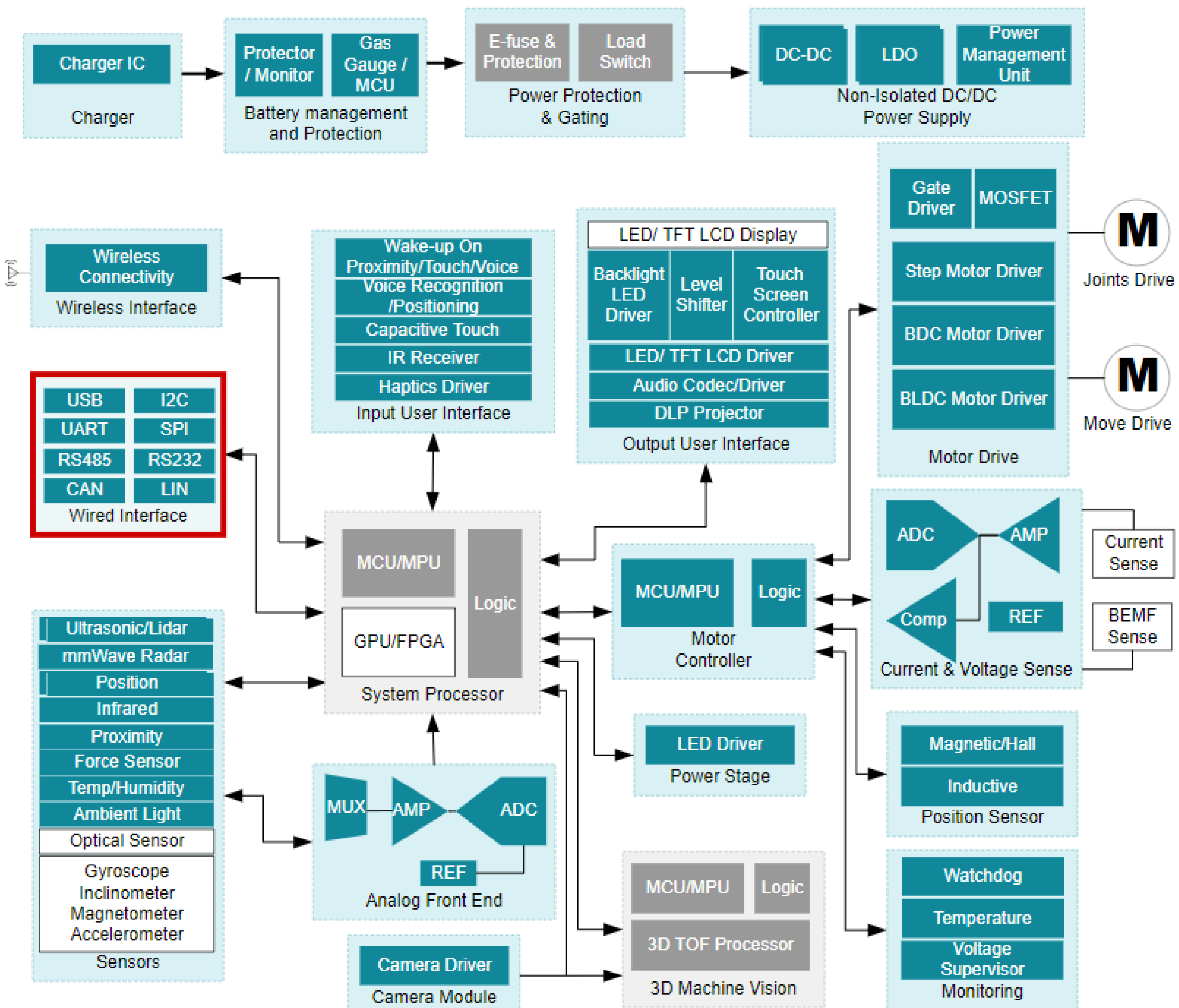
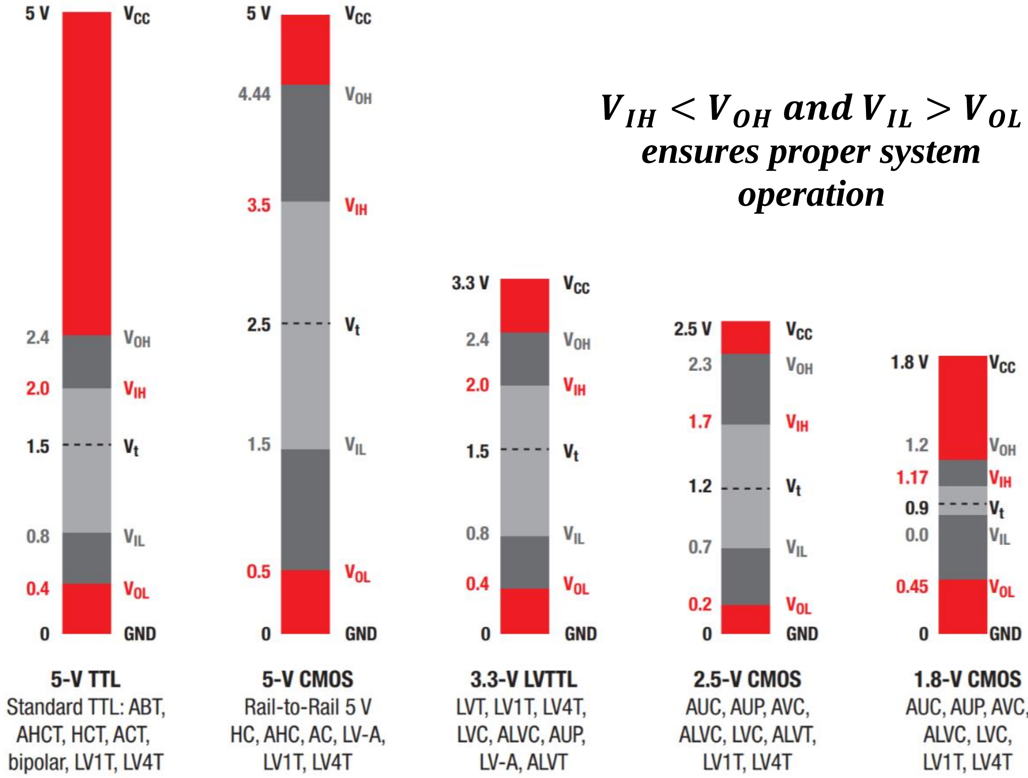


Figure 1 – Example Humanoid Robot System

$V_{IH} < V_{OH}$ and $V_{IL} > V_{OL}$ ensures proper system operation



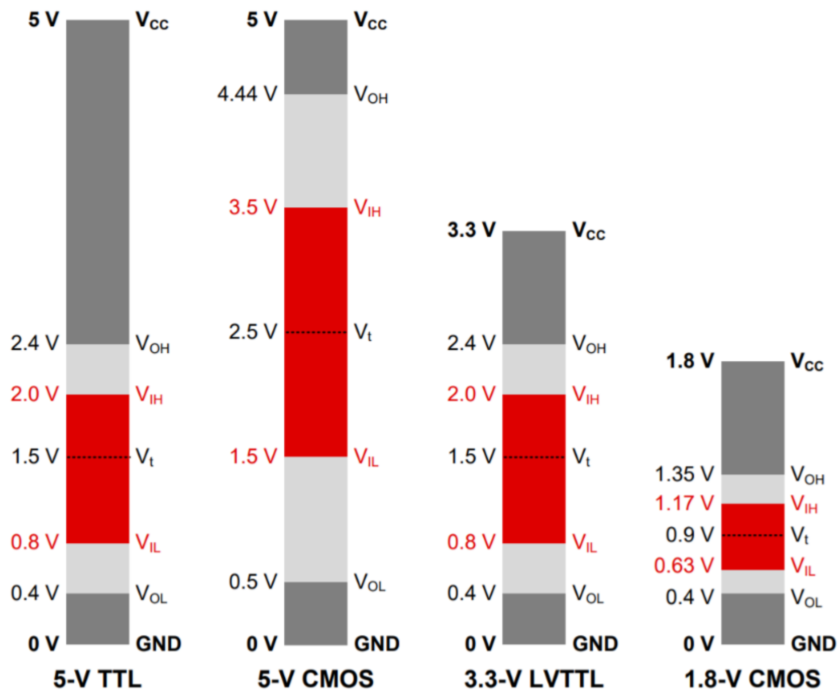


Figure 2 – Logic Level Thresholds

SPI bus (Serial Peripheral Interface) hardware overview

- In SPI interfaces the master can connect to one or more slave devices
- In cases when multiple slave devices are used, the master will use multiple chip select ($\overline{CS}$) lines

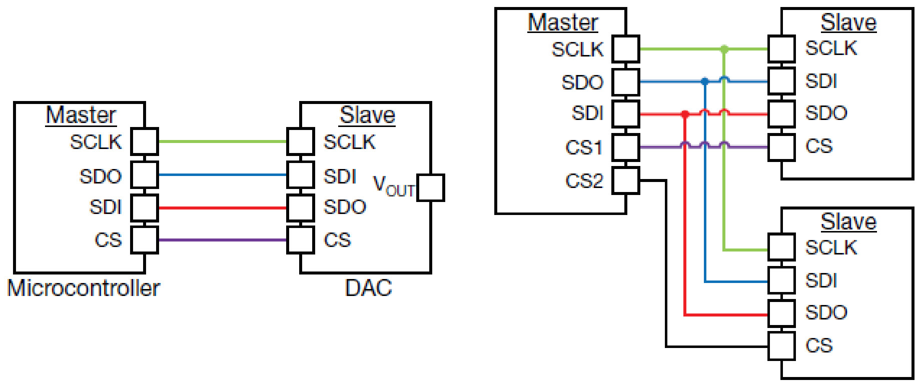


Figure 69: SPI master and slave configurations

Data and control lines

$\overline{CS}$ (chip select) = sometimes referred to as slave select. $\overline{CS}$ is driven by the master and arbitrates over the SPI bus. When driven low, the SPI bus is active.

SDO/SDI (serial data in and serial data out) = these names describe data flow for the device. The system names describe the data flow relationship between the master and slave. System names: MOSI = Master Out Slave In and MISO = Master In Slave Out. Example: SDO on a slave is MISO in the system and SDI is MOSI in the system.

SCLK (serial clock) = this is a square wave driven by the SPI master. Data on SDO and SDI have relative timing to the SCLK signal which controls the latching of the data on the SPI bus.

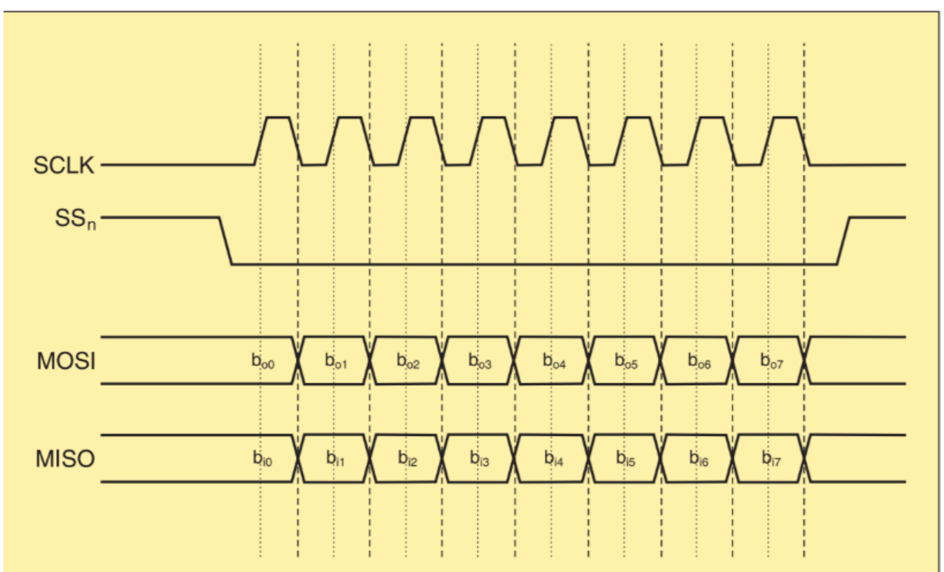


Figure 3 – SPI overview

I^2C bus (Inter-Integrated Circuit) hardware overview

- On I^2C buses the master can connect to one or more slave devices
- The slave is selected by its I2C address. This allows one controller to connect to many slaves on the two-wire bus.

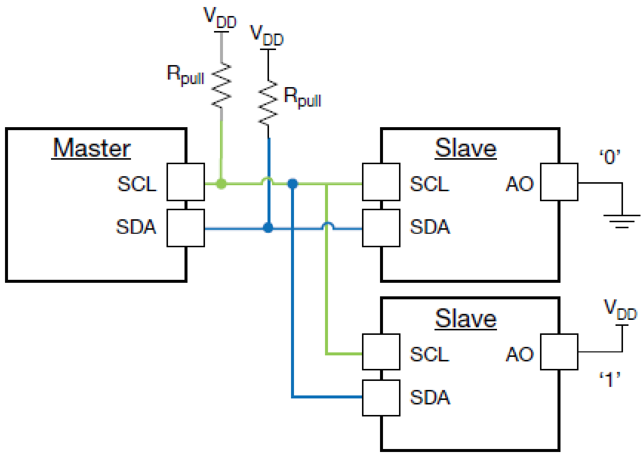


Figure 74: : I^2C master and slave hardware connections

Data and control lines

SCL (serial clock) = this is a square wave driven by the master that controls how fast data is sent and when data is latched to the slave device(s)

SDA (serial data) = both master and slave place data on this line in sync with the clock pulses in a half-duplex fashion. Data on this line includes address, control, and communication data.

Master Controls SDA Line

Slave Controls SDA Line

<u>Write to One Register in a Device</u>

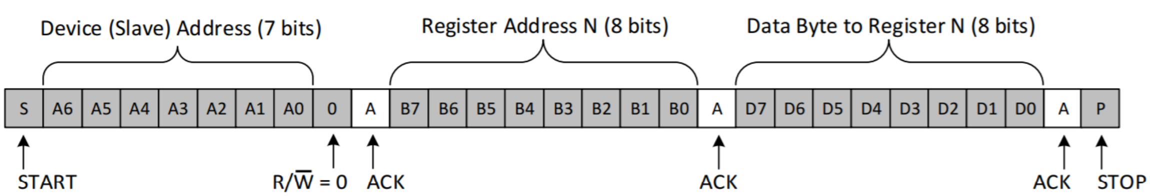


Figure 8. Example I^2C Write to Slave Device's Register

<u>Read From One Register in a Device</u>

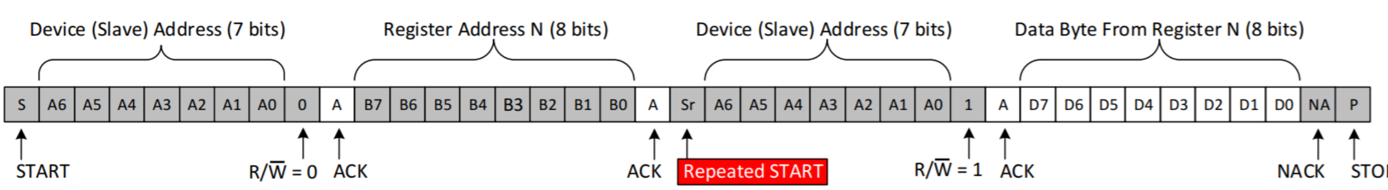


Figure 9. Example I^2C Read from Slave Device's Register

Figure 4 – I2C overview

3 References & Resources

3.1 References

The following references may be helpful to complete the next lab.

1. http://www.ti.com/solution/service_robots?variantid=11713&subsystemid=19430
2. https://e2e.ti.com/blogs_/b/analogwire/archive/2017/11/02/how-to-reduce-the-number-of-i-o-pins-with-a-switch-matrix-module
3. http://wiringpi.com/reference/i2c-library/
4. http://www.ni.com/tutorial/6552/en/
5. https://chromium.googlesource.com/chromium/src/+/HEAD/styleguide/c++/c++-dos-and-donts.md
6. https://google.github.io/styleguide/cppguide.html
7. http://alanclements.org/clocks%20and%20timing.html
8. http://www.physics.ohio-state.edu/~hughes/cdf_osu/xft/documents/layout.pdf

4 Pre-lab

This section should be worked on prior to arriving in lab.

4.1 Items needed to complete lab two

Make sure you read this entire lab.

5 Laboratory

Complete the exercises and save all code and follow the procedure to turn in your work.

5.1 Requirements & Hardware

1. We will be using an impedance analyzer to observe the I2C signal
    - Info: https://store.digilentinc.com/pmod-ia-impedance-analyzer/
    - More Info: https://reference.digilentinc.com/reference/pmod/pmodia/reference-manual
2. Bread Board
3. Oscilloscope
4. Wires
5. Resistors
6. Capacitors
7. USB memory stick.

5.2 Procedure

1. Download the example executable
2. Gather the needed materials.
3. Build the different circuits.
4. For each circuit
    a. Use the digital probes and capture the signals using the trigger functions and save the signals with the screen capture function on the oscilloscope.
    b. Use the analog probes and capture the signals using the trigger functions and save the signals with the screen capture function on the oscilloscope.

5. Save all data, solutions, and results. They will be turned in with the next lab.

5.3 Exercises

1. Build the first circuit, using any resistance over 250 for the resistors R. Hookup the digital probe, to the SCL and SDA line. Try to capture the bus data using the bus analysis on the oscilloscope. Now Hookup the analog probes to the SCL and SDA lines. Use the trigger to capture the signals. Calculate:
   a. The clock frequency
   b. The time constant for rising edge data line.
   c. The time constant for falling edge data line.
   d. The overshoot if any for the rising and falling line.
2. Build the second circuit using a 0.1 uf capacitor for C . Hookup the digital probe, to the SCL and SDA line. Try to capture the bus data using the bus analysis on the oscilloscope. Now Hookup the analog probes to the SCL and SDA lines. Use the trigger to capture the signals. Calculate and comment on:
   a. The time constant for the data line falling or rising. What happens to the program when you run it?
   b. Try using different resistance and capacitors in series or parallel to see how it effects the signal lines.

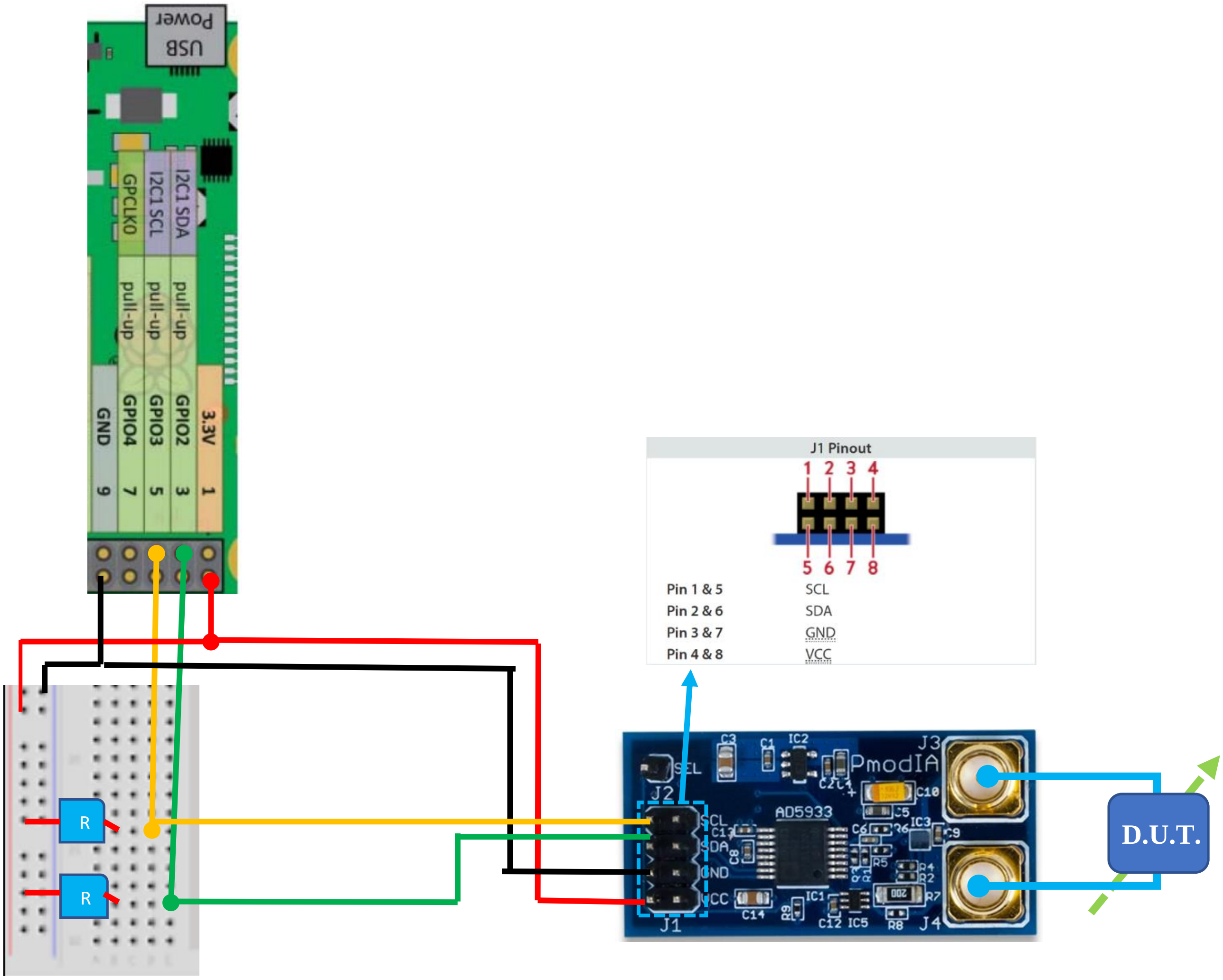


Figure 5 – Circuit 1 Setup

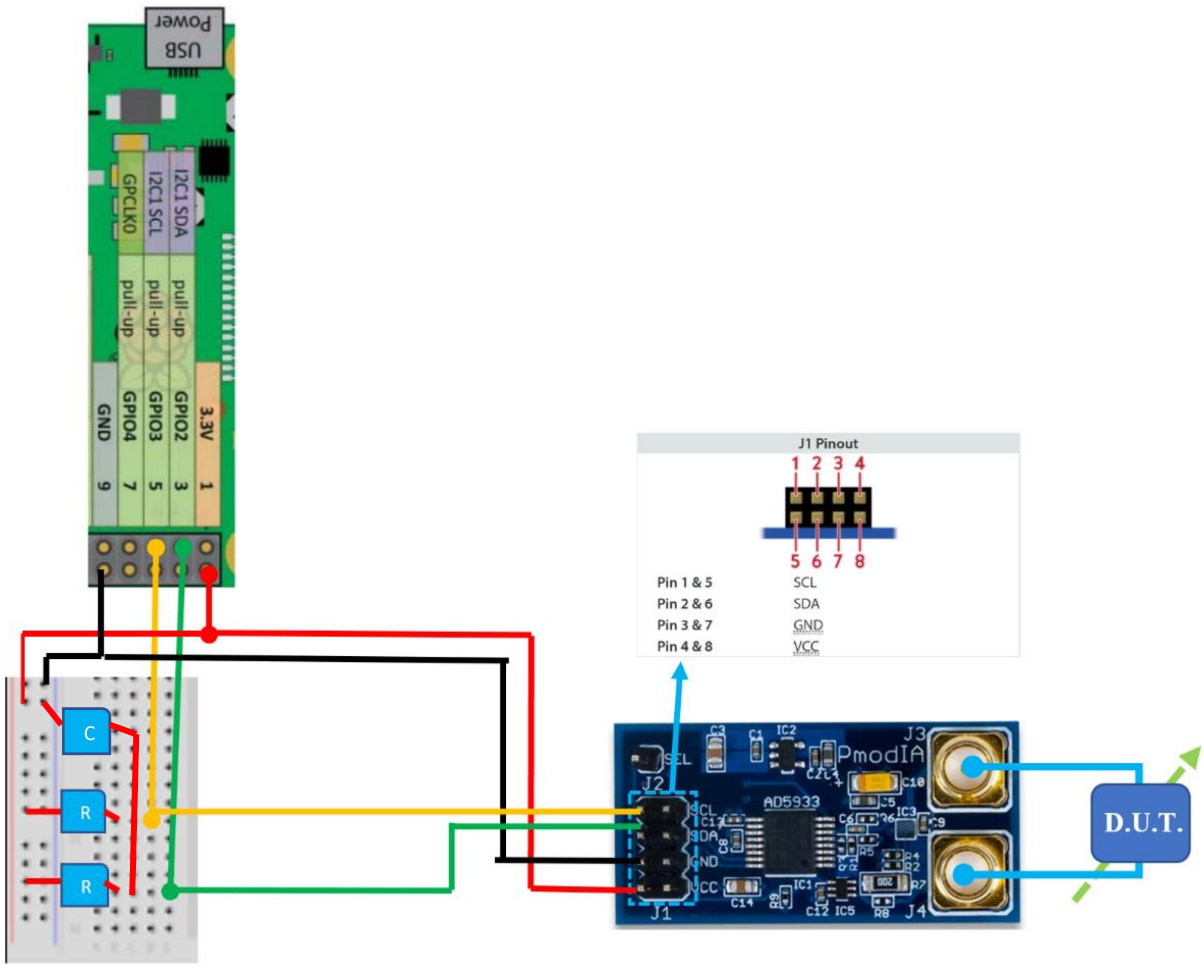


Figure 6 – Circuit 2 Setup

Appendix

Understanding the Data Sheet – Example: I2C Temperature Sensor (MCP9800)

This example will show you how to interpret a data sheet for a wired-communication based peripheral using a I2C to read from a temperature sensor integrated chip. The data sheet for this example can be found at:

- http://ww1.microchip.com/downloads/en/DeviceDoc/21909d.pdf

2-Wire High-Accuracy Temperature Sensor

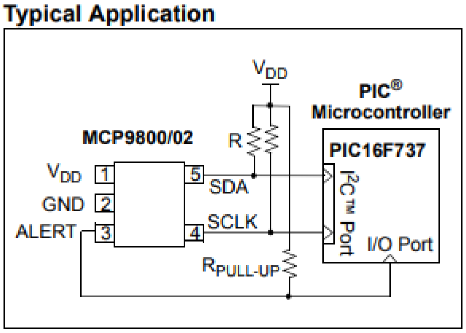
Features:

- Temperature-to-Digital Converter
- Accuracy with 12-bit Resolution:
  - ±0.5°C (typical) at +25°C
  - ±1°C (maximum) from -10°C to +85°C
  - ±2°C (maximum) from -10°C to +125°C
  - ±3°C (maximum) from -55°C to +125°C
- User-selectable Resolution: 9-12 bit
- Operating Voltage Range: 2.7V to 5.5V
- 2-wire Interface: I²C™/SMBus Compatible
- Operating Current: 200 µA (typical)
- Shutdown Current: 1 µA (maximum)
- Power-saving One-shot Temperature Measurement
- Available Packages: SOT-23-5, MSOP-8, SOIC-8

Typical Applications:

- Personal Computers and Servers
- Hard Disk Drives and Other PC Peripherals
- Entertainment Systems
- Office Equipment
- Data Communication Equipment
- Mobile Phones
- General Purpose Temperature Monitoring

Typical Application



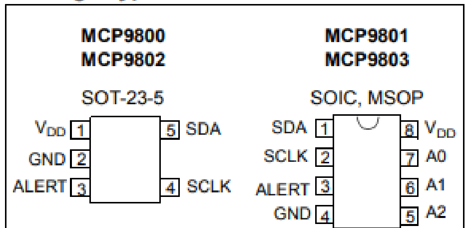
Description:

Microchip Technology Inc.'s MCP9800/1/2/3 family of digital temperature sensors converts temperatures between -55°C and +125°C to a digital word. They provide an accuracy of ±1°C (maximum) from -10°C to +85°C.

The MCP9800/1/2/3 family comes with user-programmable registers that provide flexibility for temperature sensing applications. The register settings allow user-selectable 9-bit to 12-bit temperature measurement resolution, configuration of the power-saving Shutdown and One-shot (single conversion on command while in Shutdown) modes and the specification of both temperature alert output and hysteresis limits. When the temperature changes beyond the specified limits, the MCP9800/1/2/3 outputs an alert signal. The user has the option of setting the alert output signal polarity as an active-low or active-high comparator output for thermostat operation, or as temperature event interrupt output for microprocessor-based systems.

This sensor has an industry standard 2-wire, I²C™/SMBus compatible serial interface, allowing up to eight devices to be controlled in a single serial bus. These features make the MCP9800/1/2/3 ideal for sophisticated multi-zone temperature-monitoring applications.

Package Types



MCP9802/03: Serial Bus time-out 35 ms (typ.)
MCP9800/01: No Serial Bus time-out

Most of the time, the most important information is on the front page. So, what to look for:

Operating Ranges: How am I to power the device, how much power will it consume, is the current and voltage compatible with my main MCU

Communication Options: How am I to communicate with the device: I2C, SPI, CAN, Analog…

Package types: how am I building the circuit around the device. Two general options: through-hole and surface mount. These are surface mounts.

MCP9800/1/2/3

More details on the electrical characteristics tells you what the values of device's properties should be under both operating conditions and maximum conditions.

1.0 ELECTRICAL CHARACTERISTICS

Absolute Maximum Ratings †

V_{DD} 6.0V
Voltage at all Input/Output pins .....GND – 0.3V to 5.5V
Storage temperature .... -65°C to +150°C
Ambient temp. with power applied ..... -55°C to +125°C
Junction Temperature (T_J) .... 150°C
ESD protection on all pins (HBM:MM) ....(4 kV:400V)
Latch-Up Current at each pin .... ±200 mA

†Notice: Stresses above those listed under "Maximum ratings" may cause permanent damage to the device. This is a stress rating only and functional operation of the device at those or any other conditions above those indicated in the operational listings of this specification is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability.

DC CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated, V_{DD} = 2.7V to 5.5V, GND = Ground, and T_A = -55°C to +125°C.

Parameters	Sym	Min	Typ	Max	Unit	Conditions
Power Supply						
Operating Voltage Range	V_{DD}	2.7	—	5.5	V	
Operating Current	I_{DD}	—	200	400	µA	Continuous Operation
Shutdown Current	I_{SHDN}	—	0.1	1	µA	Shutdown mode
Power-on-Reset Threshold (POR)	V_{POR}	—	1.7	—	V	V_{DD} falling edge
Line Regulation	Δ°C/ΔV	—	0.2	—	°C/V	V_{DD} = 2.7V to 5.5V
Temperature Sensor Accuracy						
Accuracy with 12-bit Resolution:						
T_A = +25°C	T_{ACY}	—	±0.5	—	°C	V_{DD} = 3.3V
-10°C < $T_A \le$ +85°C	T_{ACY}	-1.0	—	+1.0	°C	V_{DD} = 3.3V
-10°C < $T_A \le$ +125°C	T_{ACY}	-2.0	—	+2.0	°C	V_{DD} = 3.3V
-55°C < $T_A \le$ +125°C	T_{ACY}	-3.0	—	+3.0	°C	V_{DD} = 3.3V
Internal ΣΔ ADC						
Conversion Time:						
9-bit Resolution	t_{CONV}	—	30	75	ms	33 samples/sec (typical)
10-bit Resolution	t_{CONV}	—	60	150	ms	17 samples/sec (typical)
11-bit Resolution	t_{CONV}	—	120	300	ms	8 samples/sec (typical)
12-bit Resolution	t_{CONV}	—	240	600	ms	4 samples/sec (typical)
Alert Output (Open-drain)						
High-level Current	I_{OH}	—	—	1	µA	V_{OH} = 5V
Low-level Voltage	V_{OL}	—	—	0.4	V	I_{OL} = 3 mA
Thermal Response						
Response Time	t_{RES}	—	1.4	—	s	Time to 63% (89°C) 27°C (Air) to 125°C (oil bath)

DIGITAL INPUT/OUTPUT PIN CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated, V_{DD} = 2.7V to 5.5V, GND = Ground and T_A = -55°C to +125°C.

Parameters	Sym	Min	Typ	Max	Units	Conditions
Serial Input/Output (SCLK, SDA, A0, A1, A2)						
Input						
High-level Voltage	V_{IH}	0.7 V_{DD}	—	—	V	
Low-level Voltage	V_{IL}	—	—	0.3 V_{DD}	V	
Input Current	I_{IN}	-1	—	+1	µA	
Output (SDA)						
Low-level Voltage	V_{OL}	—	—	0.4	V	I_{OL} = 3 mA
High-level Current	I_{OH}	—	—	1	µA	V_{OH} = 5V
Low-level Current	I_{OL}	6	—	—	mA	V_{OL} = 0.6V
Capacitance	C_{IN}	—	10	—	pF	
SDA and SCLK Inputs						
Hysteresis	V_{HYST}	0.05 V_{DD}	—	—	V	

Digital input/output reading levels tell you what is the minimum or maximum voltage/ current that a pin must be at for it know whether the digital state is high or low.

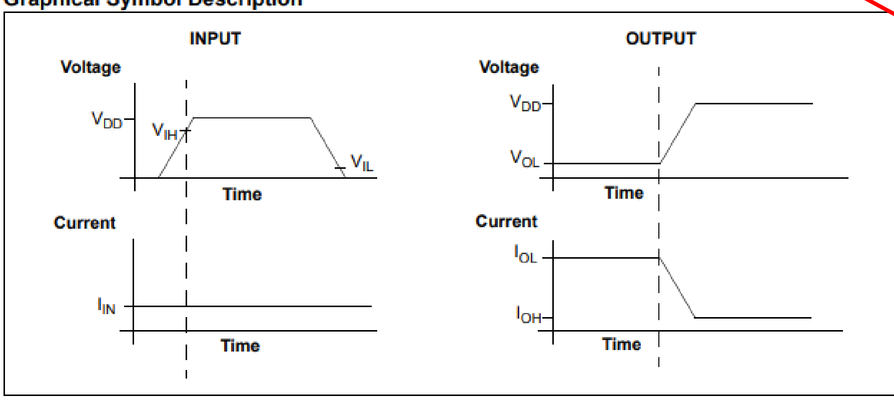
VIH: What is the minimum voltage I can send into the device for it to know that I am telling it the digital state is high.

VIL: What is the maximum voltage I can send into the device for it to know that I am telling it the digital state is low.

VOH: What is the minimum voltage that the device will send to me to indicate a digital state is high. Usually VOH = VDD (the supply voltage).

VOL: What is the maximum voltage that the device will send to me to indicate a digital state is low.

Graphical Symbol Description



TEMPERATURE CHARACTERISTICS

Electrical Specifications: Unless otherwise indicated, V_{DD} = +2.7V to +5.5V, GND = Ground.

Parameters	Sym	Min	Typ	Max	Units	Conditions
Temperature Ranges						
Specified Temperature Range	T_A	-55	—	+125	°C	(Note 1)
Operating Temperature Range	T_A	-55	—	+125	°C	
Storage Temperature Range	T_A	-65	—	+150	°C	
Thermal Package Resistances						
Thermal Resistance, 5L-SOT23	θ_{JA}	—	256	—	°C/W	
Thermal Resistance, 8L-SOIC	θ_{JA}	—	163	—	°C/W	
Thermal Resistance, 8L-MSOP	θ_{JA}	—	206	—	°C/W	

Note 1: Operation in this range must not cause T_J to exceed Maximum Junction Temperature (+150°C).

SERIAL INTERFACE TIMING SPECIFICATIONS

Electrical Specifications: Unless otherwise indicated, V_{DD} = 2.7V to 5.5V, GND = Ground, -55°C < T_A < +125°C, C_L = 80 pF, and all limits measured to 50% point.

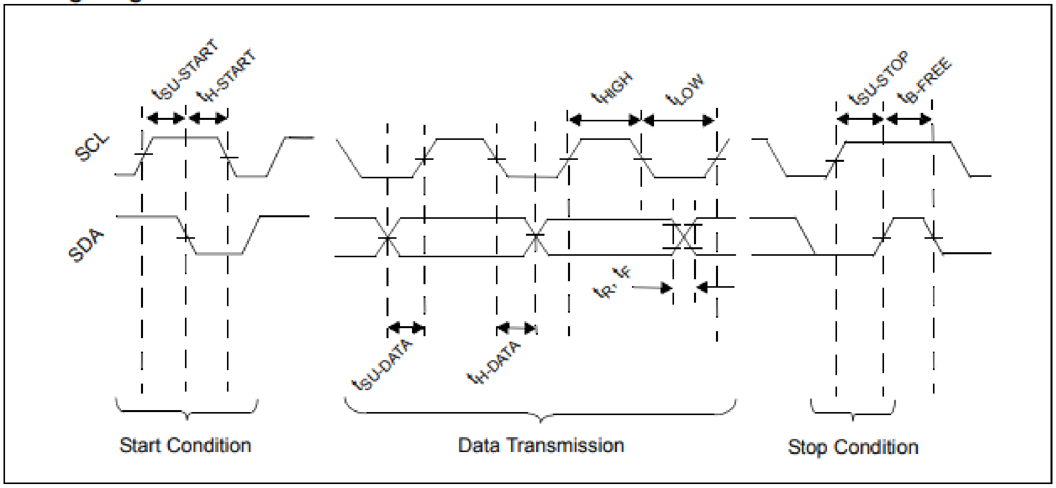
Parameters	Sym	Min	Typ	Max	Units	Conditions
2-Wire I²C™/SMBus Compatible Interface						
Serial Port Frequency	f_{SC}	0	—	400	kHz	I²C **MCP9800/01**
	f_{SC}	10	—	400	kHz	SMBus **MCP9802/03**
Clock Period	t_{SC}	2.5	—	—	µs	
Low Clock	t_{LOW}	1.3	—	—	µs	
High Clock	t_{HIGH}	0.6	—	—	µs	
Rise Time	t_R	20	—	300	ns	10% to 90% of V_{DD} (SCLK, SDA)
Fall Time	t_F	20	—	300	ns	90% to 10% of V_{DD} (SCLK, SDA)
Data Setup Before SCLK High	$t_{SU\text{-}DATA}$	0.1	—	—	µs	
Data Hold After SCLK Low	$t_{H\text{-}DATA}$	0	—	0.9	µs	
Start Condition Setup Time	$t_{SU\text{-}START}$	0.6	—	—	µs	
Start Condition Hold Time	$t_{H\text{-}START}$	0.6	—	—	µs	
Stop Condition Setup Time	$t_{SU\text{-}STOP}$	0.6	—	—	µs	
Bus Idle	t_{IDLE}	1.3	—	—	µs	
Time Out	t_{OUT}	25	35	50	ms	**MCP9802/03 only**

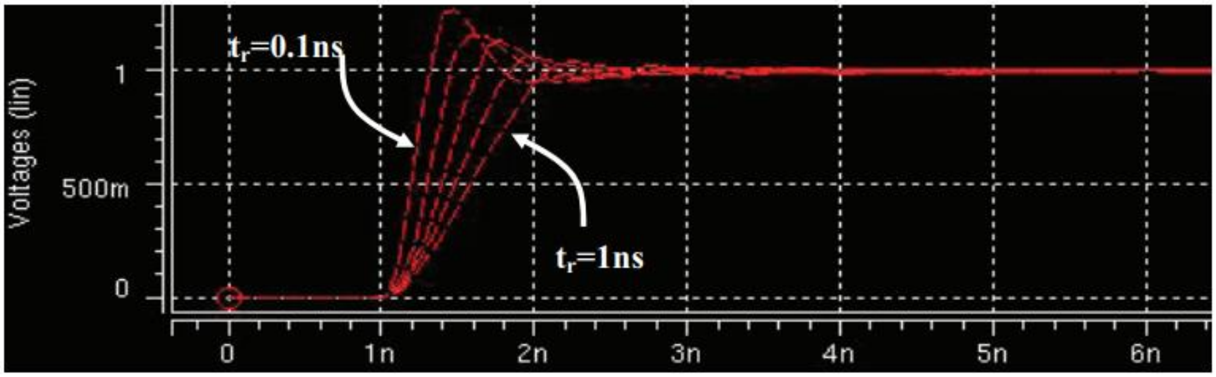
Serial timing or sometimes referred to as AC characteristics provide information on how to setup the communication lines and how to engineer the circuitry to avoid missed bits.

Clock times & Frequency: What is the range of frequency which I can transmit in data at. In other words what frequency should my clock line be switch from high to low.

Time constants: Time constants or rise and fall times of the communication lines determine the time in which it should take for digital states to transition from one to the other. Too fast of a transient probably will result in overshoot. Too slow and you could start dropping bits of information

Timing Diagram





3.0 PIN DESCRIPTION

The descriptions of the pins are listed in Table 3-1.

Pin descriptions will tell you what each pin does. Some devices allow for programmable slave addresses to be able to have multiple slaves on one line.

TABLE 3-1: PIN FUNCTION TABLE

MCP9800 MCP9802 SOT-23-5	MCP9801 MCP9803 MSOP, SOIC	Symbol	Function
5	1	SDA	Bidirectional Serial Data
4	2	SCLK	Serial Clock Input
3	3	ALERT	Temperature Alert Output
2	4	GND	Ground
—	5	A2	Address Select Pin (bit 2)
—	6	A1	Address Select Pin (bit 1)
—	7	A0	Address Select Pin (bit 0)
1	8	V_{DD}	Power Supply Input

3.1 Serial Data Pin (SDA)

The SDA is a bidirectional input/output pin, used to serially transmit data to and from the host controller. This pin requires a pull-up resistor to output data.

3.2 Serial Clock Pin (SCLK)

The SCLK is a clock input pin. All communication and timing is relative to the signal on this pin. The clock is generated by the host controller on the bus.

3.3 Power Supply Input (V_{DD})

The V_{DD} pin is the power pin. The operating voltage, as specified in the DC electrical specification table, is applied on this pin.

3.4 Ground (GND)

The GND pin is the system ground pin.

3.5 ALERT Output

The MCP9800/1/2/3's ALERT pin is an open-drain output pin. The device outputs an alert signal when the ambient temperature goes beyond the user-programmed temperature limit.

3.6 Address Pins (A2, A1, A0)

These pins are device or slave address input pins and are available only with the MCP9801/03. The device addresses for the MCP9800/02 are factory-set.

The address pins are the Least Significant bits (LSb) of the device address bits. The Most Significant bits (MSb) (A6, A5, A4, A3) are factory-set to <1001>. This is illustrated in Table 3-2.

TABLE 3-2: SLAVE ADDRESS

Device	A6	A5	A4	A3	A2	A1	A0
MCP9800/02A0	1	0	0	1	0	0	0
MCP9800/02A1	1	0	0	1	0	0	1
MCP9800/02A2	1	0	0	1	0	1	0
MCP9800/02A3	1	0	0	1	0	1	1
MCP9800/02A4	1	0	0	1	1	0	0
MCP9800/02A5	1	0	0	1	1	0	1
MCP9800/02A6	1	0	0	1	1	1	0
MCP9800/02A7	1	0	0	1	1	1	1
MCP9801/03	1	0	0	1	X	X	X

Note: User-selectable address is shown by X.

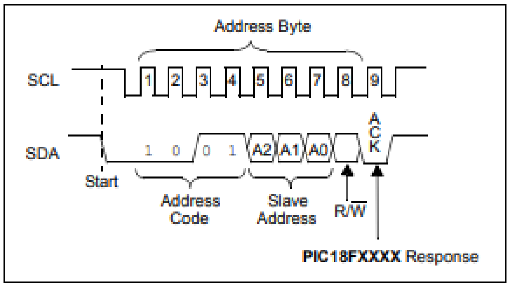


FIGURE 4-1: *Device Addressing.*

With I2C slaves usually have 7-bit address that uniquely identify them. This is always the first packet that is sent of the data line. For this example lets say that we pulled all of the user selectable address pins to low (A0=A1=A2=0). Then our first packet sent would be…

Int slaveAddress = 0x48;

The LSB tells the slave whether the next word transmitted will be written to (W) it or sent from it (R)

4.1.5 DATA VALID

After the Start condition, each bit of data in transmission needs to be settled for a time specified by $t_{SU\text{-}DATA}$ before SCL toggles from low-to-high (see **"Serial Interface Timing Specifications" on Page 5**).

REGISTER 5-1: REGISTER POINTER

U-0	U-0	U-0	U-0	U-0	U-0	R/W-0	R/W-0
0	0	0	0	0	0	P1	P0
bit 7							bit 0

Legend:			
R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

bit 7-2 **Unimplemented:** Read as '0'

bit 1-0 **Px<1:0>:** Pointer bits

- 00 = Temperature register (T_A)
- 01 = Configuration register (CONFIG)
- 10 = Temperature Hysteresis register (T_{HYST})
- 11 = Temperature Limit-set register (T_{SET})

Register Pointer: The pointer to a register may have to be set before accessing information from that specific register. If we want to read the temperature first we have to write to the slave address 0x48 the value …

Int register_readTemp = 0x00;

Or set the configuration

Int register_Config = 0x01;

TABLE 5-1: BIT ASSIGNMENT SUMMARY FOR ALL REGISTERS

Register Pointer P1 P0	MSB/ LSB	Bit Assignment 7	6	5	4	3	2	1	0
Ambient Temperature Register (T_A)									
0 0	MSB	Sign	2^{6}°C	2^{5}°C	2^{4}°C	2^{3}°C	2^{2}°C	2^{1}°C	2^{0}°C
	LSB	2^{-1}°C	2^{-2}°C	2^{-3}°C	2^{-4}°C	0	0	0	0
Sensor Configuration Register (CONFIG)									
0 1	LSB	One-Shot	Resolution		Fault Queue		ALERT Polarity	COMP/INT	Shutdown
Temperature Hysteresis Register (T_{HYST})									
1 0	MSB	Sign	2^{6}°C	2^{5}°C	2^{4}°C	2^{3}°C	2^{2}°C	2^{1}°C	2^{0}°C
	LSB	2^{-1}°C	0	0	0	0	0	0	0
Temperature Limit-Set Register (T_{SET})									
1 1	MSB	Sign	2^{6}°C	2^{5}°C	2^{4}°C	2^{3}°C	2^{2}°C	2^{1}°C	2^{0}°C
	LSB	2^{-1}°C	0	0	0	0	0	0	0

Bit functionality for Register: Each register will have definition definitions of what each bit of the word it holds. Some registers might need two words to store all the data, in which case two registers are used and the pointer, points to the beginning of first register. Some bits may be data values and other may be functions.

5.3.1 AMBIENT TEMPERATURE REGISTER (T_A)

The MCP9800/1/2/3 has a 16-bit read-only Ambient Temperature register that contains 9-bit to 12-bit temperature data. (0.5°C to 0.0625°C resolutions, respectively). This data is formatted in two's complement. The bit assignments, as well as the corresponding resolution, is shown in the register assignment below.

The refresh rate of this register depends on the selected ADC resolution. It takes 30 ms (typical) for 9-bit data and 240 ms (typical) for 12-bit data. Since this register is double-buffered, the user can read the register while the MCP9800/1/2/3 performs Analog-to-Digital conversion in the background. The decimal code to ambient temperature conversion is shown in Equation 5-2:

EQUATION 5-2:

$$T_A = \text{Code} \times 2^{-4}$$

Where:

T_A = Ambient Temperature (°C)

Code = MCP9800 output in decimal

REGISTER 5-2: AMBIENT TEMPERATURE REGISTER (T_A) – ADDRESS <0000 0000>b

Upper Half:

R-0	R-0	R-0	R-0	R-0	R-0	R-0	R-0
Sign	2^6 °C	2^5 °C	2^4 °C	2^3 °C	2^2 °C	2^1 °C	2^0 °C
bit 15							bit 8

Lower Half:

R-0	R-0	R-0	R-0	R-0	R-0	R-0	R-0
2^{-1} °C/bit	2^{-2} °C	2^{-3} °C	2^{-4} °C	0	0	0	0
bit 7							bit 0

Legend:

R = Readable bit	W = Writable bit	U = Unimplemented bit, read as '0'	
-n = Value at POR	'1' = Bit is set	'0' = Bit is cleared	x = Bit is unknown

Note 1: When the 0.5°C, 0.25°C or 0.125°C resolutions are selected, bit 6, bit 7 or bit 8 will remain clear <0>, respectively.

Here we want to read the data of the temperature readings. So we first would send the address with a write intention then write the pointer to the register.

```
setSlaveAddress(slaveAddress)

write8(register_readTemp);

int tempData_16bit = read16();

int left = (tempData & 0xFF00)>>8;

int right = (tempData & 0xFF);

float temp =((float)(left)) + ((float)(right))/255.0;
```

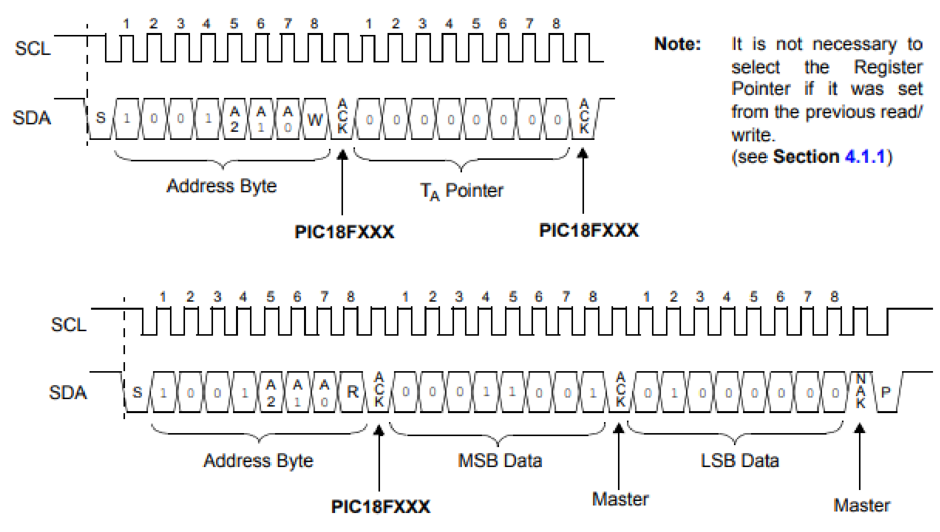


FIGURE 5-3: Timing Diagram for Reading +25.25°C Temperature from the T_A Register (See Section 5.3.1 "Ambient Temperature Register (T_A)").

```
#include <iostream>
#include <wiringPi.h>
#include <wiringSerial.h>
#include <wiringPiSPI.h>
#include <wiringPiI2C.h>

#include <sys/stat.h>
#include <linux/i2c-dev.h>
#include <linux/i2c.h>
#include <sys/ioctl.h>

#include <stdio.h>
#include <stdlib.h>
#include <stdint.h>
#include <unistd.h>
#include <string.h>


int setSlaveAddress(int fd_i2c, int slaveAddress)
{
    /*
    Sets the I2C to communicate with this device
    */
    if (ioctl(this->fd_i2c, I2C_SLAVE, slaveAddress) < 0)
    {
        printf("problem setting slave\n");
        return -1;
    }
    return 0;
}


int main()
{
    /*
        Code to show how to use WiringPi I2C
    */
    int slaveAddress = 0x48;
    int register_readTemp = 0x00;
    int i2c1_fd = wiringPiI2CSetup(slaveAddress);
    setSlaveAddress(i2c1_fd, slaveAddress);
    int temp_word  = wiringPiI2CRead16(i2c1_fd, register_readTemp, slaveAddr
    int left = (tempData & 0xFF00) >> 8;
    int right = (tempData & 0xFF);
    float temperature = ((float)(left)) + ((float)(right)) / 255.0;
    return 0;
}
```

Figure 7 – Example main file for communicating with a temperature sensor

SPI data latching

- SPI data is latched on the rising or falling edge of SCLK
- The edge data is latched on is called the critical edge
- The figure below illustrates latching logic 1 on rising edge and logic 0 on falling edge

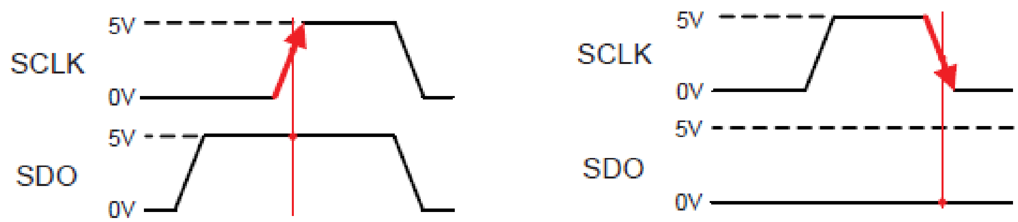


Figure 70: SPI SCLK critical edge

SPI read sequence example

1. Critical edge is rising edge
2. Master output writing to slave (SDI label relative to slave device)
3. The active low $\overline{CS}$ pin is driven low to 0V, activating the slave SPI bus
4. Data is clocked in from MSB to LSB on the rising edge of SCLK
5. Completed SPI transaction data is binary 1011001

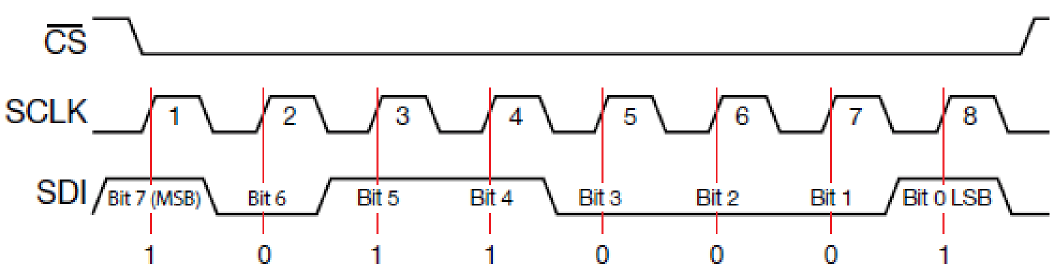


Figure 71: Example SPI write sequence

Figure 8 – SPI data latching and Read/ Write Sequence

SPI critical edge

t_{SU} (setup time) = defines how long before the critical edge that the data on SDI must already be set and settled

t_{HO} (hold time) = defines how long after the critical edge data must be maintained on SDI.

t_{DO} (delay time) - defines the delay before data is valid after the critical edge for SDO.

Violation of any timing requirement could result in corruption of data.

The timing parameters, t_{SU}, t_{HO} and t_{DO}, are defined relative to the critical edge. In the example below for SDI the rising edge of SCLK is the critical edge and for SDO the falling edge of SCLK is the critical edge.

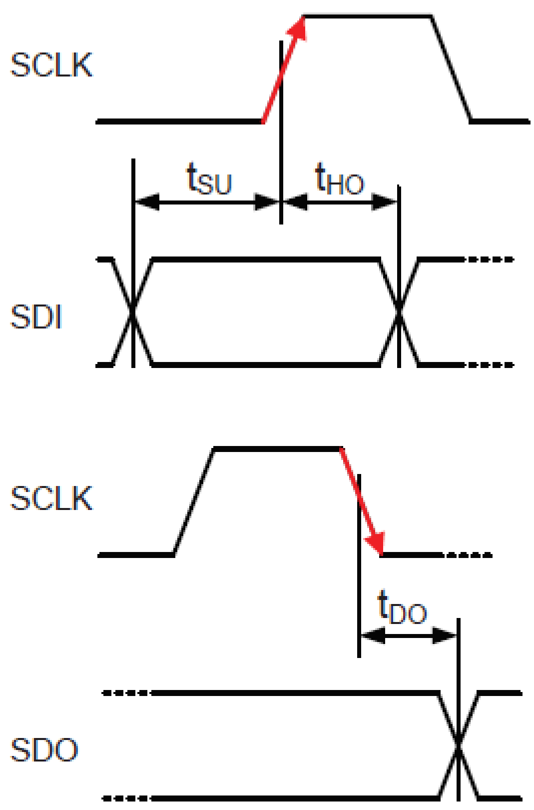


Figure 72: Setup and hold timing illustration

Figure 9 – SPI critical edges

SPI modes

CPHA (clock phase) = defines which edge data is latched on, a 0 representing the first edge and a 1 representing the second edge

CPOL (clock polarity) = defines whether the clock idles high or low in between SPI frames. CPOL = 0 idles low, CPOL = 1 idles high.

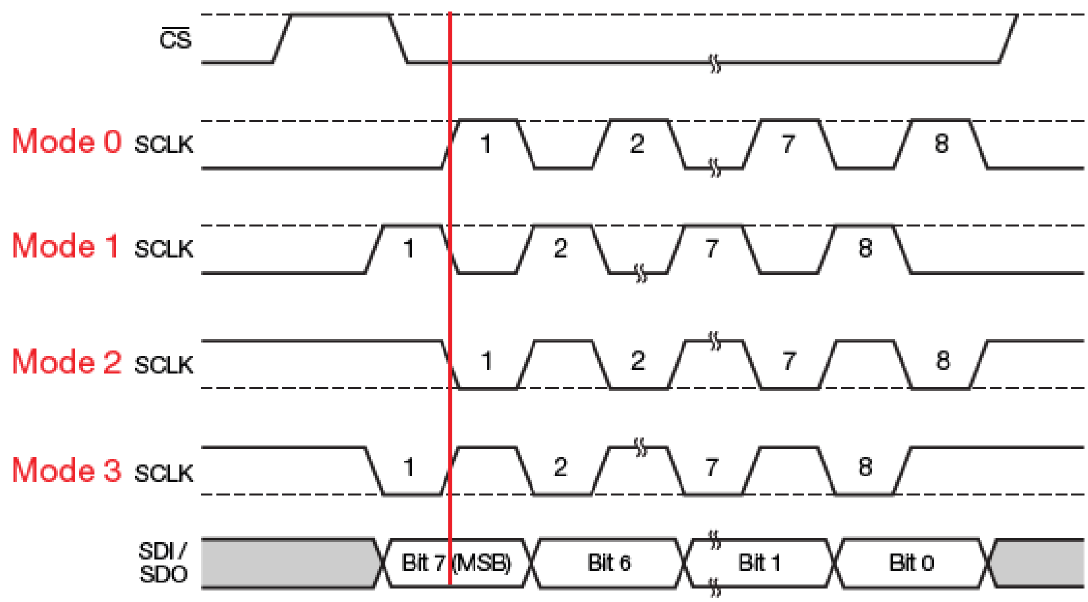


Figure 73: SPI modes of operation

Mode	CPOL	CPHA	Critical edge	Clock phase
0	0	0	Rising edge	Idles low
1	0	1	Falling edge	Idles low
2	1	0	Rising edge	Idles high
3	1	1	Falling edge	Idles high

Figure 10 – SPI Modes

I²C communication

START = initiated by the master pulling SDA low while SCL is high

STOP = initiated by the master releasing the SDA pin high while SCL is high

ACK (acknowledge) = each transfer in I²C is a single byte or 8-bits, with one SCL pulse per bit. The 9th pulse in each exchange is reserved for an acknowledgement signal from the slave, or an ACK signal. The ACK signal indicates that the previous transfer was successful.

Example I²C write sequence:

1. The master pulls down SDA to generate a START condition
2. The first bit is set up and the master pulls down and releases SCL to clock data into the DAC
3. On the 9th bit the master does not pull down SDA. If the slave pulls down SDA the 8-bit transaction is acknowledged.
4. The completed transaction in binary is 11001101

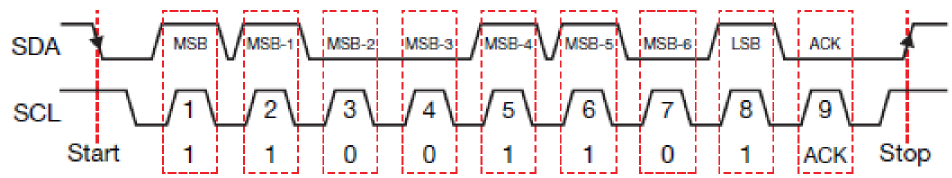


Figure 76: Complete I²C transaction

For valid data transfer:

- SDA must remain stable the entire time that SCL is high for a bit transfer to be valid
- SDA is only allowed to transition in between SCL pulses when SCL is low
- Instances where SDA changes while SCL is high are interpreted as START, RESTART, or STOP conditions

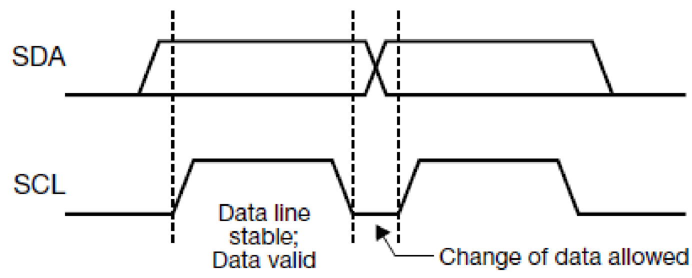


Figure 77: I²C data transfer

Figure 11 – I2C communication

I^{2}C addressing

- Typical addressing in I^{2}C is 7-bit addressing with an additional bit for read or write indication
- Each device on the I^{2}C bus must have a unique address
- Duplicate addresses will result in communication errors
- Some devices may have pin programmable I^{2}C addresses

Address byte

MSB						LSB	R/$\overline{W}$
1	0	0	1	1	0	A0	1/0

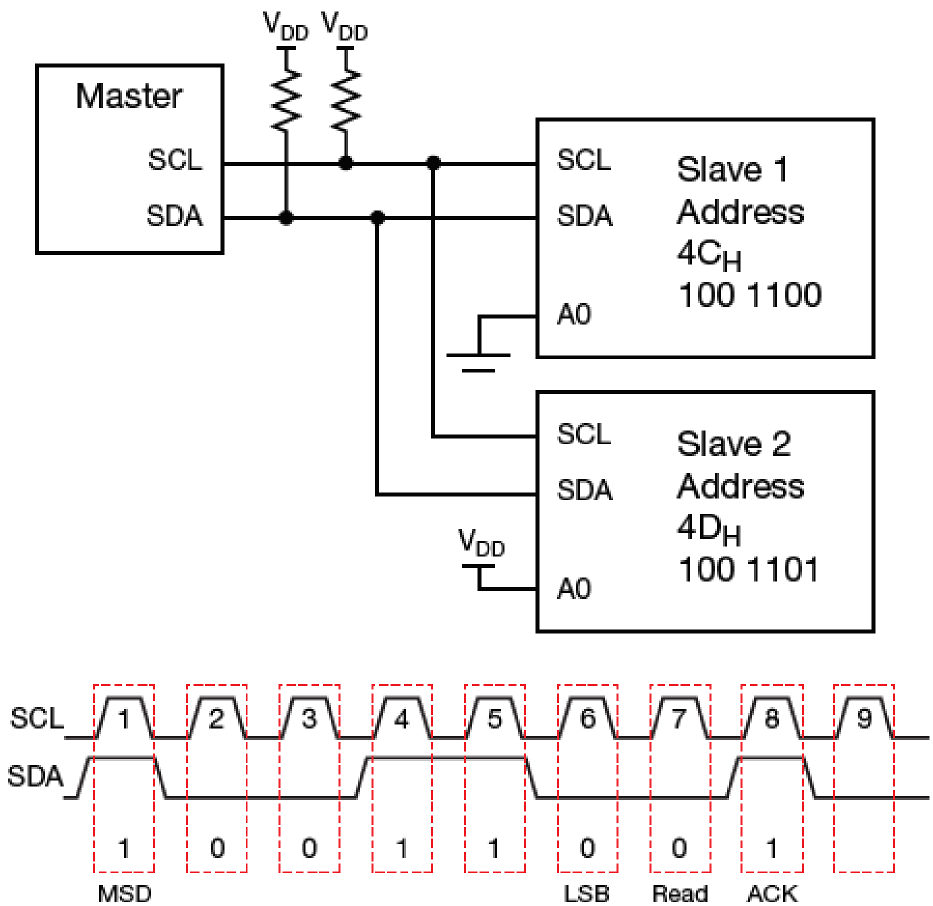


Figure 75: : I^{2}C addressing

Figure 12 – I2C addressing

I^2C pull-up resistor selection

$$R_{Pull(Min)} = \frac{(V_{DD} - V_{OLMAX})}{I_{SinkMax}} \quad \text{(179) Minimum } I^2C \text{ pull-up resistance}$$

$$R_{Pull(Max)} = \frac{t_r}{(0.8473 \times C_b)} \quad \text{(180) Maximun } I^2C \text{ pull-up resistance}$$

Where

$R_{Pull(Min)}$ = this is the minimum pull-up resistance. This will give the shortest rise time. Using a pull-up smaller than this will draw too much current when the output transistor is on (logic low) and violate the maximum logic low output specification.

$R_{Pull(Max)}$ = maximum pull-up resistance. This will give the longest rise time. Using a pull-up resistance larger than this will violate timing requirements.

V_{DD} = supply voltage

V_{OLMAX} = maximum logic low output found in device data sheet. Typically 0.4V.

$I_{SinkMax}$ = maximum sink current when the output transistor is on (logic low) found in device data sheet. Typically 3mA.

C_b = bus capacitance. Depends on width and length of PCB trace (see equation 155), and the capacitance of the devices connected to the bus.

Example

Find a pull-up resistor for: V_{DD} = 5V, V_{OLMAX} = 0.4V, t_r = 300ns, and C_b = 100pF.

Answer

$$R_{Pull(Min)} = \frac{(V_{DD} - V_{OLMAX})}{I_{SinkMax}} = \frac{(5V - 0.4V)}{0.003A} = 1.53k\Omega$$

$$R_{Pull(Max)} = \frac{t_r}{(0.8473 \times C_b)} = \frac{300ns}{0.8473 \times 100pF} = 3.54k\Omega$$

$R_{Pull} = 2k\Omega$ Selected as a standard value between $R_{Pull(Min)}$ and $R_{Pull(Max)}$

Figure 13 – Selecting Pull up resisters for I2C

I^2C interface circuitry and rise/fall timing

The figure below illustrates the internal structure for an I^2C SCL or SDA pin. The transistor will turn on for logic low discharging C_b to logic low. The transistor will turn off for a logic high and the pull-up, R_{pull}, will charge C_b to a logic high.

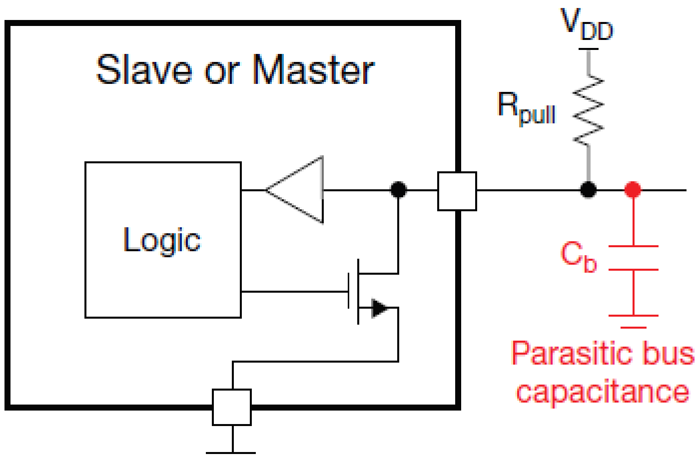


Figure 78: I^2C data transfer

t_r (rise time) = the maximum amount of time for the signal to transition from logic low to logic high. Since I^2C data is an open drain signal, rise time is set by the RC time constant of the pull-up resistance and the bus capacitance.

t_f (fall time) = the maximum amount of time for the signal to transition from logic high to logic low

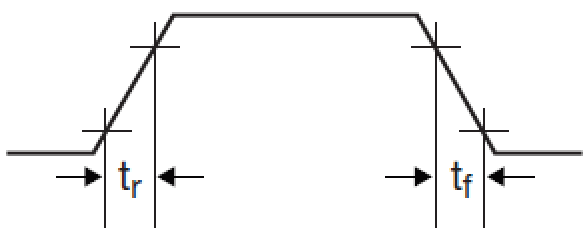


Figure 79: I^2C rise and fall timing

Figure 14 – I2C Time Constants and Parasitic Bus Capacitance

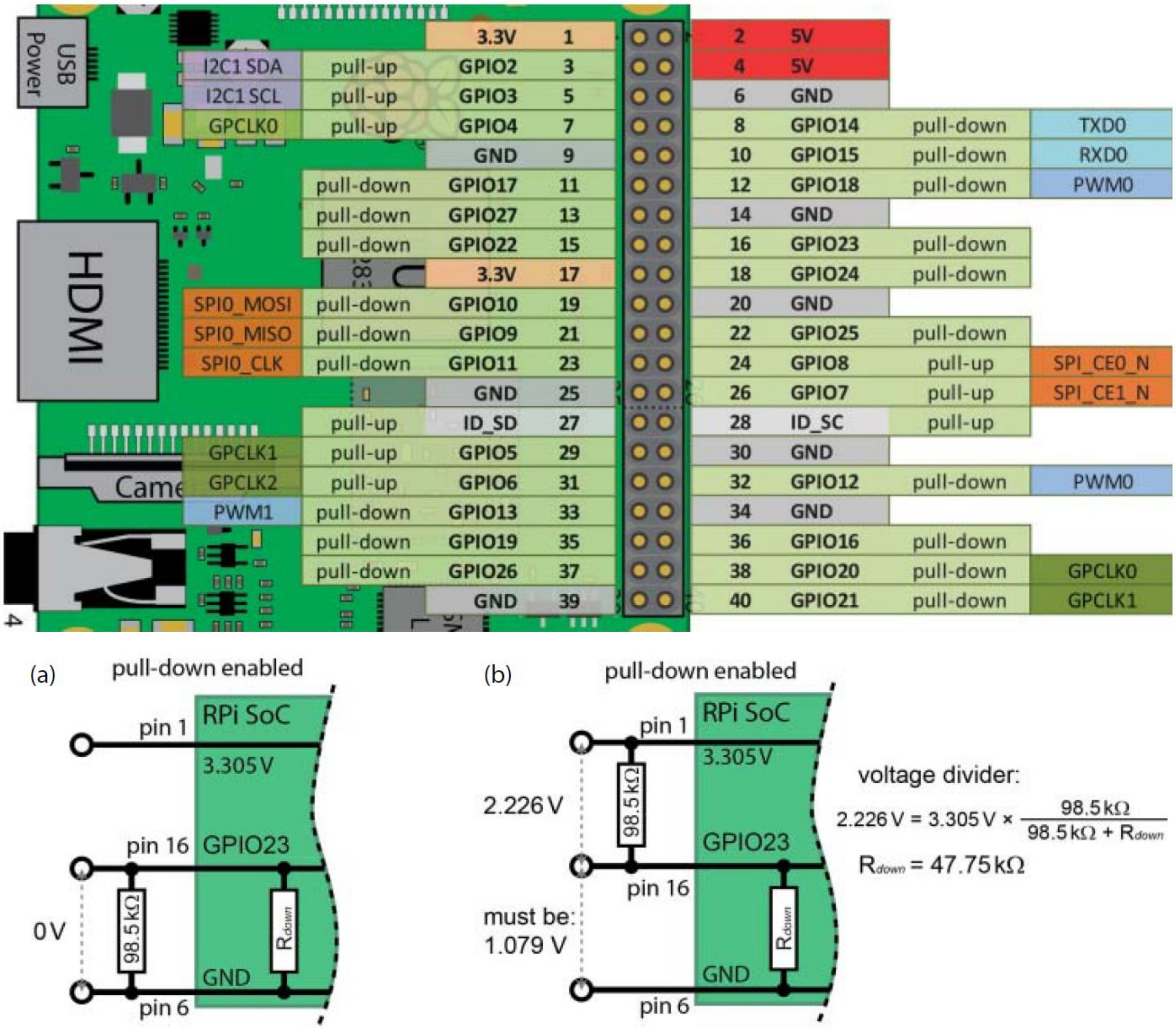


Figure 6-6: Internal pull-down resistor value determination, using a 100 kΩ resistor connected (a) from the GPIO pin to GND, and (b) from the GPIO pin to the 3.3 V supply

Figure 15 – Raspberry Pi 2/3 GPIO and pull-up/pull-down pinouts

	ALT5	ALT4	ALT3	ALT2	ALT1	ALT0	WPi	Pull	Mode	Pin Numbers		Mode	Pull	WPi	ALT0	ALT1	ALT2	ALT3	ALT4	ALT5	
RPi A, B, A+, B+, 2/3	50mA maximum on 3.3V supply								3.3V	1	2	5V	max current draw ~300mA (cover when not in use)								RPi A, B, A+, B+, 2/3
	(note 2)			reserved	SA3	I2C1 SDA	8	up	GPIO2	3	4	5V	max current draw ~300mA (cover when not in use)								
	(note 2)			reserved	SA2	I2C1 SCL	9	up	GPIO3	5	6	GND									
	ARM_TDI			reserved	SA1	GPCLK0	7	up	GPIO4	7	8	GPIO14	down	15	TXD0	SD6				TXD1	
									GND	9	10	GPIO15	down	16	RXD0	SD7				RXD1	
	RTS1	SPI1_CE1_N	RTS0	reserved	SD9	reserved	0	down	GPIO17	11	12	GPIO18	down	1	PCM_CLK	SD10		BSCSL_SDA/MOSI	SPI1_CE0_N	PWM0	
		ARM_TMS	SD1_DAT3	reserved	reserved	reserved	2	down	GPIO27	13	14	GND									
		ARM_TRST	SD1_CLK	reserved	SD14	reserved	3	down	GPIO22	15	16	GPIO23	down	4	reserved	SD15	reserved	SD1_CMD	ARM_RTCK		
	50mA maximum on 3.3V supply								3.3V	17	18	GPIO24	down	5	reserved	SD16	reserved	SD1_DAT0	ARM_TDO		
				reserved	SD2	SPI0_MOSI	12	down	GPIO10	19	20	GND									
				reserved	SD1	SPI0_MISO	13	down	GPIO9	21	22	GPIO25	down	6	reserved	SD17	reserved	SD1_DAT1	ARM_TCK		
				reserved	SD3	SPI0_CLK	14	down	GPIO11	23	24	GPIO8	up	10	SPI_CE0_N	SD0	reserved				
									GND	25	26	GPIO7	up	11	SPI_CE1_N	SWE_N / SRW_N	reserved				
RPi A+, B+, 2/3 Only	Do not use (GPIO0) -- see note 3			reserved	SA5	SDA0	30	up	ID_SD	27	28	ID_SC	up	31	SCL0	SA4	reserved	Do not use (GPIO1) -- see note 3			RPi A+, B+, 2/3 Only
	ARM_TDO			reserved	SA0	GPCLK1	21	up	GPIO5	29	30	GND									
	ARM_RTCK			reserved	SOE_N/SE	GPCLK2	22	up	GPIO6	31	32	GPIO12	down	26	PWM0	SD4	reserved			ARM_TMS	
	ARM_TCK			reserved	SD5	PWM1	23	down	GPIO13	33	34	GND									
				reserved	SD11	PCM_FS	24	down	GPIO19	35	36	GPIO16	down	27	reserved	SD8	reserved	CTS0	SPI1_CE2_N	CTS1	
		ARM_TDI	SD1_DAT2	reserved	reserved	reserved	25	down	GPIO26	37	38	GPIO20	down	28	PCM_DIN	SD12	reserved	BSCSL / MISO	SPI1_MOSI	GPCLK0	
									GND	39	40	GPIO21	down	29	PCM_DOUT	SD13	reserved	BSCSL / CE_N	SPI1_SCLK	GPCLK1	

Type	Linux DT	Description
GPIO	sysfs	general purpose input/output
SPI	spi	serial peripheral interface
I2C	i2c0/i2c1	I^2C Bus
UART	uart0	UART
PWM	pwm	Pulse Width Modulation
GPCLK	gp_clk	General purpose clock (GPCLK1 is reserved)
PCM	pcm	PCM audio
SA	smi	Secondary Memory Interface

Note 1: The data in this table was created from the www.eLinux.org web pages, system information, and datasheets where available.

Note 2: On early models of the RPi, Pin 3 is GPIO0 and Pin 5 is GPIO1. Also, these pins have permanent on-board 1.8 KΩ pull-up resistors attached (for the I^2C bus).

Note 3: ID_SD and ID_SC pins are reserved for the ID EEPROM (for different HATs). This is an I^2C interface that is probed at boot time in order to detect attached boards. This allows Linux to load the correct drivers for a HAT. See Chapter 8.

Register	Offset	MSB			32-bits for each register							LSB
Offset is from the virtual address 0x3F000000 on the RPi 2/3, and 0x20000000 on all other RPi models.												
GPFSELn	The Function Select mode for each GPIO (3 bits for each GPIO and 54 GPIOs in total)											Read/Write
Bits		[31-30]	[29-27]	[26-24]	[23-21]	[20-18]	[17-15]	[14-12]	[11-9]	[8-6]	[5-3]	[2-0]
GPFSEL0	0000	X	FSEL9	FSEL8	FSEL7	FSEL6	FSEL5	FSEL4	FSEL3	FSEL2	FSEL1	FSEL0
GPFSEL1	0004	X	FSEL19	FSEL18	FSEL17	FSEL16	FSEL15	FSEL14	FSEL13	FSEL12	FSEL11	FSEL10
GPFSEL2	0008	X	FSEL29	FSEL28	FSEL27	FSEL26	FSEL25	FSEL24	FSEL23	FSEL22	FSEL21	FSEL20
GPFSEL3	000C	X	FSEL39	FSEL38	FSEL37	FSEL36	FSEL35	FSEL34	FSEL33	FSEL32	FSEL31	FSEL30
GPFSEL4	0010	X	FSEL49	FSEL48	FSEL47	FSEL46	FSEL45	FSEL54	FSEL43	FSEL42	FSEL41	FSEL40
GPFSEL5	0014	[32-12] X							FSEL53	FSEL52	FSEL51	FSEL50
GPSETn	The Output Set register - use this to set a GPIO high (1 bit for each of the 54 GPIOs)											Read/Write
GPSET0	001C	[31-0] mapped to GPIO31 to GPIO0 (1 = set GPIO)(0 = no effect)										
GPSET1	0020	[31-22] X			[21-0] mapped to GPIO53 to GPIO32 (1 = set GPIO)(0 = no effect)							
GPCLRn	The Output Clear register - use this to set a GPIO low (1 bit for each of the 54 GPIOs)											Read/Write
GPCLR0	0028	[31-0] mapped to GPIO31 to GPIO0 (1 = clear GPIO)(0 = no effect)										
GPCLR1	002C	[31-22] X			[21-0] mapped to GPIO53 to GPIO32 (1 = clear GPIO)(0 = no effect)							
GPLVLn	The Level Read register - use this to read the value of a GPIO (1 bit for each of the 54 GPIOs)											Read Only
GPLVL0	0034	[31-0] mapped to GPIO31 to GPIO0 (1 = level is high)(0 = level is low)										
GPLVL1	0038	[31-22] X			[21-0] mapped to GPIO53 to GPIO32 (1 = level is high)(0 = level is low)							
GPPUD	The Pull-up/Pull-down Enable register - use this to define the configuration											Read/Write
GPPUD	0094	[31-2] X										[1-0]
GPPUDCLKn	The Pull-up/Pull-down Enable Clock register - use this to apply GPPUD to a particular GPIO											Read/Write
GPPUDCLK0	0098	[31-0] mapped to GPIO31 to GPIO0 (1 = assert clock)(0 = no effect)										
GPPUDCLK1	009C	[31-22] X			[21-0] mapped to GPIO53 to GPIO32 (1 = assert clock)(0 = no effect)							

Function	GPFSELn
Bits	Meaning
000	input
001	output
100	ALT0
101	ALT1
110	ALT2
111	ALT3
011	ALT4
010	ALT5

Example: Set GPIO17 to be an output and set it high.
Solution: Write bits 001 to FSEL17, which is bits 21, 22, and 23 of the GPFSEL1 register to set the pin up as an output.
Then write a 1 to bit 17 of the GPSET0 register to set the output high.

Function	PUD
Bits	Meaning
00	no pull-up/down
01	pull-down
10	pull-up
11	X

GPFSEL1

FSEL17

[31]	[30]		[24]	[23]	[22]	[21]	[20]		[0]
X	X	...	?	0	0	1	?	...	?

Do not change the "?" bits as this will affect other GPIO select modes!

Figure 17 – Raspberry Pi 2/3 GPIO memory addressing information

Name	Function	See section
SDA0	BSC[6] master 0 data line	BSC
SCL0	BSC master 0 clock line	BSC
SDA1	BSC master 1 data line	BSC
SCL1	BSC master 1 clock line	BSC
GPCLK0	General purpose Clock 0	<TBD>
GPCLK1	General purpose Clock 1	<TBD>
GPCLK2	General purpose Clock 2	<TBD>
SPI0_CE1_N	SPI0 Chip select 1	SPI
SPI0_CE0_N	SPI0 Chip select 0	SPI
SPI0_MISO	SPI0 MISO	SPI
SPI0_MOSI	SPI0 MOSI	SPI
SPI0_SCLK	SPI0 Serial clock	SPI
PWMx	Pulse Width Modulator 0..1	Pulse Width Modulator
TXD0	UART 0 Transmit Data	UART
RXD0	UART 0 Receive Data	UART
CTS0	UART 0 Clear To Send	UART
RTS0	UART 0 Request To Send	UART
PCM_CLK	PCM clock	PCM Audio
PCM_FS	PCM Frame Sync	PCM Audio
PCM_DIN	PCM Data in	PCM Audio
PCM_DOUT	PCM data out	PCM Audio
SAx	Secondary mem Address bus	Secondary Memory Interface
SOE_N / SE	Secondary mem. Controls	Secondary Memory Interface
SWE_N / SRW_N	Secondary mem. Controls	Secondary Memory Interface
SDx	Secondary mem. data bus	Secondary Memory Interface
BSCSL SDA / MOSI	BSC slave Data, SPI salve MOSI	BSC ISP slave
BSCSL SCL / SCLK	BSC slave Clock, SPI slave clock	BSC ISP slave
BSCSL - / MISO	BSC <not used>,SPI MISO	BSC ISP slave
BSCSL - / CE_N	BSC <not used>, SPI CSn	BSC ISP slave

Name	Function	See section
SPI1_CEx_N	SPI1 Chip select 0-2	Auxiliary I/O
SPI1_MISO	SPI1 MISO	Auxiliary I/O
SPI1_MOSI	SPI1 MOSI	Auxiliary I/O
SPI1_SCLK	SPI1 Serial clock	Auxiliary I/O
TXD0	UART 1 Transmit Data	Auxiliary I/O
RXD0	UART 1 Receive Data	Auxiliary I/O
CTS0	UART 1 Clear To Send	Auxiliary I/O
RTS0	UART 1 Request To Send	Auxiliary I/O
SPI2_CEx_N	SPI2 Chip select 0-2	Auxiliary I/O
SPI2_MISO	SPI2 MISO	Auxiliary I/O
SPI2_MOSI	SPI2 MOSI	Auxiliary I/O
SPI2_SCLK	SPI2 Serial clock	Auxiliary I/O
ARM_TRST	ARM JTAG reset	<TBD>
ARM_RTCK	ARM JTAG return clock	<TBD>
ARM_TDO	ARM JTAG Data out	<TBD>
ARM_TCK	ARM JTAG Clock	<TBD>
ARM_TDI	ARM JTAG Data in	<TBD>
ARM_TMS	ARM JTAG Mode select	<TBD>

Figure 18 – BCM2835 peripherals function descriptions