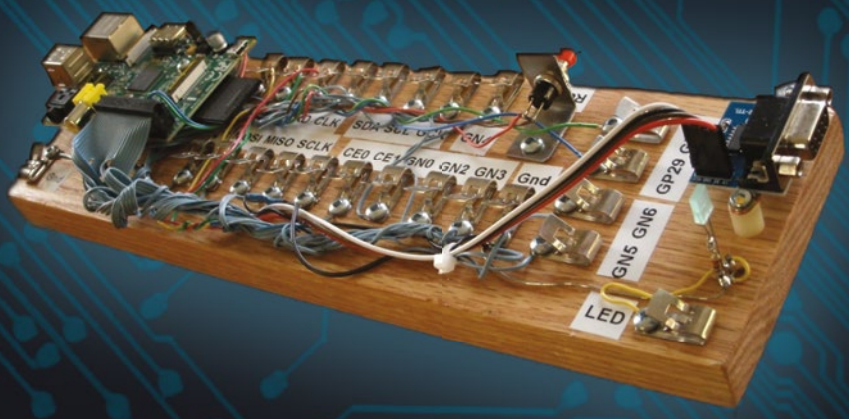
TECHNOLOGY IN ACTION™

Experimenting with Raspberry Pi

LOW-COST PROJECTS TO HELP YOU GENERATE IDEAS, FROM MASTERING THE RASPBERRY PI



Warren Gay

For your convenience Apress has placed some of the front matter material after the index. Please use the Bookmarks and Contents at a Glance links to access them.

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Introduction

These are exciting times for the computing enthusiast. AVR and PIC microcontrollers make low-level digital computing readily accessible. At the high-level there exist System on a Chip (SoC) platforms, such as the Raspberry Pi. These are capable of supporting complex applications at affordable prices.

New challengers to the Raspberry Pi regularly appear now, yet the Pi remains popular. This is because of the Raspberry Pi Foundation's excellent support and the unit's continuing dominance in price. Both are critical to success. Foundation support provides continued Raspbian Linux development, making it easier for people to get started and use the platform. The foundation also continues to provide documentation and to develop Pi specific peripherals such as the camera. Finally, low cost allows more people to participate and at lower risk, should an experiment go bad.

Content of This Book

This book was formed from a category of chapters in the full volume *Mastering the Raspberry Pi*. The focus in this particular book is experiments in Raspberry Pi interfacing to the outside world. Every chapter involves some aspect of interfacing GPIO, PWM, I2C bus, or SPI bus to some external electronics.

More than the electronic interface design is covered, however, since every interface requires software to drive it. In some cases, applications will utilize Raspbian Linux drivers to control the peripheral (such as the I2C bus). In other experiments, the application software must control the GPIO pins directly. In every case, simplified C programming is used as a place to start. The reader is encouraged therefore to apply these programs as "idea generators." Jump in and modify the programs to adapt to your own ideas. Software is infinitely malleable.

Approach Used

The focus of this text is on learning. You would not be well served if you were presented some kind of "end product" to be plugged in and simply used. Instead, you are encouraged to learn to design interfaces to the Pi for yourself—to build from scratch or to modify existing designs. This book will give you some practical examples to work through. Experience is the best teacher.

While this is not an electronics engineering text, a light engineering approach is applied. For example, the difference between the signal levels of the Pi versus the levels required by an interfaced IC is scrutinized for some experiments. These parameters are taken from the IC's datasheet. This design work is to counter the glib "seems to work" approach often given in web blogs. It is better to *know* that it will work and that it will *always* work. Getting it right is not difficult when a little care and understanding goes into the process.

Assumptions About the Reader

Since the experiments in this book involve attaching things to the Raspberry Pi's GPIO pins, some digital electronics knowledge is assumed. The reader should have a good grasp of DC voltage, current, and resistance at a minimum. Students who know Ohm's law will fare best in these experiments. For students who have not yet committed Ohm's law to memory, Appendix C serves a quick reference.

The Raspberry Pi uses 3.3 V digital logic. This creates a special problem when interfacing to older TTL logic, which operates at the 5 V level. The experiment in Chapter 4 Real Time Clock, for example, demonstrates how to interface safely to a 5 V device, after making some modifications to a purchased pcb. These experiments require extra care to avoid damaging the Pi.

Experiments involving the I2C bus require the reader to be familiar with the concept of open collector drivers. Without this understanding, the student will not appreciate why a 3.3 V Pi can interface to a 5 V real-time clock chip, using the I2C bus. This concept is also critical to understanding why several peripherals can share that same bus.

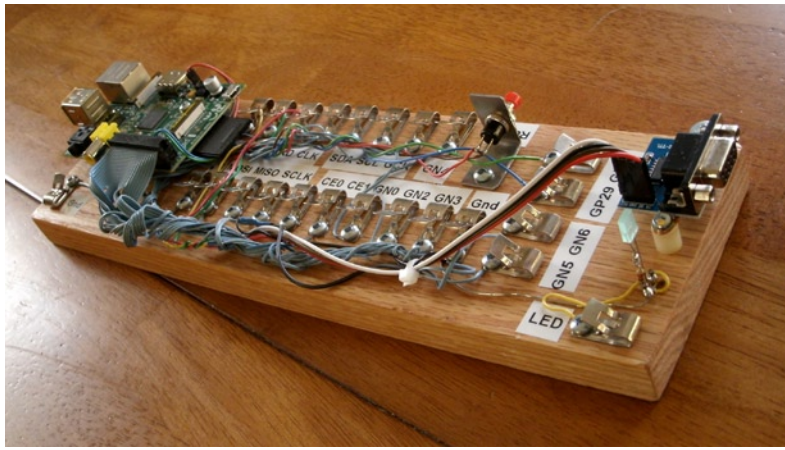
Hardware for the experiments assumes a student budget. The parts and assembled pcbs used in this book were purchased from eBay, usually as buy-it-now auctions (with free shipping). For this reason, the student need not have deep pockets to acquire the parts used in these experiments.

Since hardware needs software to direct it, C programs are used and provided. Consequently, it is best that you have at least a vague idea about the C programming language to get the most out of the experiments. The example programs are simplified as much as they could be without sacrificing function. This keeps the software accessible to the reader and eases the learning process.

Pi Hardware Assumed

All of the experiments in this book interface directly to the Raspberry Pi. No special Gertboard or other special product is used. For this "bare-metal approach," all you need is a Raspberry Pi and the involved experiment's hardware.

For my own experiments, I constructed a home-brewed setup where I placed the Pi on a block of wood and ran wires out to some retro Fahnestock clips. While this worked quite well, building this setup required considerable effort. I would recommend that students get something easier like the Adafruit Pi Cobbler.



A simple homemade Raspberry Pi workstation

For the reader, the advantage of this "bare-metal" approach is threefold:

- There is no dependence on product availability.
- There is no built-in buffering between the Pi and your peripheral.
- It costs less.

Products come and go, so why build on that foundation? Add-on products also often provide buffering between the Pi and the outside world. But this feature would eliminate the need to design this yourself.

Finally, in a large project like a robot, where several motor and sensor interfaces exist, the need to economize becomes essential. This is where learning to design your own interfaces pays off.

Test Equipment

The experiments in this book require access to a digital multimeter (DMM). This is critical for testing voltages for the Raspberry Pi's own safety. The Pi will not tolerate inputs above +3.3 V without possible damage. Consequently, voltage readings are recommended as part of several experiments to make sure that no damage to the Pi occurs whenever voltages exceeding 3.3 V are involved.

Many experiments can be laid out on breadboards without the need for soldering. A huge time saver is the use of ready-made breadboard jumper wires. These can be purchased from eBay for about $1.50 for about 50 to 65 wires. They come in different colors, fit the breadboard well, and don't require you strip the ends. Students have better things to do with their time.

Final Words

By now, you are probably itching to get started. There is no better time than the present!

CHAPTER 1

DHT11 Sensor

The DHT11 humidity and temperature sensor is an economical peripheral manufactured by D-Robotics UK (www.droboticsonline.com). It is capable of measuring relative humidity between 20 and 90% RH within the operating temperature range of 0 to 50°C, with an accuracy of ±5% RH. Additionally, temperature is measured in the range of 0 to 50°C, with an accuracy of ±2°C. Both values are returned with 8-bit resolution.

Characteristics

The signaling used by the DHT sensor is similar to the 1-Wire protocol, but the response times differ. Additionally, there is no device serial number support. These factors make the device incompatible with the 1-Wire drivers within the Linux kernel. Figure 1-1 shows a DHT11 sensor.

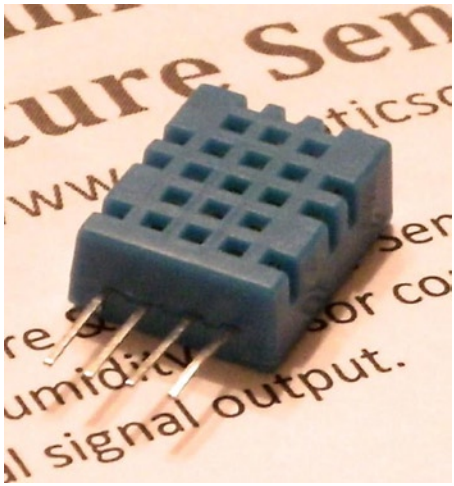


Figure 1-1. *DHT11 sensor*

The DHT11 sensor also requires a power supply. In contrast, the signal line itself powers most 1-Wire peripherals. The datasheet states that the DHT11 can be powered by a range of voltages, from 3 V to 5.5 V. Powering it from the Raspberry Pi's 3.3 V source keeps the sensor signal levels within a safe range for GPIO. The device draws between 0.5 mA and 2.5 mA. Its standby current is stated as 100 μA to 150 μA, for those concerned about battery consumption.

Circuit

Figure 1-2 shows the general circuit connections between the Raspberry Pi and the DHT11 sensor. Pin 4 connects to the common ground, while pin 1 goes to the 3.3 V supply. Pin 2 is the signal pin, which communicates with a chosen GPIO pin. The program listing for `dht11.c` is configured to use GPIO 22. This is easily modified (look for `gpio_dht11`).

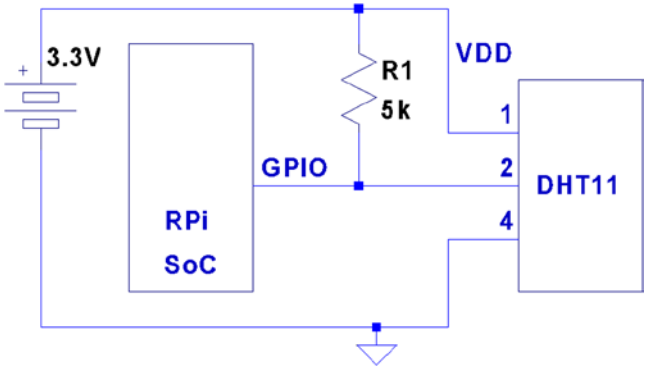


Figure 1-2. *DHT11 circuit*

When the Pi is listening on the GPIO pin and the DHT11 is not sending data, the line will float. For this reason, R_1 is required to pull the line up to a stable level of 3.3 V. The datasheet recommends a 5 kΩ resistor for the purpose (a more common 4.7 kΩ resistor can be substituted safely). This presents less than 1 mA of load on either the GPIO pin or the sensor when they are active. The datasheet also states that the 5 kΩ resistor should be suitable for cable runs of up to 20 meters.

Protocol

The sensor speaks only when spoken to by the master (Raspberry Pi). The master must first make a request on the bus and then wait for the sensor to respond. The DHT sensor responds with 40 bits of information, 8 of which are a checksum.

Overall Protocol

The overall signal protocol works like this:

1. The line idles high because of the pull-up resistor.
2. The master pulls the line low for at least 18 ms to signal a read request and then releases the bus, allowing the line to return to a high state.
3. After a pause of about 20 to 40 μs, the sensor responds by bringing the line low for 80 μs and then allows the line to return high for a further 80 μs. This signals its intention to return data.
4. Forty bits of information are then written out to the bus: each bit starting with a 50 μs low followed by:
   a. 26 to 28 μs of high to indicate a 0 bit
   b. 70 μs of high to indicate a 1 bit
5. The transmission ends with the sensor bringing the line low one more time for 50 μs.
6. The sensor releases the bus, allowing the line to return to a high idle state.

Figure 1-3 shows the overall protocol of the sensor. Master control is shown in thick lines, while sensor control is shown in thin lines. Initially, the bus sits idle until the master brings the line low and releases it (labeled Request). The sensor grabs the bus and signals that it is responding (80 μs low, followed by 80 μs high). The sensor continues with 40 bits of sensor data, ending with one more transition to low (labeled End) to mark the end of the last bit.

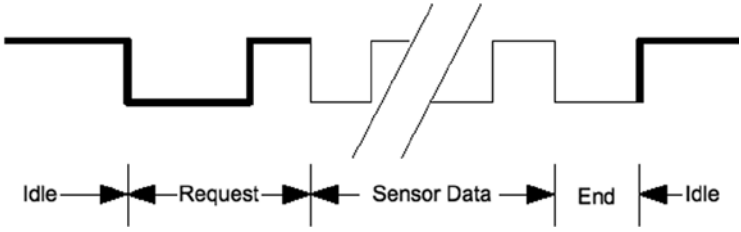


Figure 1-3. *General DHT11 protocol*

Data Bits

Each sensor data bit begins with a transition to low, followed by the transition to high, as shown in Figure 1-4. The end of the bit occurs when the line is brought low again as the start of the next bit. The last bit is marked off by one final low-to-high transition.

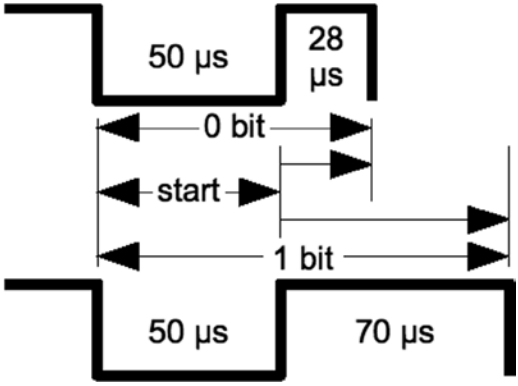


Figure 1-4. *DHT11 data bit*

Each data bit starts with a transition to low, lasting for 50 µs. The final transition to low after the last bit also lasts for 50 µs. After the bit's low-to-high transition, the bit becomes a 0 if the high lasts only 26 to 28 microseconds. A 1 bit stays high for 70 µs instead. Every data bit is completed when the transition from high to low occurs for the start of the next bit (or final transition).

Data Format

Figure 1-5 illustrates the 40-bit sensor response, transmitting the most significant bit first. The datasheet states 16 bits of relative humidity, 16 bits of temperature in Celsius, and an 8-bit checksum. However, the DHT11 always sends 0s for the humidity and temperature fractional bytes. Thus the device really has only 8 bits of precision for each measurement. Presumably, other models (or future ones) provide fractional values for greater precision.

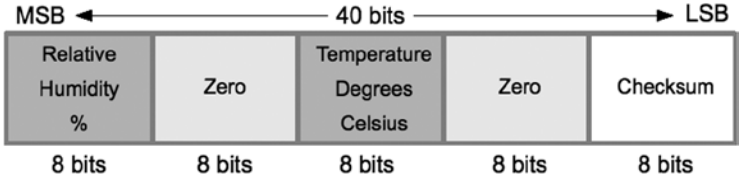


Figure 1-5. *DHT11 data format*

The checksum is a simple sum of the first 4 bytes. Any carry overflow is simply discarded. This checksum gives your application greater confidence that it has received correct values in the face of possible transmission errors.

Software

The user space software written to read the DHT11 sensor on the Raspberry Pi uses the direct register access of the GPIO pin. The challenges presented by this approach include the following:

- Short timings: 26 to 70 μs
- Preemptive scheduling delays within the Linux kernel

One approach is to count how many times the program could read the high-level signal before the end of the bit is reached (when the line goes low). Then decide on 0 bits for shorter times and 1s for longer times. After some experimentation, a dividing line could be drawn, where shorter signals mean 0 while the others are 1s.

The difficulty with this approach is that it doesn't adapt well if the Raspberry Pi is accelerated. When the CPU clock is increased through overclocking, the program will tend to fail. There is also the potential for future Raspberry Pis to include CPUs with higher clock rates.

The signal emitted by the sensor is almost a Manchester encoding. In Manchester encoding, one-half of the wave form is shorter than the other. This allows counting up for the first half and counting down for the second. Based on whether the counter underflows, a decision is made about the value of the bit seen.

The DHT11 signal uses a fixed first half of 50 μs The bit is decided based on how long the signal remains at a high level after that. So a "bit bang" application could get a relative idea by counting the number of times it could read the low-level signal. Based on that, it can get a relative idea of where the dividing line between a short and long high-level signal is.

This is the approach that was adopted by the program `dht11.c`. It counts the number of times in a spin loop that it can read the signal as low. On a 700 MHz nonturbo Raspberry Pi, I saw this count vary between 130 and 330 times, with an average of 292. This time period is supposed to be exactly 50 μs, which illustrates the real-time scheduling problem within a user space program. (The program did not use any real-time Linux priority scheduling.)

If the sensor waveform is true, a max count of 330 suggests that the Raspberry Pi can read the GPIO pin a maximum of

$$\frac{330}{50} = 6.6 reads / \mu s$$

But the minimum of 130 GPIO reads shows a worst case performance of

$$\frac{130}{50} = 2.6 reads / \mu s$$

This variability in preemptive scheduling makes it difficult to do reliable timings.

I have seen the high-level bit counts vary between 26 and 378. (The interested reader can modify the code to record the counts.) If the program is able to read 6.6 times per microsecond, a 1-bit time of 70 μs should yield a count of 462. Yet the maximum seen was 378. Preemptive scheduling prevents the code from performing that many reads without interruption.

The lower count of 26 represents the minimum count for 0 bits, where the line stays high for a shorter period of time. This suggests that each GPIO read is about 1 μs or longer during the 0-bit highs.

The preceding information is just a crude sampling of the problem to illustrate the variability that must be grappled with in a user space program, on a multitasking operating system.

Chosen Approach

The program shown in this chapter uses the following general approach:

1. Count the number of GPIO reads that report that the line is low (call it C_{low}).
2. Compute an adjustment bias B based on $B = \frac{C_{low}}{D}$, where D is some fixed divisor.
3. Compute a new count $K = B + C_{high}$, where C_{high} is the number of times the line was read as high.
4. If the count value $K > C_{low}$, the value is considered a 1-bit; otherwise, it's considered a 0-bit.

The method is intended to at least partially compensate for the level of preemption being seen by the application program. By measuring the low read counts, we get an idea of the number of times we can sample the line at the moment. The approach is intended to adapt itself to a faster-running Raspberry Pi.

Table 1-1 shows some experimental results on an idle Raspberry Pi running at the standard 700 MHz. Different divisors were tried and tested over 5-minute intervals. When the program runs, it attempts to read and report as many sensor readings as it can, tracking good reports, time-out, and error counts. The program was terminated by pressing ^C when an egg timer went off.

Table 1-1. *Bias Test Results*

Divisor	Results	Time-outs	Errors
2	1	17	103
3	48	17	63
4	30	25	56
5	49	14	63
6	45	20	52
7	60	16	47
8	41	20	56
9	42	17	62
10	39	22	53
11	40	14	72
12	43	13	71
13	47	10	75
14	32	19	67
15	28	23	63
16	38	16	69
17	33	14	81
18	34	13	82
19	31	16	75
20	22	18	81

Using no bias at all, no successful reads result (which prompted the idea of applying a bias). Using a divisor of 2 applies too much adjustment, as can be seen by the low number of results (1). Increasing the divisor to the value 3 or more produced a much higher success rate, near 48, which is almost 10 reports per minute. Setting the divisor to 3 seems to yield the most repeatable results overall.

It is uncertain from the datasheets how rapidly the sensor can be requeried. The program takes the conservative approach of pausing 2 seconds between each sensor read attempt or waiting 5 seconds when a time-out has occurred.

The program reports an error when the checksum does not match. Time-outs occur if the code gets stuck waiting for the signal to go low, for too long. This can happen if the program misses a critical event because of preemptive scheduling. It sometimes happens that the high-to-low-to-high event can occur without the program ever seeing it. If the going-low event takes too long, the program performs a `longjmp` into the main loop, to allow a retry.

The errors are reported to `stderr`, allowing them to be suppressed by redirecting unit 2 to `/dev/null` from the command line.

The way that the Raspberry Pi relinquishes the sensor bus is by changing the GPIO pin from an output to an input. When configured as an input, the pull-up resistor brings the bus line high when the bus is idle (the pull-up applies when neither master or slave is driving the bus). When requested, the sensor grabs the bus and drives it high or low. Finally, when the master speaks, we configure the pin as an output, causing the GPIO pin to drive the bus.

Example Run

When the program `dht11` is run, you should see output similar to the following:

```
$ sudo ./dht11
RH 37% Temp 18 C Reading 1
(Error # 1)
(Timeout # 1)
RH 37% Temp 18 C Reading 2
(Timeout # 2)
RH 37% Temp 18 C Reading 3
RH 37% Temp 18 C Reading 4
RH 37% Temp 18 C Reading 5
(Error # 2)
(Timeout # 3)
(Error # 3)
(Error # 4)
(Error # 5)
RH 37% Temp 18 C Reading 6
(Error # 6)
RH 37% Temp 18 C Reading 7
(Error # 7)
(Error # 8)
(Error # 9)
RH 36% Temp 19 C Reading 8
RH 37% Temp 18 C Reading 9
(Timeout # 4)
RH 36% Temp 19 C Reading 10
^C
Program exited due to SIGINT:

Last Read: RH 36% Temp 19 C, 9 errors, 4 timeouts, 10 readings
```

Source Code

The next few pages list the source code for the program. This was assembled into one compile unit by using the `#include` directive. This was done to save pages by eliminating additional header files and `extern` declarations.

■ **Note** The source code for `gpio_io.c` is found in Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014).

```
1  /************************************************************************
2   * dht11.c: Direct GPIO access reading DHT11 humidity and temp sensor.
3   ************************************************************************/
4
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <fcntl.h>
8  #include <unistd.h>
9  #include <errno.h>
10 #include <setjmp.h>
11 #include <sys/mman.h>
12 #include <signal.h>
13
14 #include "gpio_io.c"                 /* GPIO routines */
15 #include "timed_wait.c"              /* timed_wait() */
16
17 static const int gpio_dht11 = 22;    /* GPIO pin */
18 static jmp_buf timeout_exit;         /* longjmp on timeout */
19 static int is_signaled = 0;          /* Exit program if signaled */
20
21/*
22 * Signal handler to quit the program:
23 */
24 static void
25 sigint_handler(int signo) {
26         is_signaled = 1;             /* Signal to exit program */
27 }
28
29 /*
30  * Read the GPIO line status:
31  */
32 static inline unsigned
33 gread(void) {
34          return gpio_read(gpio_dht11);
35 }
36
```

```
37 /*
38  * Wait until the GPIO line goes low:
39  */
40 static inline unsigned
41 wait_until_low(void) {
42         const unsigned maxcount = 12000;
43         unsigned count = 0;
44
45         while ( gread() )
46                if ( ++count >= maxcount || is_signaled )
47                       longjmp(timeout_exit,1);
48         return count;
49 }
50
51 /*
52  * Wait until the GPIO line goes high:
53  */
54 static inline unsigned
55 wait_until_high(void) {
56         unsigned count = 0;
57
58         while ( !gread() )
59                ++count;
60         return count;
61 }
62
63 /*
64  * Read 1 bit from the DHT11 sensor:
65  */
66 static unsigned
67 rbit(void) {
68           unsigned bias;
69           unsigned lo_count, hi_count;
70
71           wait_until_low();
72           lo_count = wait_until_high();
73           hi_count = wait_until_low();
74
75           bias = lo_count / 3;
76
77           return hi_count + bias > lo_count ? 1 : 0 ;
78 }
79
80 /*
81  * Read 1 byte from the DHT11 sensor :
82  */
```

```
83 static unsigned
84 rbyte(void) {
85          unsigned x, u = 0;
86
87          for ( x=0; x<8; ++x )
88                u = (u << 1) | rbit();
89          return u;
90 }
91
92 /*
93  * Read 32 bits of data + 8 bit checksum from the
94  * DHT sensor. Returns relative humidity and
95  * temperature in Celsius when successful. The
96  * function returns zero if there was a checksum
97  * error.
98  */
99  static int
100 rsensor(int *relhumidity, int *celsius) {
101          unsigned char u[5], cs = 0, x;
102          for ( x=0; x<5; ++x ) {
103                u[x] = rbyte();
104                if ( x < 4 )        /* Only checksum data..*/
105                      cs += u[x];   /* Checksum */
106          }
107
108          if ( (cs & 0xFF) == u[4] ) {
109                *relhumidity = (int)u [0];
110                *celsius = (int)u [2];
111                return 1;
112     }
113         return 0;
114 }
115
116 /*
117  * Main program:
118  */
119 int
120 main(int argc, char **argv) {
121           int relhumidity = 0, celsius = 0;
122           int errors = 0, timeouts = 0, readings = 0;
123           unsigned wait;
124
125           signal(SIGINT,sigint_handler); /* Trap on SIGINT */
126
127           gpio_init();                   /* Initialize GPIO access */
128           gpio_config(gpio_dht11,Input); /* Set GPIO pin as Input */
129
```

```
130           for (;;) {
131                   if ( setjmp(timeout_exit) ) { /* Timeouts go here */
132                           if ( is_signaled )  /* SIGINT? */
133                                   break;       /* Yes, then exit loop */
134                           fprintf(stderr," (Timeout # %d)\
                              n",++timeouts);
135                           wait = 5;
136                   } else  wait = 2;
137
138                   wait_until_high();    /* Wait GPIO line to go high */
139                   timed_wait(wait,0,0); /* Pause for sensor ready */
140
141                   gpio_config(gpio_dht11,Output);  /* Output mode */
142                   gpio_write(gpio_dht11,0);        /* Bring line low */
143                   timed_wait(0,30000,0);     /* Hold low min of 18ms */
144                   gpio_write(gpio_dht11,1);  /* Bring line high */
145
146                   gpio_config(gpio_dht11,Input); /* Input mode */
147                   wait_until_low()        /* Wait for low signal */
148                   wait_until_high();      /* Wait for return to high */
149
150                   if ( rsensor(&relhumidity,& celsius) )
151                          printf("RH %d%% Temp %d C Reading %d\n",
                        relhumidity, celsius,++readings);
152                   else fprintf(stderr," (Error # %d)\n",++errors);
153           }
154
155           gpio_config(gpio_dht11,Input); /* Set pin to input mode */
156
157           puts("\ nProgram exited due to SIGINT: \n");
158           printf("Last Read: RH %d%% Temp %d C, %d errors, "
                  "%d timeouts, %d readings \n",
159                    relhumidity, celsius, errors, timeouts, readings);
160           return 0;
161 }
162
163 /* End dht11.c */
```

```
/*************************************************************************
 * Implement a precision "timed wait". The parameter early_usec
 * allows an interrupted select(2) call to consider the wait as
 * completed, when interrupted with only "early_usec" left remaining.
 *************************************************************************/
static void
timed_wait(long sec,long usec,long early_usec) {
  fd_set mt;
  struct timeval timeout;
  int rc;

  FD_ZERO(&mt);
  timeout.tv_sec = sec;
  timeout.tv_usec = usec;
  do {
      rc = select (0,&mt,&mt,&mt,&timeout);
      if ( ! timeout.tv_sec && timeout.tv_usec < early_usec )
          return;   /* Wait is good enough, exit */
   } while ( rc < 0 && timeout.tv_sec && timeout.tv_usec );
}

/* End timed_wait.c */
```

CHAPTER 2

MCP23017 GPIO Extender

Microchip's MCP23017 provides 16 additional GPIO pins that can be purchased for as little as $1.99. The chip communicates using the I2C bus. (The companion MCP23S17 is available for SPI bus.) The I2C bus allows the chip to be remote from the Raspberry Pi, requiring only a four-wire ribbon cable (power, ground, and a pair of I2C bus lines). This chapter explores the features and limits of this peripheral.

DC Characteristics

When shopping for chips or interface PCBs based on a particular chip, the first thing I look at is the operating supply voltage. 5 V parts are inconvenient for the Pi because of its 3.3 V GPIO interface. Many newer devices operate over a range of voltages, which include 3.3 V. The MCP23017 supply V_{DD} operates from an extended range of +1.8 V to +5.5 V. This clearly makes it compatible, if we power the chip from a +3.3 V source. Figure 2-1 shows the MCP23017 chip pinout diagram.

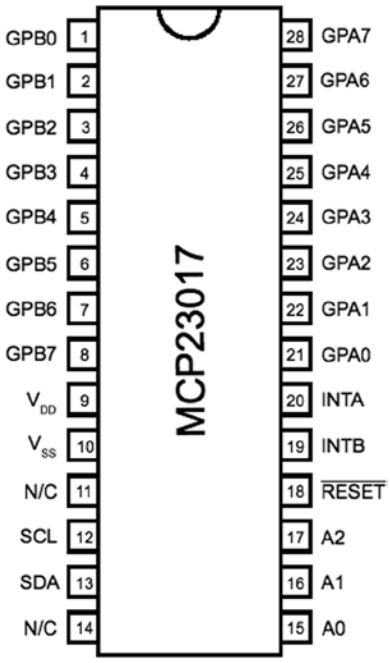


Figure 2-1. *MCP23017 pinout*

GPIO Output Current

Another factor in choosing a peripheral chip is its output drive capability. How well can the GPIO pin source or sink current? As covered in Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014), the Raspberry Pi's own GPIO pins can source/sink up to 16 mA, depending on configuration. The MCP23017 chip specifications indicate that it can source or sink up to 25 mA.

We still need to remember that if the MCP23017 is powered from the Raspberry Pi's 3.3 V regulator on header P1, the total current budget must not exceed 50 mA. This budget includes the Pi's own GPIO pin current usage. If, on the other hand, the MCP23017 is powered from a separate 3.3 V power supply, this limitation is eliminated.

There are still reasons to budget current, however. The chip must not consume more than 700 mW of power. This implies a total current limit as follows:

$$\begin{aligned} I_{VDD} &= \frac{P}{V_{DD}} \\ &= \frac{0.7}{3.3} \\ &= 212mA \end{aligned}$$

This power figure gives us an upper current limit. However, the datasheet of the MCP23017 also lists a maximum of 125 mA for supply pin V_{DD}. If every GPIO output is sourcing power, this leaves us with the following average pin limit:

$$\frac{125mA}{16} = 7.8mA$$

So while the output GPIO pins can *source* up to 25 mA, we cannot have all of them doing so simultaneously.

Likewise, the datasheet lists V_{SS} (ground) as limited to an absolute maximum of 150 mA. If every GPIO pin is an output and sinking current, the average for each output pin cannot exceed the following:

$$\frac{150mA}{16} = 9.4mA$$

Once again, while each output pin can *sink* up to 25 mA, we see that they cannot all do so at the same time without exceeding chip limits. This should not be discouraging, because in most applications, not all GPIO pins will be outputs, and not all will all be driving heavy loads. The occasional pin that needs driving help can use a transistor driver like the one discussed in Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014).

Before we leave the topic of GPIO output driving, we can apply one more simple formula to help with interface design. With the foregoing information, we can calculate the number of 25 mA outputs available:

$$\frac{125mA}{25mA} = 5$$

From this, it is known that four to five GPIO pins can operate near their maximum limits, as long as the remaining GPIO pins are inputs or remain unconnected.

GPIO Inputs

In normal operation, the GPIO inputs should never see a voltage below the ground potential V_{SS}. Nor should they ever see a voltage above the supply voltage V_{DD}. Yet, variations can sometimes happen when interfacing with the external world, particularly with inductive components.

The datasheet indicates that clamping diodes provide some measure of protection against this. Should the voltage on an input drop below 0, it is clamped by a diode so it will not go further negative and cause harm. The voltage limit is listed at –0.6 V, which is the voltage drop of the clamping diode. Likewise, if the voltage goes over V_{DD} (+3.3 V in our case), the clamping diode will limit the excursion to $V_{DD} + 0.6\ V$ (+3.9 V).

This protection is limited by the current capability of the clamping diodes. The datasheet lists the maximum clamping current as 20 mA. If pins are forced beyond their limits and the clamping current is exceeded, damage will occur.

While we have focused on GPIO inputs in this section, the clamping diodes also apply to outputs. Outputs can be forced beyond their limits by external circuits like pull-up resistors. Pull-up resistors should not be attached to +5 V, for example, when the MCP23017 is operating from a +3.3 V supply.

Standby Current

If the MCP23017 device is not sourcing or sinking output currents, the standby current is stated as 3 μA (for 4.5 to 5.5 V operation). This operating parameter is important to designers of battery-operated equipment.

Input Logic Levels

Since the device operates over a range of supply voltages, the datasheet defines the logic levels in terms of the supply voltage. For example, the GPIO input low level is listed as $0.2 \times V_{DD}$. So if we operate with V_{DD}= +3.3 V, the input low voltage is calculated as follows:

$$\begin{aligned} V_{IL_{\max}} &= 0.2 \times V_{DD} \\ &= 0.2 \times 3.3 \\ &= 0.66V \end{aligned}$$

Therefore, a voltage in the range of 0 to 0.66 V is guaranteed to read as a 0 bit.

Likewise, let's calculate the input high voltage threshold, where the multiplier is given as 0.8:

$$\begin{aligned} V_{IH_{\min}} &= 0.8 \times V_{DD} \\ &= 0.8 \times 3.3 \\ &= 2.64V \end{aligned}$$

Thus any voltage greater than or equal to 2.64 V is read as a 1 bit, when powered from a +3.3 V supply. Any voltage between V_{ILmax} and V_{IHmin} is undefined and reads as a 1 or a 0, and perhaps randomly so.

Output Logic Levels

The output logic levels are stated differently. The datasheet simply states that the output low voltage should not exceed a fixed limit. The high level is also stated as a minimum value relative to V_{DD}. This pair of parameters is listed here:

$$\begin{aligned} V_{OL\max} &= 0.6\,V \\ V_{OH\min} &= V_{DD} - 0.7\ V \\ &= 3.3 - 0.7 \\ &= 2.7\,V \end{aligned}$$

Reset Timing

The only parameter of interest for timing apart from the I2C bus is the device reset time. In order for the device to see a reset request, pin $\overline{RESET}$ must remain active (low) for a minimum of 1 µs. The device resets and places outputs into the high-impedance mode within a maximum of 1 µs.

Circuit

Figure 2-2 shows a circuit with two remote MCP23017 GPIO extenders connected to one I2C bus. In the figure, the power, ground, I2C data, and optional $\overline{RESET}$ and $\overline{INT}$ connections are shown connected through a six-conductor ribbon cable. This allows the Raspberry Pi to communicate remotely to peripherals in a robot, for example.

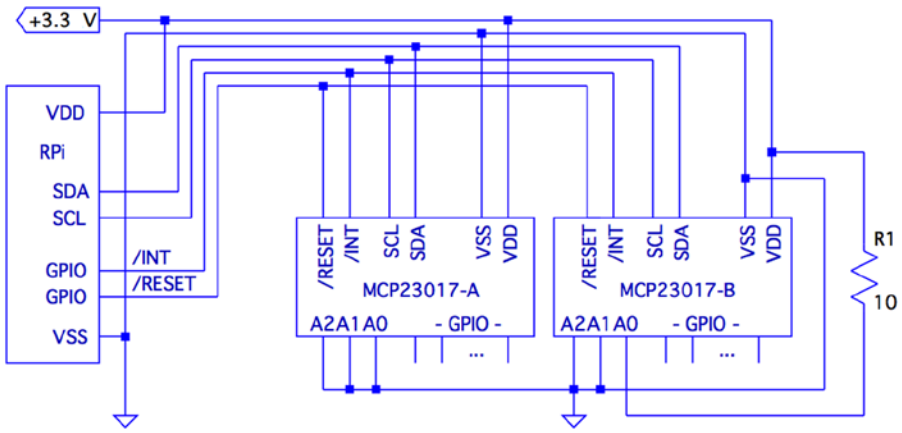


Figure 2-2. *MCP23017 circuit*

The data communication occurs over the pair of signals SDA and SCL. These are connected to the Raspberry Pi's pins P1-03 and P1-05, respectively (GPIO 2 and 3 for Rev 2.0+). The other end of the I2C data bus is common to all slave peripherals.

Each MCP23017 slave device is addressed by its individually configured A2, A1, and A0 pins. For device A, these pins are shown grounded to define it as device number `0x20` (low bits are zeroed). A1 is tied high for device B so that its peripheral address becomes `0x21`. In this configuration, the Raspberry Pi will use addresses `0x20` and `0x21` to communicate with these slave devices.

Lines labeled $\overline{RESET}$ and $\overline{INT}$ are optional connections. The $\overline{RESET}$ line can be eliminated if you never plan to force a hardware reset of the slaves (tie to V_{DD} through a 10 K resistor). Usually the power-on reset is sufficient. The $\overline{INT}$ line is more desirable, since the MCP23017 can be programmed to indicate interrupts when a GPIO input has changed in value (or does not match a comparison value). The $\overline{INT}$ line is an open collector pin so that many can be tied together on the same line. However, the Pi will have

to poll each peripheral to determine which device is causing the interrupt. Alternatively, each slave could provide a separate $\overline{INT}$ signal, with a corresponding increase in signal lines.

Each MCP23017 chip has two interrupt lines, named $\overline{INT\ A}$ and $\overline{INT\ B}$. There is the option of separate interrupt notifications for the A group or the B group of GPIO pins. For remote operation, it is desirable to take advantage of MCP23017's ability to configure these to work in tandem, so that only one $\overline{INT}$ line is required.

On the Raspberry Pi end, the GPIO pin used for the $\overline{RESET}$ line would be configured as an output and held high, until a reset is required. When activating a reset, the line must be held low for at least 1 microsecond, plus 1 more microsecond to allow for the chip reset operation itself (and possibly longer, if non-MCP23017 slaves are connected to the bus).

The $\overline{INT}$ line should be connected to a GPIO *input* on the Pi. This GPIO input either needs to be polled by the application, or to have the GPIO configured to trigger on changes. Then the `select(2)` or `poll(2)` system calls can be used to detect when an interrupt is raised by one or more peripherals.

The interrupt line, when used, should have a pull-up resistor configured (see Chapter 10 of *Raspberry Pi Hardware Reference* [Apress, 2014] for information about internal pull-up resistors). It may be best to use an external pull-up resistor, especially for longer cable runs. To keep the sink current at 2 mA or less, the pull-up resistance used should be no lower than the following:

$$R_{pullup} = \frac{+3.3V}{2mA} = 1650\Omega$$

A 2.2 *k*Ω 10% resistor will do nicely.

The +3.3 V line should be powered separately from the Raspberry Pi, unless the slaves expect to drive very low currents. The main concern here is to not overload the remaining 50 mA capacity of the Pi's +3.3 V regulated supply. See Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014) about budgeting +3.3 V power.

I2C Bus

Throughout this chapter, we are assuming a Rev 2.0 or later Raspberry Pi. This matters for the I2C bus because the early versions wired I2C bus 0 to P1-03 and P1-05 (GPIO 0 and 1). Later this was changed to use bus 1. See Chapter 12 of *Raspberry Pi Hardware Reference* (Apress, 2014) for more information about identifying your Pi and which I2C bus to use. If you are using an early Raspberry Pi revision, you'll need to substitute 0 for bus number 1, in commands and in the C source code that follows.

Wiring and Testing

The connections to the MCP23017 are simple enough that you can wire it up on a breadboard. The first step after wiring is to determine that you can detect the peripheral on the I2C bus.

But even before that, check your kernel module support. If `lsmod` doesn't show these modules loaded, you can manually load them now:

```
$ sudo modprobe i2c-dev
$ sudo modprobe i2c-bcm2708
```

If you haven't already done so, install `i2c-tools`:

```
$ sudo apt-get install i2c-tools
```

If your I2C support is there, you should be able to list the available I2C buses:

```
$ i2cdetect -l
i2c -0  unknown         bcm2708_i2c.0                   N/A
i2c -1  unknown         bcm2708_i2c.1                   N/A
```

The I2C device nodes should also appear in `/dev`. These nodes give us access to the I2C drivers:

```
$ ls -l /dev/i2c*
crw-rw---T  1  root root  89, 0  Feb 18 23:53  /dev/i2c-0
crw-rw---T  1  root root  89, 1  Feb 18 23:53  /dev/i2c-1
```

The ultimate test is to see whether the MCP23017 chip is detected (change the 1 to 0 for older Pi revisions):

```
$ sudo i2cdetect -y 1
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:          -- -- -- -- -- -- -- -- -- -- -- -- --
10: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
20: 20 -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
30: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
40: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
50: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
60: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
70: -- -- -- -- -- -- -- --
```

In this example, the A2, A1, and A0 pins of the MCP23017 were grounded. This gives the peripheral the I2C address of `0x20`. In the session output, we see that address `0x20` was detected successfully.

The `i2cdump` utility can be used to check the MCP23017 register:

```
$  sudo  i2cdump  -y  -r   0x00-0x15 1 0x20 b
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f  0123456789abcdef
00: ff ff 00 00 00 00 00 00 00 00 00 00 00 00 00 00  ................
10: 00 00 00 00 00 00                               ......
```

Here we have dumped out registers `0x00` to `0x15` on I2C bus 1, at peripheral address `0x20`, in byte mode. This was performed after a power-on reset, so we can check whether the register values match the datasheet values documented. As expected, `IODIRA` (register `0x00`) and `IODIRB` (register `0x01`) have the default of all 1s (`0xFF`). This also confirms that the registers are in `BANK=0` mode (this is discussed in the following sections). All other MCP23017 registers default to 0 bits, which is also confirmed.

Software Configuration

The MCP23017 datasheet describes the full register complement and options available. In this chapter, we'll concern ourselves with a subset of its functionality, which is perhaps considered "normal use." The extended functionality is left as an exercise for you.

For this chapter's project, we're going to do the following:

- Configure some GPIOs as inputs
- Configure some GPIOs as outputs
- Configure the group A and B inputs to signal an interrupt on any change

General Configuration

The MCP23017 peripheral has 10 registers for the GPIO-A pins, 10 registers for the GPIO-B pins, and one shared register. In other words, there are 22 registers, with one pair of addresses referencing a common register. These registers may be accessed in banks or interleaved. We'll use interleaved mode in this chapter, to avoid having to reset the device.

Interleaved register addresses are shown in Table 2-1. These are valid addresses when the `IOCON` register value for `BANK=0` (discussed later in this section).

Table 2-1. *MCP23017 Register Addresses*

Register	A	B	Description
IODIRx	0x00	0x01	I/O direction
IPOLx	0x02	0x03	Input polarity
GPINTENx	0x04	0x05	Interrupt on change control
DEFVALx	0x06	0x07	Default comparison value
INTCONx	0x08	0x09	Interrupt control
IOCONx	0x0A	0x0B	Configuration
GPPUx	0x0C	0x0D	Pull-up configuration
INTFx	0x0E	0x0F	Interrupt flags
INTCAPx	0x10	0x11	Interrupt captured value
GPIOx	0x12	0x13	General-purpose I/O
OLATx	0x14	0x15	Output latch

IOCON Register

This is the first register that must be configured, since it affects how registers are addressed. Additionally, other settings are established that affect the entire peripheral.

Table 2-2 illustrates the layout of the `IOCON` register. Setting the `BANK` bit determines whether we use banked or interleaved register addressing. The MCP23017 is in interleaved mode after a power-on reset. Once you set `BANK=1`, the register addresses change. However, once this change is made, it is impossible to tell, after a program restart, which register mode the peripheral is in. The only option is a hardware reset of the MCP23017 chip, to put it in a known state. For this reason, we'll keep the peripheral in its power-on reset state of `BANK=0`.

Table 2-2. *IOCON Register*

Bit	Meaning	R	W	Reset	Description
7	BANK	Y	Y	0	Set to 0 for interleaved access
6	MIRROR	Y	Y	0	Set to 1 to join INTA & INTB
5	SEQOP	Y	Y	0	Set to 0 for auto-address increment
4	DISSLW	Y	Y	0	Set to 1 to disable slew rate control
3	HAEN	Y	Y	0	Ignored: I2C always uses address
2	ODR	Y	Y	0	Set to 1 for open-drain INT pins
1	INTPOL	Y	Y	0	Set to 0 for INT active low
0	N/A	0	X	0	Ignored: reads as zero

	GPIO	**Address**	**Note**
	A	0x0A	These access a shared register
	B	0x0B	

In the tables that follow, a Y under the R (read) or W (write) column/row indicates that you can read or write the respective value. The Reset column indicates the state of the bit after a device reset. An X indicates a "don't care" or an undefined value when read. An N indicates no access or no effect when written.

The bit `MIRROR=1` is used to make $\overline{INT\ A}$ equivalent to $\overline{INT\ B}$. In other words, GPIO A and B interrupts are reported to both pins. This allows a single pin to be used for A and B groups.

Setting bit `SEQOP=0` allows the peripheral to automatically increment the register address as each byte is read or written. This eliminates the need to transmit a register address in many cases.

Bit `DISSLW` affects the physical handling of the SDA I2C bus line.

`HAEN` is applicable only to the MCP23S17 SPI device, since addresses are always enabled for I2C devices.

This project uses `ODR=1` to configure the $\overline{INT\ A}$ pin as an open-drain pin. This allows multiple MCP23017 devices to share the same interrupt line. Use a pull-up resistor on the $\overline{INT}$ line when this is in effect. Otherwise, you may experience several sporadic interrupts.

Finally, `INTPOL=0` is configured so that the interrupt is active low. This is required for an open-drain connected line along with a pull-up resistor.

OLATx Register

GPIO pins are all configured as inputs after a power-on reset (or use of $\overline{RESET}$). Prior to configuring pins as outputs, it is usually a good idea to set the required output values. This is accomplished by writing the OLAT register, for group A or B. For this project, we'll just write 0x00 to both OLATA and OLATB.

	OLATx Register								GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x14
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x15
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	0	0	0	0	0	0	0	0		

OLATx Bit Value	
0	Output set to 0
1	Output set to 1

GPPUx Register

A given project should also define a known value for its input pull-up resistors. Setting a given bit to 1 enables a weak 100 *K*Ω internal pull-up resistor. This setting affects only the inputs. The pull-up resistors are configured off after a reset. In our example code, we turn them on.

	GPPUx Register								GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x0C
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x0D
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	0	0	0	0	0	0	0	0		

GPPUx Bit Value	
0	Pull-up resistor disabled
1	100 KΩ pull-up resistor enabled

DEFVALx Register

This register is associated with interrupt processing. Interrupts are produced from conditions arising from input GPIO pins only. An interrupt can be generated if the input differs from the DEFVALx register or if the input value has *changed*. In the project presented, we simply zero this value because it is not used when detecting *changed* inputs.

DEFVALx Register									GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x06
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x07
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	0	0	0	0	0	0	0	0		

DEFVALx Bit Value	
0	Interrupt when input not 0
1	Interrupt when input not 1

INTCONx Register

This register specifies how input comparisons will be made. In our project, we set all these bits to 0 so that inputs interrupt on *change*.

INTCONx Register									GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x08
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x09
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	0	0	0	0	0	0	0	0		

INTCONx Bit Value	
0	Input compared against its previous value
1	Input compared against DEFCONx bit value

IPOLx Register

Bits set in this register will invert the logic sense of the corresponding GPIO inputs. In our project, we used no inversion and set the bits to 0.

IPOLx Register									GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x02
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x03
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	0	0	0	0	0	0	0	0		

IPOLx Bit Value	
0	Read same logic as input pin
1	Read inverted logic of input pin

IODIRx Register

This register determines whether a given GPIO pin is an input or an output. Our project defines bits 4 through 7 as inputs, with the remaining bits 0 through 3 of each 8-bit port as outputs.

IODIRx Register									GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x00
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x01
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	1	1	1	1	1	1	1	1		

IODIRx Bit Value	
0	Pin is configured as an output
1	Pin is configured as an input

GPINTENx Register

This register enables interrupts on input pin events. Only inputs generate interrupts, so any enable bits for output pins are ignored. How the interrupt is generated by the input is determined by registers DEFVALx and INTCONx.

GPINTENx Register									GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x04
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x05
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	0	0	0	0	0	0	0	0		

GPINTENx Bit Value	
0	Disable interrupts on this input
1	Enable interrupts for this input

For this project, we enabled interrupts on all inputs for ports A and B.

INTFx Register

This interrupt flags register contains the indicators for each input pin causing an interrupt. This register is *unwritable*.

Interrupt service routines start with this register to identify which inputs are the cause of the interrupt. The DEFVALx and INTCONx registers configure how those interrupts are generated. The INTFx flags are cleared by reading the corresponding INTCAPx or GPIOx register.

INTFx Register									GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x0E
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x0F
W	N	N	N	N	N	N	N	N		
Reset	0	0	0	0	0	0	0	0		

INTFx Bit Value	
0	No interrupt for this input
1	Input has changed or does not compare

INTCAPx Register

The interrupt capture register reports the status of the inputs as the interrupt is being raised. This register is read-only. Reading this register clears the INTFx register, to allow new interrupts to be generated. When $\overline{INT\ A}$ is linked to $\overline{INT\ B}$, both INTCAPA and INTCAPB must be read to clear the interrupt (or read the GPIOx registers).

	INTCAPx Register								GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x10
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x11
W	N	N	N	N	N	N	N	N		
Reset	0	0	0	0	0	0	0	0		

INTCAPx Bit Value	
0	Input state was 0 at time of interrupt
1	Input state was 1 at time of interrupt

GPIOx Register

Reading this register provides the current input pin values, for pins configured as inputs. Reading the GPIOx register also clears the interrupt flags in INTFx. When $\overline{INT\ A}$ is linked to $\overline{INT\ B}$, both GPIOA and GPIOB must be read to clear the interrupt (or read the INTCAPx registers).

Presumably, the OLATx register is read, for pins configured for output (the datasheet doesn't say). Writing to the GPIOx register alters the OLATx settings in addition to immediately affecting the outputs.

	GPIOx Register								GPIO	Address
Bit	7	6	5	4	3	2	1	0	A	0x12
R	Y	Y	Y	Y	Y	Y	Y	Y	B	0x13
W	Y	Y	Y	Y	Y	Y	Y	Y		
Reset	X	X	X	X	X	X	X	X		

Value	R/W	GPIOx Bit Value
0	R	Current input pin state is low
	W	Write 0 to OLATx and output pin
1	R	Current input pin state is high
	W	Write 1 to OLATx and output pin

Main Program

Here are some change notes for the main program:

1. If you have a pre-revision 2.0 Raspberry Pi, change line 36 to use `/dev/i2c-0`.
2. Change line 55 if your MCP23017 chip is using a different I2C address than `0x20` (A2, A1, and A0 grounded).
3. Change line 56 if you use a different Raspberry Pi GPIO for your interrupt sense pin.

The main program is fairly straightforward. Here are the basic overall steps:

1. A signal handler is registered in line 180, so `^C` will cause the program to exit cleanly.
2. Routine `i2c_init()` is called to open the I2C driver and initialize.
3. Routine `mcp23017_init()` is called to initialize and configure the MCP23017 device on the bus (only one is currently supported).
4. Routine `gpio_open_edge()` is called to open `/sys/class/gpio17/value`, so changes on the interrupt line can be sensed. This is discussed in more detail later.
5. Finally, the main program enters a loop in lines 190 to 200, looping until `^C` is entered.

Once inside the main loop, the following events occur:

1. Execution stalls when `gpio_poll()` is called. This blocks until the interrupt on GPIO 17 transitions from a high to a low.
2. The interrupt flags are read using routine `mcp23017_interrupts()`. They're only reported and otherwise not used.
3. Routine `mcp23017_captured()` is used to read the `INTCAPA` and `INTCAPB` registers in order to clear the interrupt.
4. Finally, the routine `post_outputs()` reads the real-time input values and sends the bits to the outputs.

Program mcp23017.c is shown here:

```
/*****************************************************************
* mcp23017.c :  Interface with MCP23017 I/O Extender Chip
*
* This code assumes the following :
*
*      1.   MCP23017 is configured for address 0x20
*      2.   RPi's GPIO 17 (GEN0) will be used for sensing interrupts
*      3.   Assumed there is a pull up on GPIO 17.
*      4.   MCP23017 GPA4-7 and GPB4-7 will be inputs, with pull-ups.
*      5.   MCP23017 GPA0-3 and GPB0-3 will be ouputs.
*      6.   MCP23017 signals interrupt active low.
*      7.   MCP23017 operating in non-banked register mode.
*
*  Inputs sensed will be copied to outputs :
*      1. GPA4-7 copied to GPA0-3
*      2. GPB4-7 copied to GPB0-3
*
*****************************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <unistd.h>
#include <string.h>
#include <errno.h>
#include <signal.h>
#include <assert.h>
#include <sys/ioctl.h>
#include <sys/poll.h>
#include <linux/i2c.h>
#include <linux/i2c-dev.h>

#include "i2c_funcs.c"              /* I2C  routines  */

/* Change to i2c 0 if using early Raspberry Pi */
static const char * node = "/dev/i2c-1";

#define GPIOA        0
#define GPIOB        1

#define IODIR        0
#define IPOL         1
#define GPINTEN      2
#define DEFVAL       3
#define INTCON       4
#define IOCON        5
```

```
47  #define GPPU         6
48  #define INTF         7
49  #define INTCAP       8
50  #define GPIO         9
51  #define OLAT         10
52
53  #define MCP_REGISTER(r,g) (((r) <<1)|(g)) /* For I2C routines */
54
55  static unsigned gpio_addr = 0x20;   /* MCP23017 I2C Address */
56  static const int gpio_inta = 17;    /* GPIO pin for INTA connection */
57  static int is_signaled = 0;         /* Exit program if signaled */
58
59  #include "sysgpio.c"
60
61  /*
62   * Signal handler to quit the program  :
63   */
64  static void
65  sigint_handler(int signo) {
66          is_signaled = 1;            /* Signal to exit program */
67  }
68
69  /*
70   * Write to MCP23017 A or B register set:
71   */
72  static int
73  mcp23017_write(int reg,int AB,int value) {
74           unsigned reg_addr = MCP_REGISTER(reg,AB);
75           int rc;
76
77           rc = i2c_write8(gpio_addr,reg_addr,value);
78           return rc;
79  }
80
81  /*
82   * Write value to both MCP23017 register sets  :
83   */
84  static void
85  mcp23017_write_both(int reg,int value) {
86          mcp23017_write(reg,GPIOA,value);  /* Set A */
87          mcp23017_write(reg,GPIOB,value);  /* Set B */
88  }
89
90  /*
91   * Read the MCP23017 input pins (excluding outputs,
92   * 16-bits) :
93   */
```

```
94  static unsigned
95  mcp23017_inputs(void) {
96          unsigned reg_addr = MCP_REGISTER(GPIO,GPIOA);
97
98
99          return i2c_read16(gpio_addr,reg_addr) & 0xF0F0;
100 }
101
102 /*
103  * Write 16 bits to outputs  :
104  */
105 static void
106 mcp23017_outputs(int value) {
107         unsigned  reg_addr = MCP_REGISTER(GPIO,GPIOA);
108
109         i2c_write16 (gpio_addr,reg_addr,value & 0x0F0F);
110 }
111
112 /*
113  * Read MCP23017 captured values (16-bits):
114  */
115  static unsigned
116  mcp23017_captured(void) {
117          unsigned reg_addr = MCP_REGISTER(INTCAP,GPIOA);
118
119          return i2c_read16(gpio_addr,reg_addr) & 0xF0F0;
120 }
121
122 /*
123  * Read interrupting input flags (16-bits) :
124  */
125 static unsigned
126 mcp23017_interrupts(void) {
127         unsigned  reg_addr = MCP_REGISTER(INTF,GPIOA);
128
129         return i2c_read16(gpio_addr,reg_addr) & 0xF0F0;
130 }
131
132 /*
133  * Configure the MCP23017 GPIO Extender :
134  */
135 static void
136 mcp23017_init(void) {
137        int v, int_flags;
138
139        mcp23017_write_both(IOCON,0b01000100); /* MIRROR=1,ODR=1 */
140        mcp23017_write_both(GPINTEN,0x00);    /* No interrupts enabled */
```

```
141         mcp23017_write_both(DEFVAL,0x00);       /* Clear default value */
142         mcp23017_write_both(OLAT,0x00);         /* OLATx=0 */
143         mcp23017_write_both(GPPU,0b11110000);   /* 4-7 are pull up */
144         mcp23017_write_both(IPOL,0b00000000);   /* No inverted polarity */
                                                    /* 4-7 inputs, 0-3 outputs */
145         mcp23017_write_both(IODIR,0b11110000);
146         mcp23017_write_both(INTCON,0b00000000); /* Cmp to previous */
147         mcp23017_write_both(GPINTEN,0b11110000); /* Int on changes */
148
149         /*
150          * Loop until all interrupts are cleared:
151          */
152         do    {
153                 int_flags = mcp23017_interrupts();
154                 if ( int_flags != 0 ) {
155                         v = mcp23017_captured();
156                         printf("  Got change %04X values %04X\n",int_
                                flags,v);
157                 }
158         } while ( int_flags  != 0x0000 && !is_signaled  );
159 }
160
161 /*
162  * Copy input bit settings to outputs :
163  */
164 static void
165 post_outputs(void) {
166          int inbits = mcp23017_inputs(); /* Read inputs */
167          int outbits = inbits >> 4;      /* Shift to output bits */
168          mcp23017_outputs(outbits);      /* Copy inputs to outputs */
169          printf ("   Outputs:     %04X\n",outbits);
170 }
171
172 /*
173  *Main program  :
174  */
175 int
176 main(int argc,char **argv) {
177           int int_flags, v;
178           int fd;
179
180           signal(SIGINT,sigint_handler);  /* Trap on SIGINT */
181
182           i2c_init(node);                 /* Initialize for I2C */
183           mcp23017_init();                /* Configure MCP23017 @ 20 */
184
185           fd = gpio_open_edge(gpio_inta); /* Configure INTA pin */
186
```

```
187          puts("Monitoring for MCP23017 input changes :\n");
188          post_outputs();                 /* Copy inputs to outputs */
189
190          do    {
191                  gpio_poll(fd);          /* Pause until an interrupt */
192
193                  int_flags = mcp23017_interrupts();
194                  if ( int_flags )  {
195                         v = mcp23017_captured();
196                         printf(" Input change: flags %04X values
                           %04X\n",
197                                    int_flags,v);
198                         post_outputs();
199                  }
200          } while ( !is_signaled  );  /* Quit if ^C' d */
201
202          fputc('\n', stdout);
203
204          i2c_close();                /* Close I2C driver */
205          close(fd);                  /* Close gpio17/value */
206          gpio_close(gpio_inta);      /* Unexport gpio17 */
207          return 0;
208 }
209
210 /* End mcp23017.c */
```

Module i2c_funcs.c

To compile code when making use of I2C, you will need to install the `libi2c` development library:

```
$ sudo apt-get install libi2c-dev
```

The `i2c_funcs.c` is a small module that wraps the `ioctl(2)` calls into neat little I/O functions:

`i2c_write8()`: Writes 8-bit value to MCP23017 register

`i2c_write16()`: Writes 16-bit value to MCP23017 register

`i2c_read8()`: Reads 8-bit value from MCP23017 register

`i2c_read16()`: Reads 16-bit value from MCP23017 register

Additionally, the open and close routines are provided:

`i2c_init()`: Opens the bus driver for `/dev/i2c-x`

`i2c_close()`: Closes the opened I2C driver

The C API for these I2C functions are described in Chapter 12 of *Raspberry Pi Hardware Reference* (Apress, 2014).

```
/************************************************************************
 * i2c_funcs.c : I2C Access Functions
 ************************************************************************/

static int i2c_fd =  -1;              /* Device node : /dev/i2c-1 */
static unsigned long i2c_funcs = 0;   /* Support flags */

/*
 * Write 8 bits to I2C bus peripheral:
 */
int
i2c_write8(int addr,int reg,int byte) {
        struct i2c_rdwr_ioctl_data msgset;
        struct i2c_msg iomsgs[1];
        unsigned char buf[2];
        int rc;

        buf[0] = (unsigned char)reg;   /* MCP23017 register no. */
        buf[1] = (unsigned char)byte;  /* Byte to write to register */

        iomsgs[0].addr  = (unsigned)addr;
        iomsgs[0].flags = 0;           /* Write */
        iomsgs[0].buf   = buf;
        iomsgs[0].len   = 2;

        msgset.msgs  = iomsgs;
        msgset.nmsgs = 1;

        rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
        return rc < 0 ? -1 : 0;
}

/*
 * Write 16 bits to Peripheral at address :
 */
int
i2c_write16(int addr, int reg, int value) {
        struct i2c_rdwr_ioctl_data msgset;
        struct i2c_msg iomsgs[1];
        unsigned char buf[3];
        int rc;

```

```
43          buf[0] = (unsigned char)reg;
44          buf[1] = (unsigned char)(( value >> 8 ) & 0xFF);
45          buf[2] = (unsigned char)(value & 0xFF);
46
47          iomsgs[0].addr = (unsigned)addr;
48          iomsgs[0].flags = 0;          /* Write */
49          iomsgs[0].buf = buf;
50          iomsgs[0].len = 3;
51
52          msgset.msgs = iomsgs;
53          msgset.nmsgs = 1;
54
55          rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
56          return rc < 0 ? -1 : 0;
57  }
58
59  /*
60   * Read 8-bit value from peripheral at addr :
61   */
62  int
63  i2c_read8(int addr,int reg) {
64            struct i2c_rdwr_ioctl_data msgset;
65            struct i2c_msg iomsgs[2];
66            unsigned char buf[1], rbuf[1];
67            int rc;
68
69            buf[0] = (unsigned char)reg;
70
71            iomsgs[0].addr = iomsgs[1].addr = (unsigned)addr;
72            iomsgs[0].flags = 0;          /* Write */
73            iomsgs[0].buf = buf;
74            iomsgs[0].len = 1;
75
76            iomsgs[1].flags = I2C_M_RD;   /* Read */
77            iomsgs[1].buf = rbuf;
78            iomsgs[1].len = 1;
79
80            msgset.msgs = iomsgs;
81            msgset.nmsgs = 2;
82
83            rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
84            return rc < 0 ? -1 : ((int)(rbuf[0]) & 0x0FF);
85  }
86
```

```
87  /*
88   * Read 16- bits of data from peripheral :
89   */
90  int
91  i2c_read16(int addr,int reg)  {
92            struct i2c_rdwr_ioctl_data msgset;
93            struct i2c_msg iomsgs[2];
94            unsigned char buf[1], rbuf [2];
95            int rc;
96
97            buf[0] = (unsigned char)reg;
98
99            iomsgs[0].addr = iomsgs[1].addr = (unsigned)addr;
100           iomsgs[0].flags = 0;          /* Write */
101           iomsgs[0].buf = buf;
102           iomsgs[0].len = 1;
103
104           iomsgs[1].flags = I2C_M_RD;
105           iomsgs[1].buf = rbuf;          /* Read */
106           iomsgs[1].len = 2;
107
108           msgset.msgs = iomsgs;
109           msgset.nmsgs = 2;
110
111           if ( (rc = ioctl(i2c_fd,I2C_RDWR,&msgset)) < 0 )
112                 return  -1;
113           return  (rbuf[0] << 8) | rbuf[1];
114 }
115
116 /*
117  * Open I2C bus and check capabilities :
118  */
119 static void
120 i2c_init(const char * node) {
121         int rc;
122
123         i2c_fd = open(node,O_RDWR);         /* Open driver /dev/i2s-1 */
124         if ( i2c_fd < 0 ) {
125                  perror("Opening /dev/i2s-1");
126                  puts("Check that the i2c dev & i2c-bcm2708  kernel
                         modules "
127                       "are loaded.");
128                  abort();
129         }
130
```

```
131         /*
132          * Make sure the driver supports plain I2C I/O:
133          */
134         rc = ioctl(i2c_fd,I2C_FUNCS,&i2c_funcs);
135         assert(rc >= 0) ;
136         assert(i2c_funcs & I2C_FUNC_I2C);
137 }
138
139 /*
140  * Close the I2C driver  :
141  */
142 static void
143 i2c_close(void) {
144         close(i2c_fd);
145         i2c_fd = -1;
146 }
147
148 /* End i2c_funcs.c  */
```

Module sysgpio.c

The `sysgpio.c` module performs some grunt work in making the `/sys/class/gpio17/value` node available and configuring it. This node is opened for reading, so that `poll(2)` can be called upon it.

The interesting code in this module is found in lines 89 to 106, where `gpio_poll()` is defined. The file descriptor passed to it as `fd` is the `/sys/class/gpio17/value` file that is

- Configured as input
- Triggered on the falling edge (high-to-low transition)

The `poll(2)` system call in line 99 blocks the execution of the program until the input (`GPIO 17`) changes from a high state to a low state. This is connected to the MCP23017 $\overline{INT\ A}$ pin, so it can tell us when its GPIO extender input(s) have changed.

The `poll(2)` system call can return an error if the program has handled a signal. The error returned will be `EINTR` when this happens (as discussed in Chapter 9 of *Raspberry Pi Hardware Reference* [Apress, 2014], section "Error EINTR"). If the program detects that `^C` has been pressed (`is_signaled` is true), then it exits, returning `-1`, to allow the main program to exit.

A value of `rc=1` is returned if `/sys/class/gpio17/value` has a changed value to be read. Before returning from `gpio_poll()`, a `read(2)` of any unread data is performed. This is necessary so that the next call to `poll(2)` will block until new data is available.

```
/*************************************************************************
 * sysgpio.c : Open/configure /sys GPIO pin
 *
 * Here we must open the /sys/class/gpio/gpio17/value and do a
 * poll(2) on it, so that we can sense the MCP23017 interrupts.
 *************************************************************************/

typedef enum {
        gp_export = 0,     /* /sys/class/gpio/export */
        gp_unexport,        /* /sys/class/gpio/unexport */
        gp_direction,       /* /sys/class/gpo%d/direction */
        gp_edge,            /* /sys/class/gpio%d/edge */
        gp_value            /* /sys/class/gpio%d/value */
} gpio_path_t;

/*
 * Internal : Create a pathname for type in buf.
 */
static const char *
gpio_setpath(int pin,gpio_path_t type,char *buf,unsigned bufsiz) {
        static const char *paths[] = {
                "export",  "unexport",  "gpio%d/direction",
                "gpio%d/edge", "gpio%d/value" };
        int slen;

        strncpy(buf,"/sys/class/gpio/",bufsiz);
        bufsiz -= (slen = strlen(buf));
        snprintf(buf+slen,bufsiz,paths[type],pin);
        return buf;
}

/*
 * Open /sys/class/gpio%d/value for edge detection  :
 */
static int
gpio_open_edge(int pin) {
         char buf[128];
         FILE *f;
         int fd;

         /* Export pin: /sys/class/gpio/export */
         gpio_setpath(pin,gp_export,buf,sizeof buf);
         f = fopen(buf, "w");
         assert(f);
         fprintf(f,"%d\n",pin);
         fclose(f);

```

```
48          /* Direction: /sys/class/gpio%d/direction  */
49          gpio_setpath(pin,gp_direction,buf,sizeof buf);
50          f = fopen(buf,"w");
51          assert(f);
52          fprintf(f,"in\n");
53          fclose(f);
54
55          /* Edge: /sys/class/gpio%d/edge */
56          gpio_setpath(pin,gp_edge,buf,sizeof buf);
57          f = fopen(buf,"w");
58          assert(f);
59          fprintf(f,"falling\n");
60          fclose(f);
61
62          /* Value: /sys/class/gpio%d/value  */
63          gpio_setpath(pin,gp_value,buf,sizeof buf);
64          fd = open(buf,O_RDWR);
65          return fd;
66  }
67
68  /*
69   * Close (unexport) GPIO pin :
70   */
71  static void
72  gpio_close(int pin) {
73          char buf[128];
74          FILE *f ;
75
76          /* Unexport: /sys/class/gpio/unexport */
77          gpio_setpath(pin,gp_unexport,buf,size of buf);
78          f = fopen(buf,"w");
79          assert(f);
80          fprintf(f,"%d\n",pin);
81          fclose(f);
82  }
83
84  /*
85   * This routine will block until the open GPIO pin has changed
86   * value. This pin should be connected to the MCP23017 /INTA
87   * pin.
88   */
89  static int
90  gpio_poll(int fd) {
91          unsigned char buf[32];
92          struct pollfd polls;
93          int rc;
94
```

```
95          polls.fd = fd;                  /* /sys/class/gpio17/value */
96          polls.events = POLLPRI;         /* Exceptions  */
97
98          do     {
99                     rc = poll(&polls,1,-1);  /* Block */
100                  if ( is_signaled )
101                        return -1;         /* Exit if ^Creceived */
102         } while ( rc < 0  && errno == EINTR );
103
104         (void)read(fd,buf,sizeof buf);     /* Clear interrupt */
105         return 0;
106 }
107
108 /* End sysgpio.c */
```

Example Run

The first time you run the program, you might encounter an error:

```
$ ./mcp23017
Opening /dev/i2s-1: No such file or directory
Check that the i2c-dev & i2c-bcm2708 kernel modules are loaded.
Aborted
$
```

As the program states in the error message, it is unable to open the I2C driver, because the I2C kernel modules have not been loaded. See Chapter 12 of *Raspberry Pi Hardware Reference* (Apress, 2014) for modprobe information.

The following is a successful session. After the program is started, the program pauses after issuing the message "Monitoring for MCP23017 input changes." At this point, the program is in the `poll(2)` system call, waiting to be notified of an interrupt from the MCP23017 peripheral. If you open another session, you can confirm that little or no CPU resource is consumed by this.

```
$ sudo ./mcp23017
Monitoring for MCP23017 input changes :

  Outputs :       0F0F
  Input change :  flags 8000 values 70F0
  Outputs :       070F
  Input change :  flags 8000 values F0F0
  Outputs :       070F
  Input change :  flags 8000 values F0F0
  Outputs :       070F
  Input change :  flags 8000 values F0F0
  Outputs :       070F
```

```
  Input change :  flags 8000 values F0F0
  Outputs :       070F
  Input change :  flags 8000 values 70F0
  Outputs :       0F0F
^C
$
```

While this was running, I carefully grounded pin 28 of the MCP28017 chip, which is input GPA7. This is reflected immediately in the message:

```
Input change : flags 8000 values 70F0
```

The flags value reported as 8000 is decoded next, showing that GPA7 did indeed *change* in value:

INTFA								INTFB							
7	**6**	**5**	**4**	**3**	**2**	**1**	**0**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The value reported as 70F0 is from the INTCAPx register pair:

INTCAPA								INTCAPB							
7	**6**	**5**	**4**	**3**	**2**	**1**	**0**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
0	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0

This shows us that the GPA7 pin is found in the zero state at the time of the interrupt. All remaining inputs show high (0s indicate output pins).

While I grounded the GPA7 pin only once, you can see from the session output that several events occur. This is due to the *bounce* of the wire as it contacts. You'll also note that some events are lost during this bounce period. Look at the input events:

```
1    Input change:  flags 8000 values  70F0
2    Input change:  flags 8000 values  F0F0
3    Input change:  flags 8000 values  F0F0
4    Input change:  flags 8000 values  F0F0
5    Input change:  flags 8000 values  F0F0
6    Input change:  flags 8000 values  70F0
```

Each interrupt correctly shows that pin GPA7 changed. But look closely at the captured values for the inputs:

1. The captured level of the input is 0 (line 1).
2. The captured level change of the input is now 1 (line 2).
3. The next input change shows a captured level of 1 (line 3).

How does the state of an input change from a 1 to a 1? Clearly what happens is that the input GPA7 changes to low but returns to high by the time the interrupt is captured.

Push button, switch, and key bounces can occur often with a variety of pulse widths, in the range of microseconds to milliseconds, until the contact stabilizes (off or on). The very action of pushing a button can initiate a series of a thousand pulses. Some pulses will be too short for the software to notice, so it must be prepared to deal with this. Sometimes electronics circuits are applied to eliminate "key debouncing" so that the software will see a clean and singular event. This is what is accomplished in Chapter 8, where a flip-flop is used.

Response Times

You should be aware of the interrupt notification limitations provided by the poll(2) system call. The input lines could easily change faster than the Raspberry Pi can respond. Consider the process involved:

1. An input GPIO extender pin changes in value.
2. The MCP23017 device activates $\overline{INT\ A}$ by bringing it from a high to a low (a few cycles later).
3. The Raspberry Pi's GPIO 17 pin sees a falling input level change.
4. The device driver responds to the GPIO pin change by servicing an interrupt and then notifies the application waiting in poll(2).
5. The application sends some I2C traffic to query the INTFA and INTFB flag registers in the MCP23017.
6. Registers GPIOA and GPIOB must also be read to clear the interrupt, involving more I/O on the I2C bus.

Consequently, there is considerable delay in sensing a GPIO change and the clearing of the device interrupt.

An informal test using select(2) purely for delay purposes (no file descriptors) required a minimum of approximately 150 µs on a 700 MHz Pi. The poll(2) call is likely to be nearly identical. Attempting to set smaller timed delays bottomed out near 150 µs. This suggests that the quickest turnaround for reacting to an $\overline{INT}$ signal from the MCP23017 will be 150 µs (excluding the time needed to actually service the registers in

the peripheral). This means that the absolute maximum number of interrupts per second that can be processed will be 6,600.

To estimate the effects of the IC2 bus, let's do some additional simplified calculations. The I2C bus operates at 100 kHz on the Raspberry Pi (for more information, see Chapter 12 of *Raspberry Pi Hardware Reference* [Apress, 2014]). A single byte requires 8 data bits and an acknowledgment bit. This requires about 90 μs per byte. To read one MCP23017 register requires the following:

1. The peripheral's address byte to be sent (1 byte).
2. The MCP23017 register address to be sent (1 byte).
3. The MCP23017 responds back with 1 byte.

This requires 3 × 90 = 270 μs, just to read one register. Add to this the following:

1. Both interrupt flag registers `INTFA` and `INTFB` must be read.
2. Both `GPIOA` and `GPIOB` registers must be read, to clear the interrupt.

So, ignoring the start and stop bits, this requires $4 \times 270 = 1.08\ ms$ to respond to one input level change. (This also ignores the effect of multiple peripherals on the bus.) This, added to the minimum of about 150 μs overhead for `poll(2)`, leads to the minimum response time of about 1.08 + 0.150 = 1.23 *ms*. This results in a practical limit of about 800 signal changes per second.

Because of the response-time limitations, it is recommended that the `INTCAPx` register values be ignored. By the time the application can respond to a signal change, it may have changed back again. This is why the program presented uses the values read in `GPIOA` and `GPIOB`, rather than the captured values in the `INTCAPx`. But if your application needs to know the state at the time of the event, the `INTCAPx` register values are available.

Some reduced I2C overhead can be attained by tuning the I/O operations. For example, with use of the auto-increment address feature of the MCP23017, it is possible to read both `INTFx` flags and `GPIOx` registers in one `ioctl(2)` call:

$$\begin{aligned} T &= t_{addr} + t_{register} + t_{INTFA} + t_{INTFB} + t_{register} + t_{GPIOA} + t_{GPIOB} \\ &= 7 \times 90 \\ &= 0.630 ms \end{aligned}$$

That approach reduces the I2C time to approximately 7-byte times. The total turnaround time can then be reduced to about 0.63 + 0.150 = 0.78 *ms*.

CHAPTER 3

Nunchuk-Mouse

This chapter's project is about attaching the Nintendo Wii Nunchuk to the Raspberry Pi. The Nunchuk has two buttons; an X-Y joystick; and an X, Y, and Z accelerometer. The sensor data is communicated through the I2C bus. Let's have some fun using a Nunchuk as a pointing device for the X Window System desktop.

Project Overview

The challenge before us breaks down into two overall categories:

- The I2C data communication details of the Nunchuk device
- Inserting the sensed data into the X Window System desktop event queue

Since you've mastered I2C communications in other parts of this book, we'll focus more on the Nunchuk technical details. The remainder of the chapter looks at the Linux `uinput` API that will be used for the X-Windows interface. The final details cover a small but critical X-Windows configuration change, to bring about the Nunchuk-Mouse.

Nunchuk Features

The basic physical and data characteristics of the Nunchuk are listed in Table 3-1.[50]

Table 3-1. *Nunchuk Controls and Data Characteristics*

User-Interface Features	Bits	Data	Hardware/Chip
C Button	1	Boolean	Membrane switch
Z button	1	Boolean	Membrane switch
X-Y joystick	8x2	Integers	30 $k\Omega$ potentiometers
X, Y, and Z accelerometer	10x3	Integers	ST LIS3L02 series

For application as a mouse, the C and Z buttons fill in for the left and right mouse buttons. The joystick is used to position the mouse cursor.

While the Nunchuk normally operates at a clock rate of 400 kHz, it works just fine at the Raspberry Pi's 100 kHz I2C rate.

■ **Note** I encourage you to experiment with the accelerometer.

Connector Pinout

There are four wires, two of which are power and ground (some units may have two additional wires, one that connects to the shield and the other to the unused center pin). The remaining two wires are used for I2C communication (SDA and SCL). The connections looking into the cable-end connector are shown in Table 3-2.

Table 3-2. *Nuncheck Cable Connections*

SCL		GND
+3.3 V	N/C	SDA

The Nunchuk connector is annoyingly nonstandard. Some folks have rolled their own adapters using a double-sided PCB to mate with the inner connections. Others have purchased adapters for around $6. Cheap Nunchuk clones may be found on eBay for about half that price. With the growing number of clone adapters becoming available at more-competitive prices, there is less reason to cut off the connector.

■ **Tip** Beware of Nunchuk forgeries and nonfunctional units.

If you do cut off the connector, you will quickly discover that there is no standard wire color scheme. The only thing you can count on is that the pins are laid out as in Table 3-2. If you have a genuine Wii Nunchuk, the listed wire colors in Table 3-3 might be valid. The column labeled Clone Wire lists the wire colors of my own clone's wires. *Yours will likely differ*.

Table 3-3. *Nunchuk Connector Wiring*

Pin	Wii Wire	CloneWire†	Description	P1
Gnd	White	White	Ground	P1-25
SDA	Green	Blue	Data	P1-03
+3.3 V	Red	Red	Power	P1-01
SCL	Yellow	Green	Clock	P1-05

†*Clone wire colors vary!*

Before you cut that connector off your clone, consider that you'll need to trace the connector to a wire color. Cut the cable, leaving about 3 inches of wire for the connector. Then you can cut the insulation off and trace the pins to a wire by using an ohmmeter (or by looking inside the cable-end connector).

Figure 3-1 shows the author's clone Nunchuk with the connector cut off. In place of the connector, solid wire ends were soldered on and a piece of heat shrink applied over the solder joint. The solid wire ends are perfect for plugging into a prototyping breadboard.

Figure 3-1. *Nunchuk with wire ends*

Testing the Connection

Once you've hooked up the Nunchuk to the Raspberry Pi, you'll want to perform some simple tests to make sure it is working. The first step is to make sure your I2C drivers are loaded:

```
$ lsmod | grep i2c
i2c_bcm2708            3759         0
i2c_dev                5620         0
```

If you see these modules loaded, you're good to go. Otherwise, manually load them now:

```
$ sudo modprobe i2c-bcm2708
$ sudo modprobe i2c-dev
```

Assuming the Raspberry Pi rev 2.0+, you'll use I2C bus 1 (see Chapter 12 of *Raspberry Pi Hardware Reference* [Apress, 2014] if you're not sure). Scan to see whether your Nunchuk is detected:

```
$ sudo i2cdetect -y 1
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:          -- -- -- -- -- -- -- -- -- -- -- -- --
10:  -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
20:  -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
30:  -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
40:  -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
50:  -- -- 52 -- -- -- -- -- -- -- -- -- -- -- -- --
60:  -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
70:  -- -- -- -- -- -- -- --
```

If the Nunchuk is working, it will show up in this display at address 0x52. With the hardware verified, it is time to move on to the software.

Nunchuk I2C Protocol

The Nunchuk contains a quirky little controller that communicates through the I2C bus. In order to know where to store bytes written to it, the first byte must be an 8-bit register address. In other words, each write to the Nunchuk requires the following:

- One register address byte, followed by
- Zero or more data bytes to be written to sequential locations

Thus for write operations, the first byte sent to the Nunchuk tells it where to start. Any following write bytes received are written with the register address incremented.

■ **Tip** Don't confuse the register address with the Nunchuk's I2C address of 0x52.

It is possible to write the register address and then read bytes instead. This procedure specifies the starting location of data bytes to be read.

A quirky aspect of the Nunchuk controller is that there must be a short delay between writing the register address and reading the data. Performing the write followed by an immediate read does not work. Writing data immediately after the register address does succeed, however.

■ **Note** The Nunchuk uses I2C address 0x52.

Encryption

The Nunchuk is designed to provide an encrypted link. However, that can be disabled by initializing it a certain way.[60] The defeat procedure is as follows:

1. Write 0x55 to Nunchuk location 0xF0.
2. Pause.
3. Write 0x00 to Nunchuk location 0xFB.

The following illustrates the message sequence involved. Notice that this is performed as *two* separate I2C write operations:

Write		Pause	Write	
F0	55	-	FB	00

Once this is successfully performed, all future data is returned unencrypted.

Read Sensor Data

The whole point of the Nunchuk is to read its sensor data. When requested, it returns 6 bytes of data formatted as shown in Table 3-4.

Table 3-4. *Nunchuk Data*

Byte	Bits	Description
1		Analog stick x axis value
2		Analog stick y axis value
3		X acceleration bits 9:2
4		Y acceleration bits 9:2
5		Z acceleration bits 9:2
6	0	Z button pressed (active low)
	1	C button pressed (active low)
	3:2	X acceleration bits 1:0
	5:4	Y acceleration bits 1:0
	7:6	Z acceleration bits 1:0

Some of the data is split over multiple bytes. For example, the X acceleration bits 9:2 are obtained from byte 3. The lowest 2 bits are found in byte 6, in bits 3 and 2. These together form the 9-bit X acceleration value.

To retrieve this data, we are always required to tell the Nunchuk where to begin. So the sequence always begins with a write of offset 0x00 followed by a pause:

Write	Pause	Read 6 bytes					
00	-	01	02	03	04	05	06

The Nunchuk doesn't allow us to do this in one `ioctl(2)` call, using two I/O messages. A write of 0 must be followed by a pause. Then the 6 data bytes can be read as a separate I2C read operation. If the pause is too long, however, the Nunchuk controller seems to time out, resulting in incorrect data being returned. So we must do things the Nunchuk way.

Linux uinput Interface

While reading the Nunchuk is fun, we need to apply it to our desktop as a mouse. We need to insert mouse events based on what we read from it.

The Linux `uinput` driver allows programmers to develop nonstandard input drivers so that events can be injected into the input stream. This approach allows new input streams to be added without changing application code. Certainly the Nunchuk qualifies as a nonstandard input device!

A problem with this `uinput` API is its general lack of documentation. The best information available on the Internet seems to be from these three online sources:

- "Getting started with uinput: the user level input subsystem" http://thiemonge.org/getting-started-with-uinput
- "Using uinput driver in Linux- 2.6.x to send user input" http://www.einfochips.com/download/dash_jan_tip.pdf
- "Types" http://www.kernel.org/doc/Documentation/input/event-codes.txt

The only other source of information seems to be the device driver source code itself:

```
drivers/input/misc/uinput.c
```

The example program provided in this chapter can help pull all the necessary details together for you.

Working with Header Files

The header files required for the `uinput` API include the following:

```
#include <sys/ioctl.h>
#include <linux/input.h>
#include <linux/uinput.h>
```

To compile code, making use of I2C, you also need to install the `libi2c` development library, if you have not done that already:

```
$ sudo apt-get install libi2c-dev
```

Opening the Device Node

The connection to the `uinput` device driver is made by opening the device node:

```
/dev/uinput
```

The following is an example of the required `open(2)` call:

```
int fd;

fd = open("/dev/uinput",O_WRONLY|O_NONBLOCK);
if ( fd < 0 ) {
    perror("Opening /dev/uinput");
    ...
```

Configuring Events

In order to inject events, the driver must be configured to accept them. Each call to `ioctl(2)` in the following code enables one class of events based on the argument *event*. The following is a generalized example:

```
int rc;
unsigned long event = EV_KEY;

rc = ioctl(fd,UI_SET_EVBIT,event);
assert(!rc);
```

The list of `UI_SET_EVBIT` event types is provided in Table 3-5. The most commonly needed event types are `EV_SYN`, `EV_KEY`, and `EV_REL` (or `EV_ABS`).

Table 3-5. *List of uinput Event Types*

Macro	From Header File input.h[53]] Description
EV_SYN	Event synchronization/separation
EV_KEY	Key/button state changes
EV_REL	Relative axis mouse-like changes
EV_ABS	Absolute axis mouse-like changes
EV_MSC	Miscellaneous events
EV_SW	Binary (switch) state changes
EV_LED	LED on/off changes
EV_SND	Output to sound devices
EV_REP	For use with autorepeating devices
EV_FF	Force feedback commands to input device
EV_PWR	Power button/switch event
EV_FF_STATUS	Receive force feedback device status

■ **Caution** Do not `or` the event types together. The device driver expects each event type to be registered *separately*.

Configure EV_KEY

Once you have registered your intention to provide `EV_KEY` events, you need to register all key codes that might be used. While this seems a nuisance, it does guard against garbage being injected by an errant program. The following code registers its intention to inject an Escape key code:

```
int rc;

rc = ioctl(fd,UI_SET_KEYBIT,KEY_ESC);
assert(!rc);
```

To configure all possible keys, a loop can be used. But do not register key code 0 (`KEY_RESERVED`) nor 255; the include file indicates that code 255 is reserved for the special needs of the AT keyboard driver.

```
int rc;
unsigned long key;

for ( key=1; key<255; ++key ) {
    rc = ioctl(fd,UI_SET_KEYBIT,key);
    assert(!rc);
}
```

Mouse Buttons

In addition to key codes, the same `ioctl(2,UI_SET_KEYBIT)` call is used to register mouse, joystick, and other kinds of button events. This includes touch events from trackpads, tablets, and touchscreens. The long list of button codes is defined in header file `linux/input.h`. The usual suspects are shown in Table 3-6.

Table 3-6. *Key Event Macros*

Macro	Synonym	Description
BTN_LEFT	BTN_MOUSE	Left mouse button
BTN_RIGHT		Right mouse button
BTN_MIDDLE		Middle mouse button
BTN_SIDE		Side mouse button

The following example shows the application's intention to inject left and right mouse button events:

```
int rc;

rc = ioctl(fd,UI_SET_KEYBIT,BTN_LEFT);
assert(!rc);
rc = ioctl(fd,UI_SET_KEYBIT,BTN_RIGHT);
assert(!rc);
```

Configure EV_REL

In order to inject `EV_REL` events, the types of relative movements must be registered in advance. The complete list of valid argument codes is shown in Table 3-7. The following example indicates an intention to inject x and y relative axis movements:

```
rc = ioctl(fd,UI_SET_RELBIT,REL_X);
assert(!rc);
rc = ioctl(fd,UI_SET_RELBIT,REL_Y);
assert(!rc);
```

Table 3-7. *UI_SET_RELBIT Options*

Macro	Intention
REL_X	Send relative X changes
REL_Y	Send relative Y changes
REL_Z	Send relative Z changes
REL_RX	x-axis tilt
REL_RY	y- axis tilt
REL_RZ	z- axis tilt
REL_HWHEEL	Horizontal wheel change
REL_DIAL	Dial-turn change
REL_WHEEL	Wheel change
REL_MISC	Miscellaneous

Configure EV_ABS

While we don't use the `EV_ABS` option in this project, it may be useful to introduce this feature at this point. This event represents absolute cursor movements, and it too requires registration of intentions. The complete list of `EV_ABS` codes is defined in `linux/input.h`. The usual suspects are defined in Table 3-8.

Table 3-8. *Absolute Cursor Movement Event Macros*

Macro	Description
ABS_X	Move X to this absolute X coordinate
ABS_Y	Move Y to this absolute Y coordinate

The following is an example of registering intent for absolute x- and y-axis events:

```
int rc;

rc = ioctl(fd,UI_SET_ABSBIT,ABS_X);
assert(!rc);
rc = ioctl(fd,UI_SET_ABSBIT,ABS_X);
assert(!rc);
```

In addition to registering your intentions to inject these events, you need to define some coordinate parameters. The following is an example:

```
struct uinput_user_dev uinp;

uinp.absmin[ABS_X] = 0;
uinp.absmax[ABS_X] = 1023;

uinp.absfuzz[ABS_X] = 0;
uinp.absflat[ABS_X] = 0;

uinp.absmin[ABS_Y] = 0;
uinp.absmax[ABS_Y] = 767;

uinp.absfuzz[ABS_Y] = 0;
uinp.absflat[ABS_Y] = 0;
```

These values must be established as part of your `ioctl(2,UI_DEV_CREATE)` operation, which is described next.

Creating the Node

After all registrations with the `uinput` device driver have been completed, the final step is to create the `uinput` node. This will be used by the receiving application, in order to read injected events. This involves two programming steps:

1. Write the struct `uinput_user_dev` information to the file descriptor with `write(2)`.
2. Perform an `ioctl(2,UI_DEV_CREATE)` to cause the `uinput` node to be created.

The first step involves populating the following structures:

```
struct input_id {
    __u16       bustype;
    __u16       vendor;
    __u16       product;
    __u16       version;
};

struct uinput_user_dev {
    char        name[UINPUT_MAX_NAME_SIZE];
    struct input_id id;
    int         ff_effects_max;
    int         absmax[ABS_CNT];
    int         absmin[ABS_CNT];
    int         absfuzz[ABS_CNT];
    int         absflat[ABS_CNT];
};
```

An example populating these structures is provided next. If you plan to inject EV_ABS events, you must also populate the abs members, mentioned in the "Configure EV_ABS" section.

```
        struct uinput_user_dev uinp;
        int rc;

        memset(&uinp,0,sizeof uinp);

        strncpy(uinp.name,"nunchuk",UINPUT_MAX_NAME_SIZE);

        uinp.id.bustype = BUS_USB;
        uinp.id.vendor = 0x1;
        uinp.id.product = 0x1;
        uinp.id.version = 1;

//      uinp.absmax[ABS_X] = 1023; /* EV_ABS only */
//      ...

        rc = write(fd,&uinp,sizeof(uinp));
        assert(rc == sizeof(uinp));
```

The call to write(2) passes all of this important information to the uinput driver. Now all that remains is to request a device node to be created for application use:

```
int rc;

rc = ioctl(fd,UI_DEV_CREATE);
assert(!rc);
```

This step causes the uinput driver to make a device node appear in the pseudo directory /dev/input. An example is shown here:

```
$ ls -l /dev/input
total 0
drwxr-xr-x 2 root root     120 Dec 31  1969 by-id
drwxr-xr-x 2 root root     120 Dec 31  1969 by-path
crw-rw---T 1 root input 13, 64 Dec 31  1969 event0
crw-rw---T 1 root input 13, 65 Dec 31  1969 event1
crw-rw---T 1 root input 13, 66 Dec 31  1969 event2
crw-rw---T 1 root input 13, 67 Feb 23 13:40 event3
crw-rw---T 1 root input 13, 63 Dec 31  1969 mice
crw-rw---T 1 root input 13, 32 Dec 31  1969 mouse0
crw-rw---T 1 root input 13, 33 Feb 23 13:40 mouse1
```

The device /dev/input/event3 was the Nunchuck's created uinput node, when the program was run.

Posting EV_KEY Events

The following code snippet shows how to post a key down event, followed by a key up event:

```
 1 static void
 2 uinput_postkey(int fd,unsigned key) {
 3    struct input_event ev;
 4    int rc;
 5
 6    memset(&ev,0,sizeof(ev));
 7    ev.type = EV_KEY;
 8    ev.code = key;
 9    ev.value = 1;
10
11    rc = write(fd,&ev,sizeof(ev));
12    assert(rc == sizeof(ev));
13
14    ev.value = 0;
15    rc = write(fd,&ev,sizeof(ev));
16    assert(rc == sizeof(ev));
17 }
```

From this example, you see that each event is posted by writing a suitably initialized `input_event` structure. The example illustrates that the member named `type` was set to `EV_KEY`, `code` was set to the key code, and a keypress was indicated by setting the member `value` to 1 (line 9).

To inject a key up event, `value` is reset to 0 (line 14) and the structure is written again.

Mouse button events work the same way, except that you supply mouse button codes for the `code` member. For example:

```
memset(&ev,0,sizeof(ev));
ev.type = EV_KEY;
ev.code = BTN_RIGHT;        /* Right click */
ev.value = 1;
```

Posting EV_REL Events

To post a relative mouse movement, we populate the `input_event` as a type `EV_REL`. The member `code` is set to the type of event (`REL_X` or `REL_Y` in this example), with the value for the relative movement established in the member `value`:

```
static void
uinput_movement(int fd,int x,inty) {
     struct input_event ev;
     int rc;
```

```
    memset(&ev,0,sizeof(ev));
    ev.type = EV_REL;
    ev.code = REL_X;
    ev.value = x;

    rc = write(fd,&ev,sizeof(ev));
    assert(rc == sizeof(ev));

    ev.code = REL_Y;
    ev.value = y;
    rc = write(fd,&ev,sizeof(ev));
    assert (rc == sizeof(ev));
}
```

Notice that the `REL_X` and `REL_Y` events are created separately. What if you want the receiving application to avoid acting on these separately? The `EV_SYN` event helps out in this regard (next).

Posting EV_SYN Events

The `uinput` driver postpones delivery of events until the `EV_SYN` event has been injected. The `SYN_REPORT` type of `EV_SYN` event causes the queued events to be flushed out and reported to the interested application. The following is an example:

```
static void
uinput_syn(int fd) {
    struct input_event ev;
    int rc;

    memset(&ev,0,sizeof(ev));
    ev.type = EV_SYN;
    ev.code = SYN_REPORT;
    ev.value = 0;
    rc = write(fd,&ev,sizeof(ev));
    assert(rc == sizeof(ev));
}
```

For a mouse relative movement event, for example, you can inject a `REL_X` and `REL_Y`, followed by a `SYN_REPORT` event to have them seen by the application as a group.

Closing uinput

There are two steps involved:

1. Destruction of the `/dev/input/event%d` node
2. Closing of the file descriptor

The following example shows both:

```
int rc;

rc = ioctl(fd,UI_DEV_DESTROY);
assert(!rc);
close(fd);
```

Closing the file descriptor implies the `ioctl(2,UI_DEV_DESTROY)` operation. The application has the option of destroying the device node while keeping the file descriptor open.

X-Window

The creation of our new `uinput` device node is useful only if our desktop system is listening to it. Raspbian Linux's X-Windows system needs a little configuration help to notice our Frankenstein creation. The following definition can be added to the `/usr/share/X11/xorg.config.d` directory. Name the file `20-nunchuk.conf`:

```
# Nunchuck event queue

Section "InputClass"
        Identifier "Raspberry Pi Nunchuk"
        Option "Mode" "Relative"
        MatchDevicePath "/dev/input/event3"
        Driver "evdev"
EndSection

# End 20-nunchuk.conf
```

This configuration change works only if your Nunchuk `uinput` device shows up as `/dev/input/event3`. If you have other specialized input device creations on your Raspberry Pi, it could well be `event4` or some other number. See the upcoming section "Testing the Nunchuk" for troubleshooting information.

Restart your X-Windows server to have the configuration file noticed.

■ **Tip** Normally, your Nunchuk program should be running already. But the X-Window server will notice it when the Nunchuk does start.

Input Utilities

When writing `uinput` event-based code, you will find the package `input-utils` to be extremely helpful. They can be installed from the command line as follows:

```
$ sudo apt-get install input-utils
```

The following commands are installed:

`lsinput(8)`: List `uinput` devices

`input-events(8)`: Dump selected `uinput` events

`input-kbd(8)`: Keyboard map display

This chapter uses the first two utilities: `lsinput(8)` and `input-events(8)`.

Testing the Nunchuk

Now that the hardware, drivers, and software are ready, it is time to exercise the Nunchuk. Unfortunately, there is no direct way for applications to identify your created `uinput` node. When the Nunchuk program runs, the node may show up as `/dev/input/event3` or some other numbered node if `event3` already exists. If you wanted to start a Nunchuk driver as part of the Linux boot process, you need to create a script to edit the file with the actual device name. The affected X-Windows config file is as follows:

```
/usr/share/X11/xord.conf.d/20-nunchuk.conf
```

The script (shown next) determines which node the Nunchuk program created. The following is an example run, while the Nunchuk program was running:

```
$ ./findchuk
/dev/input/event3
```

When the node is not found, the `findchuk` script exits with a nonzero code and prints a message to `stderr`:

```
$ ./findchuk
Nunchuk uinput device not found.
$ echo $?
1
```

The findchuk script is shown here:

```
#!/bin/bash
################################################################################
# Find the Nunchuck
################################################################################
#
# This script locates the Nunchuk uinput device by searching the
# /sys/devices/virtual/input pseudo directory for names of the form:
# input[0_9]*. For all subdirectories found, check the ./name pseudo
# file, which will contain "nunchuk". Then we derive the /dev path
# from a sibling entry named event[0_9]*. That will tell use the
# /dev/input/event%d pathname, for the Nunchuk.

DIR=/sys/devices/virtual/input         # Top level directory
set_eu

cd "$DIR"
find . -type d -name 'input[0-9]*' | (
      set -eu
      while read dirname ; do
              cd "$DIR/$dirname"
              if [-f "name"] ; then
                     set +e
                     name=$(cat name)
                     set -e
                     if [ $(cat name) = nunchuk ] ; then
                            event="/dev/input/$ (ls-devent[0-9]*)"
                            echo $event
                            exit 0            # Found it
                     fi
              fi
      done

      echo "Nunchuk uinput device not found." >&2
      exit 1
)

# End findchuk
```

Testing ./nunchuk

When you want to see what Nunchuk data is being received, you can add the `-d` command-line option:

```
$ ./nunchuk -d
Raw nunchuk data: [83] [83] [5C] [89] [A2] [63]
.stick_x = 0083 (131)
.stick_y = 0083 (131)
.accel_x = 0170 (368)
.accel_y = 0226 (550)
.accel_z = 0289 (649)
.z_button= 0
.c_button= 0
```

The first line reports the raw bytes of data that were received. The remainder of the lines report the data in its decoded form. While the raw data reports the button presses as active low, the Z and C buttons are reported as 1 in the decoded data. The value in the left column is in hexadecimal format, while the value in parenthesis is shown in decimal.

Utility lsinputs

When the Nunchuk program is running, you should be able to see the Nunchuk `uinput` device in the list:

```
$ lsinput
...
/dev/input/event2
   bustype   : BUS_USB
   vendor    : 0x45e
   product   : 0x40
   version   : 272
   name      : "Microsoft Micro soft 3-Button Mou"
   phys      : "usb-bcm2708_usb-1.3.4/input0"
   uniq      : ""
   bitsev    : EV_SYN EV_KEY EV_REL EV_MSC

/dev/input/event3
   bustype      : BUS_USB
   vendor       : 0x1
   product      : 0x1
   version      : 1
   name         : "nunchuk"
   bits ev      : EV_SYN EV_KEY EV_REL
```

In this example, the Nunchuk shows up as `event3`.

Utility input-events

When developing `uinput`-related code, the `input-events` utility is a great help. Here we run it for `event3` (the argument 3 on the command line), where the Nunchuk mouse device is:

```
$ input-events 3
/dev/input/event3
   bustype   : BUS_USB
   vendor    : 0x1
   product   : 0x1
   version   : 1
   name      : "nunchuk"
   bits ev   : EV_SYN EV_KEY EV_REL

waiting for events
23:35:15.345105: EV_KEY BTN_LEFT (0x110) pressed
23:35:15.345190: EV_SYN code=0 value=0
23:35:15.517611: EV_KEY BTN_LEFT (0x110) released
23:35:15.517713: EV_SYN code=0 value=0
23:35:15.833640: EV_KEY BTN_RIGHT (0x111) pressed
23:35:15.833727: EV_SYN code=0 value=0
23:35:16.019363: EV_KEY BTN_RIGHT (0x111) released
23:35:16.019383: EV_SYN code=0 value=0
23:35:16.564129: EV_REL REL_X -1
23:35:16.564213: EV_REL REL_Y 1
23:35:16.564261: EV_SYN code=0 value=0
...
```

The Program

The code for `nunchuk.c` is presented on the following pages. The source code for `timed_wait.c` is shown in Chapter 1. We've covered the I2C I/O in other chapters. The only thing left to note is the difficulty of providing a smooth interface for events produced by the Nunchuk. Here are a few hints for the person who wants to experiment:

1. If the mouse moves too quickly, one major factor is the timed delay used. The `timed_wait()` call in line 107 spaces out read events for the Nunchuk (currently 15 ms). This also lightens the load on the CPU. Reducing this time-out increases the number of Nunchuk reads and causes more `uinput` events to be injected. This speeds up the mouse pointer.

2. The function `curve()` in line 349 attempts to provide a somewhat exponential movement response. Small joystick excursions should be slow and incremental. More-extreme movements will result in faster mouse movements.

3. The Z button is interpreted as the left-click button, while the C button is the right-click button.

4. No keystrokes are injected by this program, but it can be modified to do so. The function `uinput_postkey()` on line 244 can be used for that purpose.

```
 1  /*********************************************************************
 2  * nunchuk.c: Read events from nunchuck and stuff as mouse events
 3  *********************************************************************/
 4
 5  #include <stdio.h>
 6  #include <math.h>
 7  #include <stdlib.h>
 8  #include <fcntl.h>
 9  #include <unistd.h>
10  #include <string.h>
11  #include <errno.h>
12  #include <signal.h>
13  #include <assert.h>
14  #include <sys/ioctl.h>
15  #include <linux/i2c-dev.h>
16  #include <linux/input.h>
17  #include <linux/uinput.h>
18
19  #include "timed_wait.c"
20
21  static int is_signaled = 0;       /* Exit program if signaled */
22  static int i2c_fd = -1;           /* Open/dev/i2c-1 device */
23  static int f_debug = 0;           /* True to print debug messages */
24
25  typedef struct {
26          unsigned char stick_x;    /* Joystick X */
27          unsigned char stick_y;    /* Joystick Y */
28          unsigned accel_x;         /* Accel X */
29          unsigned accel_y;         /* Accel Y */
30          unsigned accel_z;         /* Accel Z */
31          unsigned z_button:1;      /* Z button */
32          unsigned c_button:1;      /* C button */
33          unsigned char raw[6];     /* Raw received data */
34  } nunchuk_t;
35
36  /*
37  * Open I2C bus and check capabilities:
38  */
39  static void
40  i2c_init(const char *node) {
```

```
41          unsigned long i2c_funcs = 0;    /* Support flags */
42          int rc;
43
44          i2c_fd = open(node,O_RDWR);     /* Open driver/dev/i2s-1 */
45          if ( i2c_fd < 0 ) {
46                 perror("Opening/dev/i2s-1");
47                 puts("Check that the i2c-dev & i2c-bcm2708 kernel modules"
48                        "are loaded.");
49                 abort();
50         }
51
52          /*
53           * Make sure the driver supports plain I2C I/O:
54           */
55          rc = ioctl(i2c_fd,I2C_FUNCS,&i2c_funcs);
56          assert(rc >= 0);
57          assert(i2c_funcs & I2C_FUNC_I2C);
58 }
59
60  /*
61   * Configure the nunchuk for no encryption:
62   */
63  static void
64  nunchuk_init(void) {
65         static char init_msg1[] = {0xF0, 0x55};
66         static char init_msg2[] = {0xFB, 0x00};
67         struct i2c_rdwr_ioctl_data msgset;
68         struct i2c_msg iomsgs[1];
69         int rc;
70
71         iomsgs[0].addr = 0x52;     /* Address of Nunchuk */
72         iomsgs[0].flags = 0;       /* Write */
73         iomsgs[0].buf = init_msg1; /* Nunchuk 2 byte sequence */
74         iomsgs[0].len = 2;         /* 2 bytes */
75
76         msgset.msgs = iomsgs;
77         msgset.nmsgs = 1;
78
79         rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
80         assert(rc == 1);
81
82         timed_wait(0,200,0);        /* Nunchuk needs time */
83
84         iomsgs[0].addr = 0x52;     /* Address of Nunchuk */
85         iomsgs[0].flags = 0;       /* Write */
86         iomsgs[0].buf = init_msg2; /* Nunchuk 2 byte sequence */
87         iomsgs[0].len = 2;         /* 2 bytes */
88
```

```
89          msgset.msgs = iomsgs;
90          msgset.nmsgs = 1;
91
92          rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
93          assert(rc == 1);
94  }
95
96   /*
97    * Read nunchuk data :
98    */
99   static int
100  nunchuk_read(nunchuk_t *data) {
101          struct i2c_rdwr_ioctl_data msgset;
102          struct i2c_msg iomsgs[1];
103          char zero[1] = {0x00};    /* Written byte */
104          unsigned t;
105          int rc;
106
107          timed_wait(0,15000,0);
108
109          /*
110           * Write the nunchuk register address of 0x00:
111           */
112          iomsgs[0].addr = 0x52;    /* Nunchuk address */
113          iomsgs[0].flags = 0;      /* Write */
114          iomsgs[0].buf = zero;     /* Sending buf */
115          iomsgs[0].len = 1;        /* 1 byte */
116
117          msgset.msgs = iomsgs;
118          msgset.nmsgs = 1;
119
120          rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
121          if ( rc < 0 )
122                 return -1;         /* I /O error */
123
124          timed_wait(0,200,0);      /* Zzzz, nunchuk needs time */
125
126          /*
127           * Read 6 bytes starting at 0x00:
128           */
129          iomsgs[0].addr = 0x52;             /* Nunchuk address */
130          iomsgs[0].flags = I2C_M_RD;        /* Read */
131          iomsgs[0].buf = (char *)data->raw; /* Receive raw bytes here */
132          iomsgs[0].len = 6;                 /* 6 bytes */
133
134          msgset.msgs = iomsgs;
135          msgset.nmsgs = 1;
136
```

```
137         rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
138         if ( rc < 0 )
139                 return -1;        /* Failed */
140
141         data->stick_x = data->raw[0];
142         data->stick_y = data->raw[1];
143         data->accel_x = data->raw[2] << 2;
144         data->accel_y = data->raw[3] << 2;
145         data->accel_z = data->raw[4] << 2;
146
147         t = data->raw[5];
148         data->z_button = t & 1 ? 0 : 1;
149         data->c_button = t & 2 ? 0 : 1;
150         t >>= 2;
151         data->accel_x |= t & 3;
152         t >>= 2;
153         data->accel_y |= t & 3;
154         t >>= 2;
155         data->accel_z |= t & 3;
156         return 0;
157 }
158
159 /*
160  * Dump the nunchuk data:
161  */
162 static void
163 dump_data(nunchuk_t *data) {
164         int x;
165
166         printf("Raw nunchuk data : ");
167         for ( x=0; x<6; ++x )
168                 printf("[%02X]",data->raw[x]);
169         putchar('\n');
170
171         printf(".stick_x = %04X (%4u)\n",data->stick_x,data->stick_x);
172         printf(".stick_y = %04X (%4u)\n",data->stick_y,data->stick_y);
173         printf(".accel_x = %04X (%4u)\n",data->accel_x,data->accel_x);
174         printf(".accel_y = %04X (%4u)\n",data->accel_y,data->accel_y);
175         printf(".accel_z = %04X (%4u)\n",data->accel_z,data->accel_z);
176         printf(".z_button= %d\n",data->z_button);
177         printf(".c_button= %d\n\n",data->c_button);
178 }
179
180 /*
181  * Close the I2C driver :
182  */
```

```
183 static void
184 i2c_close(void) {
185           close(i2c_fd);
186           i2c_fd = -1;
187 }
188
189 /*
190  * Open a uinput node :
191  */
192 static int
193 uinput_open(void) {
194         int fd;
195         struct uinput_user_dev uinp;
196         int rc;
197
198         fd = open("/dev/uinput",O_WRONLY|O_NONBLOCK);
199         if ( fd < 0 ) {
200                perror("Opening/dev/uinput");
201                exit(1);
202          }
203
204         rc = ioctl(fd,UI_SET_EVBIT,EV_KEY);
205         assert(!rc);
206         rc = ioctl(fd,UI_SET_EVBIT,EV_REL);
207         assert(!rc);
208
209         rc = ioctl(fd,UI_SET_RELBIT,REL_X);
210         assert(!rc);
211         rc = ioctl(fd,UI_SET_RELBIT,REL_Y);
212         assert(!rc);
213
214         rc = ioctl(fd,UI_SET_KEYBIT,KEY_ESC);
215         assert(!rc);
216
217         ioctl(fd,UI_SET_KEYBIT,BTN_MOUSE);
218         ioctl(fd,UI_SET_KEYBIT,BTN_TOUCH);
219         ioctl(fd,UI_SET_KEYBIT,BTN_MOUSE);
220         ioctl(fd,UI_SET_KEYBIT,BTN_LEFT);
221         ioctl(fd,UI_SET_KEYBIT,BTN_MIDDLE);
222         ioctl(fd,UI_SET_KEYBIT,BTN_RIGHT);
223
224         memset(&uinp,0,sizeof uinp);
225         strncpy(uinp.name,"nunchuk",UINPUT_MAX_NAME_SIZE);
226         uinp.id.bustype = BUS_USB;
227         uinp.id.vendor = 0x1;
228         uinp.id.product = 0x1;
229         uinp.id.version = 1;
230
```

```
231         rc = write(fd,&uinp,sizeof(uinp));
232         assert(rc == sizeof(uinp));
233
234         rc = ioctl(fd,UI_DEV_CREATE);
235         assert(!rc);
236         return fd;
237 }
238
239 /*
240  * Post keystroke down and keystroke up events:
241  * (unused here but available for your own experiments)
242  */
243 static void
244 uinput_postkey(int fd,unsigned key) {
245         struct input_event ev;
246         int rc;
247
248         memset(&ev,0,sizeof(ev));
249         ev.type = EV_KEY;
250         ev.code = key;
251         ev.value = 1;             /* Key down */
252
253         rc = write(fd,&ev,sizeof(ev));
254         assert(rc == sizeof(ev));
255
256         ev.value = 0;             /* Key up */
257         rc = write(fd,&ev,sizeof(ev));
258         assert(rc == sizeof(ev));
259 }
260
261 /*
262  * Post a synchronization point :
263  */
264 static void
265 uinput_syn(int fd) {
266         struct input_event ev;
267         int rc;
268
269         memset(&ev,0,sizeof(ev));
270         ev.type = EV_SYN;
271         ev.code = SYN_REPORT;
272         ev.value = 0;
273         rc = write(fd,&ev,sizeof(ev));
274         assert(rc == sizeof(ev));
275 }
276
```

```
277 /*
278  * Synthesize a button click :
279  *   up_down   1=up,   0=down
280  *   buttons   1=Left, 2=Middle, 4=Right
281  */
282 static void
283 uinput_click(int fd,int up_down,int buttons) {
284         static unsigned codes[] = {BTN_LEFT, BTN_MIDDLE, BTN_RIGHT};
285         struct input_event ev;
286         int x;
287
288         memset(&ev,0,sizeof(ev));
289
290         /*
291          * Button down or up events:
292          */
293         for ( x=0; x < 3; ++x )  {
294               ev.type = EV_KEY;
295               ev.value = up_down;  /* Button Up or down */
296               if ( buttons & (1 << x) ) { /* Button 0, 1 or 2 */
297                       ev.code = codes[x];
298                       write(fd,&ev,sizeof(ev));
299               }
300         }
301 }
302
303 /*
304  * Synthesize relative mouse movement:
305  */
306 static void
307 uinput_movement(int fd,int x,int y) {
308         struct input_event ev;
309         int rc;
310
311         memset(&ev,0,sizeof(ev));
312         ev.type = EV_REL;
313         ev.code = REL_X;
314         ev.value = x;
315
316         rc = write(fd,&ev,sizeof(ev));
317         assert(rc == sizeof(ev));
318
319         ev.code = REL_Y;
320         ev.value = y;
321         rc = write(fd,&ev,sizeof(ev));
322         assert(rc == sizeof(ev));
323 }
324
```

```
325 /*
326  * Close uinput device :
327  */
328 static void
329 uinput_close(int fd) {
330         int rc;
331
332         rc = ioctl(fd,UI_DEV_DESTROY);
333         assert(!rc);
334         close(fd);
335 }
336
337 /*
338  * Signal handler to quit the program:
339  */
340 static void
341 sigint_handler(int signo) {
342         is_signaled = 1;      /* Signal to exit program */
343 }
344
345 /*
346  * Curve the adjustment :
347  */
348 static int
349 curve(int relxy) {
350          int ax = abs(relxy); /* abs (relxy) */
351          int sgn = relxy < 0 ? -1 : 1;   /* sign (relxy) */
352          int mv = 1;          /* Smallest step */
353
354          if ( ax > 100 )
355                 mv = 10;      /* Take large steps */
356          else if ( ax > 65 )
357                 mv = 7;
358          else if ( ax > 35 )
359                 mv = 5;
360          else if ( ax > 15 )
361                 mv = 2;        /* 2nd smallest step */
362          return mv * sgn;
363 }
364
365 /*
366  * Main program:
```

```
367  */
368 int
369 main(int argc,char **argv) {
370         int fd, need_sync, init = 3;
371         int rel_x=0, rel_y = 0;
372         nunchuk_t data0, data, last;
373
374         if ( argc > 1 && !strcmp(argv [1]," -d") )
375                f_debug = 1;     /* Enable debug messages */
376
377         (void)uinput_postkey;   /* Suppress compiler warning about unused */
378
379         i2c_init("/dev/i2c-1"); /* Open I2C controller */
380         nunchuk_init();         /* Turn off encrypt ion */
381
382         signal(SIGINT,sigint_handler); /* Trap on SIGINT */
383         fd = uinput_open();     /* Open/dev/uinput */
384
385         while ( !is_signaled ) {
386                if ( nunchuk_read(&data) < 0 )
387                       continue;
388
389                if ( f_debug )
390                       dump_data(&data);  /* Dump nunchuk data */
391
392                if ( init > 0 && !data0.stick_x && !data0.stick_y ) {
393                       data0 = data; /* Save initial values */
394                       last = data;
395                       --init;
396                       continue;
397                }
398
399                need_sync = 0;
400                if ( abs(data.stick_x - data0.stick_x) > 2
401                  || abs(data.stick_y - data0.stick_y) > 2) {
402                       rel_x = curve (data.stick_x - data0.stick_x);
403                       rel_y = curve (data.stick_y - data0.stick_y);
404                       if ( rel_x || rel_y ) {
405                           uinput_movement(fd,rel_x,-rel_y);
406                           need_sync = 1;
407                       }
408                }
409
410                if ( last.z_button != data.z_button ) {
411                       uinput_click(fd, data.z_button,1);
412                       need_sync = 1;
413                }
414
```

```
415                 if ( last.c_button != data.c_button ) {
416                         uinput_click(fd,data.c_button,4);
417                         need_sync = 1;
418                 }
419
420                 if ( need_sync )
421                         uinput_syn(fd);
422                 last = data;
423         }
424
425         putchar('\n');
426         uinput_close(fd);
427         i2c_close();
428         return 0;
429 }
430
431 /* End nunchuk.c */
```

CHAPTER 4

Real-Time Clock

The Dallas Semiconductor DS1307 Real-Time Clock is the perfect project for the Raspberry Pi, Model A. Lacking a network port, the Model A cannot determine the current date and time when it boots up. A 3 V battery attached to the DS1307 will keep its internal clock running for up to 10 years, even when the Pi is powered off. If you have a Model B, don't feel left out. There is no reason that you can't try this project too; a Model B not connected to a network could use the DS1307.

DS1307 Overview

The pinout of the DS1307 chip is provided in Figure 4-1. The chip is available in PDIP-8 form or in SO format (150 mils). Hobbyists who like to build their own will prefer the PDIP-8 form.

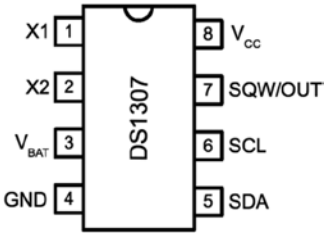


Figure 4-1. *DS1307 pinout*

A crystal is wired between pins 1 and 2 (X1 and X2). The battery powers the chip through pin 3 and flows to ground (pin 4). This keeps the clock alive while the main power is absent. When there is power, it is supplied through pin 8 (V_{CC}). The I2C communication occurs via pins 5 and 6. Pin 7 provides an optional output clock signal or can operate as an open collector output.

While you could build this circuit yourself, you can find fully assembled PCB modules using the DS1307 on eBay for as little as $2.36 (with free shipping). These are available as Buy It Now offers, so you don't have to waste your time trying to win auctions. Just keep in mind that some are not shipped with a 3 V battery. (Check the product.

The Tiny RTC I used came with a 3.6 V battery.) It is claimed that there are mailing restrictions on batteries to certain countries. So you may want to shop for suitable batteries while you wait for the mail.

■ **Tip** Buying a fresh battery ahead of time is recommended, as batteries often arrive exhausted.

Figure 4-2 shows a PCB unit that I purchased through eBay. This unit came paired with the AT24C32 EEPROM chip. The auction was labeled "Tiny RTC I2C Modules." You don't have to use this specific PCB, of course. The wiring for each chip is fairly basic and can be prototyped on a breadboard if you can't find one. But if you do choose this PCB, a modification is *required* before you attach it to the Raspberry Pi.

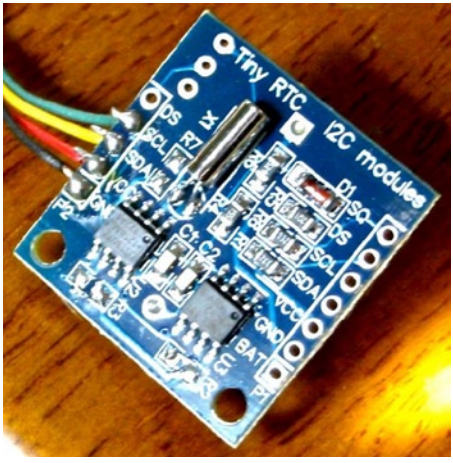


Figure 4-2. *An assembled DS1307 PCB purchased through eBay*

■ **Caution** *I2C pull-up resistors R_2 and R_3 must be removed before wiring the PCB to the Raspberry Pi.* Also, if you plan to attach the SQW/OUT output of this PCB to a GPIO input, be sure to track down and remove its pull-up resistor as well.

Pins X1 and X2

These pins are for connection to a 32.768 kHz crystal. The datasheet states that the "internal oscillator circuitry is designed for operation with a crystal having a specified load capacitance (C_L) of 12.5 pF."

Pin SQW/OUT

This is an open-drain output from the DS1307 chip that you can choose to ignore if you like. It can be used as follows:

- A GPIO-like output. If you plan on wiring this to a Pi GPIO pin, be sure to remove the pull-up resistor (on PCB) first. The +5 V from the pull-up will damage the Pi.
- A square wave clock output, at one of the following programmable frequencies:
  - 1 Hz
  - 4.096 kHz
  - 8.192 kHz
  - 32.768 kHz

The datasheet lists a current rating for output when low:

Parameter	Symbol	Min	Typ	Max	Units
Logic 0 Output ($I_{OL} = 5\ mA$)	V_{OL}			0.4	Volts

Without more-specific information, we arrive at the conclusion that a given logic pin is capable of sinking a maximum of 5 mA (SDA). While doing so, the maximum voltage appearing at the pin is 0.4 V. This is well under the 0.8 V maximum, for the V_{IL} voltage level of the Raspberry Pi.

The datasheet indicates that the SQW/OUT pin is an open-drain output. As such, you can use a pull-up to +3.3 V or +5 V as your interface requires. It could be used to drive a small LED at 1 Hz, if the current is limited to less than 5 mA (although the datasheet doesn't indicate the current capability of this open-drain transistor). Alternatively, it can be used to drive other external logic with a pull-up resistor.

The datasheet indicates that the SQW/OUT pin can pulled as high as 5.5 V, even when V_{CC} is lower in voltage (such as +3.3 V.) This is safe, provided that these higher voltages never connect to the Pi's GPIO pins.

Power

If you've looked at the datasheet for the DS1307 before, you might be wondering about the power supply voltage. The datasheet lists it as a +5 V part, and by now you are well aware that the Pi's GPIO pins operate at +3 V levels. The DC operating conditions are summarized here:

Parameter	Symbol	Min	Typ	Max	Units
Supply voltage	V_{CC}	4.5	5.0	5.5	Volts
Battery voltage	V_{BAT}	2.0		3.5	Volts

It is tempting to consider that the PCB might operate at +3.3 V, given that the battery in the unit is 3 V. However, that will not work because the DS1307 chip considers a V_{CC} lower than $1.25 \times V_{BAT} = 3.75$ V to be a *power-fail* condition (for a typical operation). When it senses a power fail, it relies on battery operation and will cease to communicate by I2C, among other things. Power-fail conditions are summarized here:

Parameter	Symbol	Min	Typ	Max	Units
Power-fail voltage	V_{PF}	$1.26 \times V_{BAT}$	$1.25 \times V_{BAT}$	$1.284 \times V_{BAT}$	Volts

The note in the datasheet indicates that the preceding figures were measured when $V_{BAT} = 3$ V. So these figures will likely deviate when the battery nears expiry. Given the power-fail conditions, we know that the device must be powered from a +5 V power supply. But the only connections made to the Raspberry Pi are the SDA and SCL I2C lines. So let's take a little closer look at those and see if we can use them.

3-Volt Compatibility

The SCL line is always driven by the master, as far as the DS1307 is concerned. This means that SCL is always seen as an input signal by the RTC clock chip. All we have to check here is whether the Raspberry Pi will meet the input-level requirements. Likewise, the AT24C32 EEPROM's SCL pin is also an input only.

The SDA line is driven by both the master (Pi) and the DS1307 chip (slave). The SDA is driven from the Pi as a 3 V signal, so again we need to make certain that the DS1307 will accept those levels. But what about the DS1307 driving the SDA line? The Pi must not see +5 V signals.

The DS1307 datasheet clearly states that "the SDA pin is open drain, which requires an external pull-up resistor." The Raspberry Pi already supplies the pull-up resistor to +3.3 V. This means that the DS1307's open drain will allow the line to be pulled up to +3.3 V for the high logic level, when the output transistor is in the off state. When the transistor is on, it simply pulls the SDA line down to ground potential. Thus with open-drain operation, we can interoperate with the Raspberry Pi. A check of the AT24C32 EEPROM datasheets leads to the same conclusion.

Logic Levels

How do the I2C logic levels compare between the Raspberry Pi and the DS1307?

Signal	Raspberry Pi	DS1307
V_{IL}	≤ 0.8 volts	≤ 0.8 volts
V_{IH}	≥ 1.3 volts	≥ 2.2 volts

The V_{IL} figure matches perfectly for both sides. As long as the Raspberry Pi provides a high level exceeding 2.2 V, the DS1307 chip should read high levels just fine. Given that the Pi's pull-up resistor is connected to +3.3 V, there is very little reason to doubt problems meeting the DS1307 V_{IH} requirement.

To summarize, we can safely power the DS1307 from +5 V, while communicating between it and the Raspberry Pi at +3 V levels. The Pi already supplies pull-up resistors for the SCL and SDA lines, and these are attached to +3.3 V. If, however, you choose to use other GPIO pins to bit-bang I2C (say), you'll need to provide these pull-up resistors (they must go to only +3.3 V).

Tiny RTC Modifications

In the preceding section, you saw that even though the DS1307 is a +5 V part, the SDA pin is driven by an open-drain transistor. With the Raspberry Pi tying the SDA line to +3.3 V, the highest voltage seen will be exactly that. The open-drain transistor can only pull it down to ground (this also applies to the AT24C32 EEPROM). Both chips have the SCL pins as inputs (only), which are not pulled high by the chips themselves.

If you purchased a PCB like the one I used, however, be suspicious of pull-up resistors! I knew that the parts would support +3.3 V I2C bus operation before the PCB arrived in the mail. However, I was suspicious of added pull-up resistors. So when the PCB arrived, I quickly determined that the PCB did indeed include pull-up resistors connected to the +5 V supply. *The extra +5 V pull-up resistors must be tracked down and removed for use with the Raspberry Pi.*

Checking for Pull-up Resistors

There are two methods to test for pull-up resistors: a DMM resistance check and a voltage reading. I recommend that you apply them both.

Since this modification is important to get correct, the following sections will walk you through the two different procedures in detail.

Performing a DMM Resistance Check

Use these steps for the DMM resistance check:

1. Attach one probe of your DMM (reading kΩ) to the +5 V line of the PCB.
2. Attach the other probe to the SDA line and take the resistance reading.
3. Reverse the leads if you suspect diode action.

On my PCB, I read 3.3 *k*Ω. Reversing the DMM leads should read the same (proving only resistance). Performing the same test with the SCL input, I also read 3.3 *k*Ω.

Performing a Voltage Reading

Do not skip this particular test. The result of this test will tell you whether your Raspberry Pi will be at risk.

1. Hook up your PCB to the +5 V supply it requires, but do not attach the SDA/SCL lines to the Pi yet. Just leave them loose for measuring with your DMM.
2. With the DMM negative probe grounded, measure the voltage seen at the PCB's SDA and SCL inputs. If there is no pull-up resistor involved, you should see a low reading of approximately 0.07 V. The reading will be very near ground potential.

On my unmodified PCB, these readings were +5 V because of the 3.3 *k*Ω pull-up resistors. If this also applies to your PCB unit, a modification is *required*.

Performing a Tiny RTC Modification

If you have the exact same PCB that I used, you can simply remove resistors R_2 and R_3 (but I would double-check with the preceding tests). These resistors are shown in Figure 4-3. Carefully apply a soldering iron to sweep them off the PCB. Make sure no solder is left, shorting the remaining contacts. I highly recommend that you repeat the tests to make sure you have corrected the pull-up problem and test for short circuits.

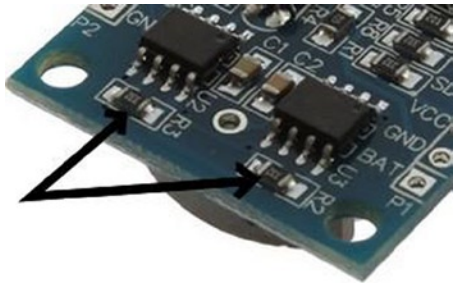


Figure 4-3. *R_2 and R_3 of the Tiny RTC I2C PCB*

Working with Other PCB Products

If you have a different PCB product, you may have optional resistors that you can *leave uninstalled*. Even though they may be optional, someone might have done you the favor of soldering them in. So make sure you check for that (use the earlier tests).

The Adafruit RTC module (http://www.adafruit.com/products/264) is reportedly *sometimes* shipped with the 2.2 *k*Ω resistors installed. For the Raspberry Pi, they must be removed.

Locating the Pull-up Resistors

Even if you don't have a schematic for your PCB product, you will need to locate the pull-up resistors. Since there aren't many components on the PCB to begin with, they tend to be easy to locate:

1. Observe static electricity precautions.
2. Attach one DMM (kΩ) probe to the +5 V input to the PCB.
3. Look for potential resistors on the component side.
4. Locate all resistors that have one lead wired directly to the +5 V supply (resistance will read 0 Ω). These will be the prime suspects.
5. Now attach your DMM (range kΩ) to the SDA input. With the other DMM probe, check the opposite ends of the resistors, looking for readings of 0 Ω. You should find one resistor end (the other end of the resistor will have been previously identified as connected to the +5 V supply).
6. Likewise, test the SCL line in the same manner as step 5.
7. Double-check: take a resistance reading between the SDA input and the +5 V supply. You should measure a resistance of 2 to 10 kΩ, depending on the PCB manufacturer. You should get the same reading directly across the resistor identified.
8. Repeat step 7 for the SCL line.

If you've done this correctly, you will have identified the two resistors that need to be removed. If you plan to interface the SQW/OUT pin to a Pi GPIO, you'll want to remove the pull-up used on that as well.

DS1307 Bus Speed

The DS1307 datasheet lists the maximum SCL clock speed at 100 kHz:

Parameter	Symbol	Min	Typ	Max	Units
SCL clock frequency	f_{SCL}	0		100	kHz

The Raspberry Pi uses 100 kHz for its I2C clock frequency (see Chapter 12 of *Raspberry Pi Hardware Reference* [Apress, 2014] for more information). The specification also states that there is no minimum frequency. If you wanted to reserve the provided I2C bus for use with other peripherals (perhaps at a higher frequency), you could bit-bang interactions with the DS1307 by using another pair of GPIO pins. (Pull-up resistors to +3.3 V will be required; the internal pull-up resistors are not adequate.) That is an exercise left for you.

Now that we have met power, signaling, and clock-rate requirements, "Let's light this candle!"

RTC and RAM Address Map

The DS1307 has 56 bytes of RAM in addition to the real-time clock registers. I/O with this chip includes an implied address register, which ranges in value from 0x00 to 0x3F. The address register will wrap around to zero after reaching the end (don't confuse the register address with the I2C peripheral address).

■ **Note** The DS1307 RTC uses I2C address 0x68.

The address map of the device is illustrated in Table 4-1. The date and time components are BCD encoded. In the table, *10s* represents the tens digit, while *1s* represents the ones digit.

Table 4-1. *DS1307 Register Map*

		Format							
Address	**Register**	7	6	5	4	3	2	1	0
0x00	Seconds	CH	10s			1s			
0x01	Minutes	0	10s			1s			
0x02	Hours	0	24hr	10s		1s			
			12hr	PM	10s	1s			
0x03	Weekday	0	0	0	0	0			1s
0x04	Day	0	0	10s		1s			
0x05	Month	0	0	0	10s	1s			
0x06	Year	10s				1s			
0x07	Control	OUT	0	0	SQWE	0	0	RS1	RS2
0x08	RAM 00	byte							
…		…							
0x3F	RAM 55	byte							

The components of the register map are further described in Table 4-2. Bit CH allows the host to disable the oscillator and thus stop the clock. This also disables the SQW/OUT waveform output (when `SQWE=1`). Bit 6 of the Hours register determines whether 12- or 24-hour format is used. When in 12-hour format, bit 5 becomes an AM/PM indicator.

Table 4-2. *RTC Register Map Components*

Bit		Meaning			
CH	0	Clock running			
	1	Clock (osc) halt			
24hr	0	24-hour format			
12hr	1	12-hour format	**RS1**	**RS0**	**Meaning**
OUT	0	SQW/OUT = Low	0	0	1 Hz
	1	SQW/OUT = High	0	1	4.096 kHz
SQWE	0	SQW/OUT is OUT	1	0	8.192 kHz
	1	SQW/OUT is SQW	1	1	32.768 kHz

The Control register at address 0x07 determines how the SQW/OUT pin behaves. When `SQWE=1`, a square wave signal is produced at the SQW/OUT pin. The frequency is selected by bits `RS1` and `RS0`. In this mode, the `OUT` setting is ignored.

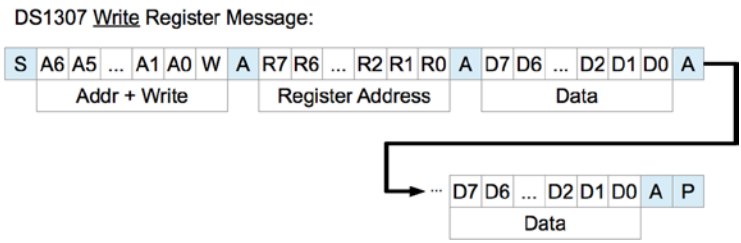
When `SQWE=0`, the `SQW/OUT` pin is set according to the bit placed in `OUT` (bit 7 of the control register). In this mode, the pin behaves as an open-drain GPIO output pin.

Reading Date and Time

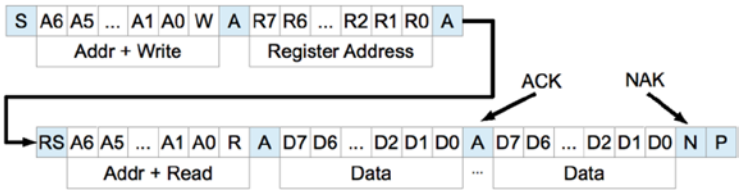
When the DS1307 device is being read, a snapshot of the current date and time is made when the I2C start bit is seen. This copy operation allows the clock to continue to run while returning a stable date/time value back to the master. If this were not done, time components could change between reading bytes. The application should therefore always read the full date/time set of registers as one I/O operation. The running clock does not affect reading the control register or the RAM locations.

I2C Communication

The DS1307 registers and RAM can be written randomly, by specifying an initial starting register address, followed by 1 or more bytes to be written. The register address is automatically incremented with each byte written and wraps around to 0. The DS1307 slave device will ACK each byte as it is received, continuing until the master writes a stop bit (P). The first byte sent is always the peripheral's I2C address, which should not be confused with the selected peripheral's register address (that immediately follows). The DS1307 I2C address is always 0x68. The general form of the write message is shown here:



The DS1307 supports multibyte reads. You can read multiple bytes from the DS1307 simply by starting with an I2C start bit (S), and peripheral address sent as a read request. The slave will then serve up bytes one after another for the master. Receiving terminates when the master sends a NAK.



If you want to be certain that the register address is established with a known value, you should always issue a write request first. In the preceding diagram, the write request immediately follows the start bit (S). Only the peripheral's register address byte is written out prior to the repeating start bit (RS), which follows.

After the RS bit, the peripheral address is transmitted once more to re-engage the DS1307, but this time as a read request. From that point on, the master reads bytes sequentially from the DS13017 until a NAK is sent. The final stop bit (P) sent by the master ends the exchange. This peripheral provides us with a good example of a multimessage I/O.

This is demonstrated in lines 27 to 45 of the program `ds1307get.c`, in the upcoming pages. The entire I/O is driven by the structures `iomsgs[0]` and `iomsgs[1]`. Structure `iomsgs[0]` directs the driver to write to peripheral address 0x68 and writes 1 0x00 data byte out to it. This establishes the RTC's internal register with a value of 0x00. The read request is described in `iomsgs[1]`, which is a read from the same peripheral 0x68, for 8 bytes. (Only 7 bytes are strictly required for the date and time, but we read the additional control byte anyway.)

The data structure is laid out in C terms in the file `ds1307.h`. An optional exercise for you is to add a command-line option to `ds1307set` to stop the clock and turn it on again using the `ch` bit (line 8 of `ds1307.h`).

Source module `i2c_common.c` has the usual I2C open/initialization and close routines in it.

Wiring

Like any I2C project for the Pi, you'll wire the SDA and SCL lines as follows:

Pre Rev 2.0		Rev 2.0+		
GPIO	**Line**	**GPIO**	**Line**	**P1**
0	SDA0	2	SDA1	P1-03
1	SCL0	3	SCL1	P1-05

The DS1307 PCB (or chip) is powered from the +5 V supply. Prior to attaching it to the Raspberry Pi, it is a good idea to power the DS1307 and measure the voltage appearing on its SDA and SCL lines. Both should measure near ground potential. If you see +5 V instead, stop and find out why.

Running the Examples

Since these programs use the I2C Linux drivers, make sure these kernel modules are either already loaded, or load them manually now:

```
$ sudo modprobe i2c-bcm2708
$ sudo modprobe i2c-dev
```

Program `ds1307set.c` (executable `ds1307set`) is used to reset the RTC to a new date/time value of your choice. For example:

```
$ ./ds1307set 20130328215900
2013-03-28 21:59:00 (Thursday)
$
```

This sets the date according to the command-line value, which is in YYYYMMDDHHMMSS format.

Once the RTC date has been established, you can use the executable `ds1307get` to read back the date and time:

```
$ ./ds1307get
2013-03-28 22:00:37 (Thursday)
$
```

In this case, a little time had passed between setting the date and reading it. But we can see that the clock is ticking away.

If you don't like the date/time format used, you can either change the source code or set the environment variable `DS1307_FORMAT`. For example:

```
$ export DS1307_FORMAT="%a %Y-%m-%d %H:%M:%S"
$ ./ds1307get
Thu 2013-03-28 22:03:38
$
```

For a description of the date/time format options available, use this:

```
$ man date
```

The setting of `DS1307_FORMAT` also affects the display format used by `ds1307set`.

The Ultimate Test

The ultimate test is to shut down the Raspberry Pi and turn off its power. Wait a minute or so to make sure that all of the power has been drained out of every available capacitor. Then bring up the Pi again and check the date/time with the program `ds1307get`. Did it lose any time?

The Startup Script

To put the RTC to good practical use, you'll want to apply `ds1307get` at a suitable point in the Linux startup sequence. You'll need to wait until the appropriate I2C driver support is available (or can be arranged). You'll need to develop a short shell script, using the

DS1307_FORMAT environment variable in order to produce a format suitable for the console date command. To set the system date (as root), you would use this command:

```
# date [-u|--utc|--universal] [MMDDhhmm[[CC]YY][.ss]]
```

The startup script for doing all of this has not been provided here. I don't want to spoil your fun when you can develop this yourself. You learn best by doing. Refer to Chapter 3 of *Raspberry Pi System Software Reference* (Apress, 2014) if you need some help.

As a further hint, you'll want to develop a script for the `/etc/rc2.d` directory, with a name starting with *S* and two digits. The digits determine where the script runs in the startup sequence (you'll want to make sure your script runs after the system has come up far enough that I2C drivers are loaded).

Once your startup script is developed, your Raspberry Pi can happily reboot after days, even years, of being powered off, and still be able to come up with the correct date and time.

■ **Note** If you're running the older Model B, where the I2C bus 0 is used instead of 1, change line 21 in `ds1307set.c` and line 21 in `ds1307get.c`. See Chapter 12 of *Raspberry Pi Hardware Reference* (Apress, 2014) for more information.

```
1  /*****************************************************************
2   * ds1307.h: Common DS1307 types and macro definitions
3   *****************************************************************/
4
5   typedef struct {
6          /* Register Address 0x00 : Seconds   */
7          unsigned char         secs_1s : 4;   /* Ones digit : seconds */
8          unsigned char         secs_10s : 3;  /* Tens digit : seconds */
9          unsigned char         ch : 1;        /* CH bit */
10         /* Register Address 0x01 : Minutes   */
11         unsigned char        mins_1s : 4;    /* Ones digit : minutes */
12         unsigned char        mins_10s : 3;   /* Tens digit : minutes */
13         unsigned char        mbz_1 : 1;      /* Zero bit */
14         /* Register Address 0x02 : Hours     */
15         unsigned char        hour_1s : 4;    /* Ones digit : hours */
16         unsigned char        hour_10s : 2;   /* Tens digit : hours
                                                   (24 hr mode) */
17         unsigned char        mode_1224 : 1;  /* Mode bit : 12/24 hour
                                                   format */
18         /* Register Address 0x03 : Weekday   */
19         unsigned char        wkday : 3;      /* Day of week (1-7) */
20         unsigned char        mbz_2 : 5;      /* Zero bits */
21         /* Register Address 0x04 : Day of Month */
22         unsigned char        day_1s : 4;     /* Ones digit : day of month
                                                   (1-31) */
```

```
23         unsigned char        day_10s : 2;    /* Tens digit : day of
                                                   month */
24         unsigned char        mbz_3 : 2; /* Zero bits */
25         /* Register Address 0x05 : Month */
26         unsigned char        month_1s : 4;  /* Ones digit : month (1-12)
*/
27         unsigned char        month_10s : 1; /* Tens digit : month */
28         unsigned char        mbz_4 : 3; /* Zero */
29         /* Register Address 0x06 : Year */
30         unsigned char        year_1s : 4     /* Ones digit : year (00-99)
*/
31         unsigned char        year_10s : 4;   /* Tens digit : year */
32         /* Register Address 0x07 : Control */
33         unsigned char        rs0 : 1;   /* RS0 */
34         unsigned char        rs1 : 1;   /* RS1 */
35         unsigned char        mbz_5 : 2; /* Zeros */
36         unsigned char        sqwe : 1;  /* SQWE */
37         unsigned char        mbz_6 : 2;
38         unsigned char        outbit : 1;     /* OUT */
39 } ds1307_rtc_regs;
40
41 /* End ds1307 . h */
```

```
1 /*********************************************************************
2  * i2c_common.c : Common I2C Access Functions
3  *********************************************************************/
4
5  static int i2c_fd = -1;             /* Device node: /dev/i2c-1 */
6  static unsigned long i2c_funcs = 0; /* Support flags */
7
8  /*
9   * Open I2C bus and check cap abilities:
10  */
11 static void
12 i2c_init(const char *node) {
13        int rc;
14
15        i2c_fd = open(node,O_RDWR);   /* Open driver /dev/i2s-1 */
16        if ( i2c_fd < 0 ) {
17            perror("Opening /dev/ i 2 s -1");
18                puts("Check that the i2c-dev & i2c-bcm2708 kernelmodules "
19                    " are loaded . " ) ;
20            abort();
21        }
22
23        /*
24         * Make sure the driver suppor tsplain I2C I /O:
```

```
25         */
26         rc = ioctl(i2c_fd,I2C_FUNCS,&i2c_funcs);
27         assert(rc >= 0);
28         assert(i2c_funcs & I2C_FUNC_I2C);
29   }
30
31   /*
32    * Close the I2C driver :
33   */
34   static void
35   i2c_close(void) {
36       close(i2c_fd);
37       i2c_fd = -1;
38   }
39
40   /* End i2c_common.c */
```

```
1  /*********************************************************************
2   * ds1307set.c : Set real-time DS1307 clock on I2C bus
3   *********************************************************************/
4
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <ctype.h>
8  #include <time.h>
9  #include <fcntl.h>
10 #include <unistd . h>
11 #include <string . h>
12 #include <errno . h>
13 #include <assert . h>
14 #include <sys / i octl . h>
15 #include <l inux / i2c-dev . h>
16
17 #include "i2c_common.c"       /* I2C routines */
18 #include "ds1307.h"           /* DS1307 types */
19
20  /* Change to i2c-0 if using early Raspberry Pi */
21  static const char *node = "/dev/i2c-1";
22
23 /*
24  * Write [ S ] 0xB0 <regaddr> <rtcbuf[0]> . . . <rtcbuf[n-1]> [P]
25  */
26  static int
27  i2c_wr_rtc(ds1307_rtc_regs *rtc) {
28         struct i2c_rdwr_ioctl_data msgset;
29         struct i2c_msg iomsgs[1];
30         char buf[sizeof *rtc+1];    /* Work buffer */
31
```

```
32         buf[0] = 0x00;                       /* Register 0x00 */
33         memcpy(buf+1,rtc,sizeof *rtc);       /* Copy RTC info */
34
35         iomsgs[0].addr = 0x68;               /* DS1307 Address */
36         iomsgs[0].flags = 0;                 /* Write */
37         iomsgs[0].buf = buf;                 /* Register + data */
38         iomsgs[0].len = sizeof *rtc + 1;     /* Total msg len */
39
40         msgset.msgs = &iomsgs[0];
41         msgset.nmsgs = 1;
42
43         return ioctl(i2c_fd,I2C_RDWR,&msgset);
44 }
45
46 /*********************************************************************
47  * Set the DS1307 real-time clock on the I2C bus :
48  *
49  * ./ds1307set YYYYMMDDHHMM[ss]
50  *********************************************************************/
51 int
52 main(int argc,char **argv) {
53         ds1307_rtc_regs rtc;  /* 8 DS1307 Register Values */
54         char buf[32];         /* Extraction buffe r */
55         struct tm t0, t1;     /* Unix date / time values */
56         int v, cx, slen;
57         char *date_format = getenv("DS1307_FORMAT");
58         char dtbuf[256];      /* Formatted date/time */
59         int rc;               /* Return code */
60
61        /*
62         * If no environment variable named DS1307_FORMAT, then
63         * set a default date/time format.
64         */
65        if ( !date_format )
66                date_format = "%Y-%m-%d %H:%M:%S (%A) " ;
67
68         /*
69          * Check command line usage :
70          */
71        if ( argc != 2 | | (slen = strlen(argv[1])) < 12 || slen > 14 ) {
72  usage: fprintf(stderr,
73                      "Usage : %s YYYYMMDDhhmm[ss]\n",
74                      argv[0]);
75                exit(1);
76         }
77
```

```
78          /*
79          * Make sure every character is a digit in argument 1 .
80          */
81         for ( cx=0; cx<slen; ++cx )
82                 if ( !isdigit(argv[1][cx]) )
83                 goto usage; /* Not a numeric digit */
84
85         /*
86          * Initialize I2C and clear rtc and t1 structures :
87          */
88         i2c_init(node) ;              /* Initialize for I2C */
89         memset(&rtc,0,sizeof rtc);
90         memset(&t1,0,sizeof t1);
91
92         /*
93          * Extract YYYYMMDDhhmm[ss] from argument 1:
94          */
95         strncpy(buf,argv[1],4)[4] = 0;       /* buf[] = "YYYY" */
96         if ( sscanf(buf,"%d",&v)  != 1 || v < 2000 || v > 2099 )
97             goto usage;
98         t1.tm_year = v - 1900;
99
100        strncpy(buf,argv[1]+4,2)[2] = 0;     /* buf[] = "MM" */
101        if ( sscanf(buf,"%d",&v) != 1 || v <= 0 || v > 12 )
102        goto usage;
103        t1.tm_mon = v-1;                     /* 0 - 11 */
104
105        strncpy(buf,argv[1]+6,2)[2] = 0;     /* buf[] = "DD" */
106        if ( sscanf(buf,"%d",&v) != 1 || v <= 0 || v > 31 )
107        goto usage ;
108        t1.tm_mday = v;                      /* 1 - 31 */
109
110        strncpy(buf,argv[1]+8,2)[2] = 0;     /* buf[] = "hh" */
111        if ( sscanf(buf,"%d",&v) != 1 || v < 0 || v > 23 )
112        goto usage;
113        t1.tm_hour = v;
114
115        strncpy(buf,argv[1]+10,2)[2] = 0;    /* buf[] = "mm" */
116        if ( sscanf(buf,"%d",&v) != 1 || v < 0 || v > 59 )
117        goto usage;
118        t1.tm_min = v;
119
120        if ( slen > 12 ) {
121            /* Optional ss was provided : */
122            strncpy(buf,argv[1]+12,2)[2] = 0;      /* buf[] = "ss" */
123            if ( sscanf(buf,"%d",&v) != 1 || v < 0 || v > 59 )
124             goto usage;
```

```
125         t1.tm_sec = v;
126     }
127
128     /*
129      * Check the validity of the date :
130      */
131     t1.tm_isdst = -1;               /* Determine if daylight savings */
132     t0 = t1;                        /* Save initial values */
133     if ( mktime(&t1) == 1L ) {      /* t1 is modified */
134  bad_date : printf("Argument '%s ' is not avalid calendar date.\
     n",argv[1]) ;
135            exit(2);
136        }
137
138        /*
139         * If struct t1 was adjusted , then the original date/time
140         * values were invalid :
141         */
142         if ( t0.tm_year != t1.tm_year || t0.tm_mon != t1.tm_mon
143          || t0.tm_mday != t1.tm_mday || t0.tm_hour != t1.tm_hour
144          || t0.tm_min != t1.tm_min || t0.tm_sec != t1.tm_sec )
145             goto bad_date;
146
147          /*
148           * Populate DS1307 registers :
149           */
150          rtc.secs_10s = t1.tm_sec / 10;
151          rtc.secs_1s = t1.tm_sec % 10;
152          rtc.mins_10s = t1.tm_min / 10;
153          rtc.mins_1s = t1.tm_min % 10;
154          rtc.hour_10s = t1.tm_hour / 10;
155          rtc.hour_1s = t1.tm_hour % 10;
156          rtc.month_10s = (t1.tm_mon + 1) / 10;
157          rtc.month_1s = (t1.tm_mon + 1) % 10;
158          rtc.day_10s = t1.tm_mday / 10;
159          rtc.day_1s = t1.tm_mday % 10;
160          rtc.year_10s = (t1.tm_year + 1900 - 2000) / 10;
161          rtc.year_1s = (t1.tm_year + 1900 - 2000) % 10;
162
163          rtc.wkday = t1.tm_wday + 1;        /* Weekday 1-7 */
164          rtc.mode_1224 = 0;                 /* Use 24 hour format */
165
166 #if 0       /* Change to a 1 for debugging */
167     printf("%d%d-%d%d-%d%d %d%d:%d%d:%d%d (wkday %d )\n",
168             rtc.year_10s,rtc.year_1s,
169             rtc.month_10s,rtc.month_1s,
170             rtc.day_10s,rtc.day_1s,
```

```
171             rtc.hour_10s,rtc.hour_1s,
172             rtc.mins_10s,rtc.mins_1s,
173             rtc.secs_10s,rtc.secs_1s,
174             rtc.wkday);
175 #end if
176     rc = i2c_wr_rtc(&rtc );
177
178     /*
179      * Display RTC values submitted :
180      */
181         strftime(dtbuf,sizeof dtbuf,date_format,&t1);
182         puts(dtbuf);
183
184         if ( rc < 0 )
185             perror("Writing to DS1307 RTC");
186         else if ( rc != 1 )
187            printf(" Incomplete write : %d msgs of 2written \n",rc);
188
189         i2c_close();
190         return rc ==1? 0 : 4;
191 }
192
```

```
1  /*********************************************************************
2    * ds1307get.c : Read real-time DS1307 clock on I2C bus
3    *********************************************************************/
4
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <ctype.h>
8  #include <time h>
9  #include <fcntl.h>
10 #include <unistd.h>
11 #include <string.h>
12 #include <errno.h>
13 #include <assert.h>
14 #include <sys/ioctl.h>
15 #include <linux/i2c-dev.h>
16
17 #include "i2c_common.c"          /* I2C routines */
18 #include "ds1307.h"              /* DS1307 types */
19
20  /* Change to i2c-0 if using early Raspberry Pi */
21  static const char *node = "/dev/i2c-1";
22
```

```
23  /*
24   * Read : [ S ] 0xB1 <regaddr> <rtcbuf[0]> . . . <rtcbuf[n-1]> [P]
25   */
26  static int
27  i2c_rd_rtc(ds1307_rtc_regs *rtc) {
28          struct i2c_rdwr_ioctl_data msgset;
29          struct i2c_msg iomsgs[2];
30          char zero = 0x00;             /* Register 0x00 */
31
32          iomsgs[0].addr = 0x68;        /* DS1307 */
33          iomsgs[0].flags = 0;          /* Write */
34          iomsgs[0].buf = &zero;        /* Register 0x00 */
35          iomsgs[0].len = 1;
36
37          iomsgs[1].addr = 0x68;        /* DS1307 */
38          iomsgs[1].flags = I2C_M_RD;   /* Read */
39          iomsgs[1].buf = (char *)rtc;
40          iomsgs[1].len = size of *rtc;
41
42          msgset.msgs=iomsgs;
43          msgset.nmsgs=2;
44
45          return ioctl(i2c_fd,I2C_RDWR,&msgset);
46  }
47
48  /*
49   * Main program :
50   */
51  int
52  main(int argc,char **argv) {
53          ds1307_rtc_regs rtc; /* 8 DS1307 Register Values */
54          struct tm t0, t1;    /* Unix date / time values */
55          char *date_format = getenv("DS1307_FORMAT");
56          char dtbuf[256];     /* Formatted date/time */
57          int rc;              /* Return code */
58
59          /*
60           * If no environment variable named DS1307_FORMAT, then
61           * set a default date/time format.
62           */
63          if ( !date_format )
64              date_format = "%Y-%m-%d%H:%M:%S(%A)";
65
66          /*
67           * Initialize I2C and clear rtc and t1 structures:
68           */
69          i2c_init(node);      /* Initialize for I2C */
```

```
70          memset(&rtc,0,sizeof rtc);
71          memset(&t1,0,sizeof t1);
72
73          rc = i2c_rd_rtc(&rtc);
74          if ( rc < 0 ) {
75                perror("Reading DS1307 RTC clock.");
76                exit(1);
77          } else if ( rc != 2 ) {
78                fprintf(stderr,"Read error: got %d of 2 msgs.\n",rc);
79                exit(1);
80          } else
81                rc = 0;
82
83          /*
84           * Check the date returned by the RTC:
85           */
86          memset(&t1,0,sizeof t1);
87          t1.tm_year = (rtc.year_10s * 10 + rtc.year_1s) + 2000 - 1900;
88          t1.tm_mon = rtc.month_10s * 10 + rtc.month_1s - 1;
89          t1.tm_mday = rtc.day_10s * 10 + rtc.day_1s;
90          t1.tm_hour = rtc.hour_10s * 10 + rtc.hour_1s;
91          t1.tm_min = rtc.mins_10s * 10 + rtc.mins_1s;
92          t1.tm_sec = rtc.secs_10s * 10 + rtc.secs_1s;
93          t1.tm_isdst = -1; /* Determine if daylight savings */
94
95          t0 = t1;
96          if ( mktime(&t1) == 1L       /* t1 is modified */
97            || t1.tm_year != t0.tm_year || t1.tm_mon != t0.tm_mon
98            || t1.tm_mday != t0.tm_mday || t1.tm_hour != t0.tm_hour
99            || t1.tm_min != t0.tm_min || t1.tm_sec != t0.tm_sec ) {
100          strftime(dtbuf,sizeof dtbuf,date_format,&t0);
101          fprintf(stderr,"Read RTC date is not valid: %s\n",dtbuf);
102          exit(2);
103       }
104
105       if ( t1.tm_wday != rtc.wkday-1 ) {
106           fprintf(stderr,
107               "Warning:RTC weekday is incorrect %d but should be %d\n",
108               rtc.wkday,t1.tm_wday);
109       }
110
111 #if 0  /* Change to a 1 for debugging */
112      printf("%d%d-%d%d-%d%d%d%d:%d%d:%d%d(wkday %d)\n",
113           rtc.year_10s,rtc.year_1s ,
114           rtc.month_10s,rtc.month_1s ,
115           rtc.day_10s, rtc.day_1s ,
116           rtc.hour_10s,rtc.hour_1s ,
```

```
117          rtc.mins_10s,rtc.mins_1s ,
118          rtc.secs_10s,rtc.secs_1s ,
119          rtc.wkday);
120 #end if
121     strftime (dtbuf,size of dtbuf,date_format,&t1);
122     puts(dtbuf);
123
124     i2c_close();
125     return rc == 8 ? 0 : 4;
126 }
127
128 /* End ds1397get.c */
```

CHAPTER 5

VS1838B IR Receiver

The VS1838B is a PIN photodiode high-gain amplifier IC in an epoxy package with an outer shield. It consists of three pins and is about the size of a signal transistor. This inexpensive part can be purchased for about $2 on eBay to give your Raspberry Pi the ability to read many IR remote-control signals.

Operating Parameters

Figure 5-1 is a close-up photo of the VS1838B.

Figure 5-1. *The VS1838B PIN photodiode*

The datasheet provided for this part is mostly in Chinese. The most important parameter to decipher is the supply voltage range, which is listed in English here:

Parameter	Symbol	Min	Typ	Max	Units
Supply voltage	V_{CC}	2.7		5.5	Volts

Given that 3.3 V is within the operating range for the device, we can use it for the Raspberry Pi. We simply power it from the +3.3 V supply pin P1. The device requires only 1 mA of current, as seen in the other datasheet parameters here:

Parameter	Symbol	Test Conditions	Min	Typ	Max	Units
Supply current	I_{CC}	V_{CC} = 5.0 volts	0.6	0.8	1.0	mA
Receiving distance	L		11	13		m
Acceptance angle	θ½		±35			Deg
Carrier frequency	f_0			37.9		kHz
Bandwidth	f_{BW}			8		kHz
Voltage out low	V_{OL}	R_{pullup} = 2.4 $k\Omega$			0.25	Volts
Voltage out high	V_{OH}		V_{CC}–0.3		V_{CC}	Volts
Operating temp.	T_{opr}		–30		+85	°C

Pinout

With the lens of the part facing toward you, the pins are as follows, from left to right:

VS1838B		
	Front View	
Out	*Gnd*	V_{CC}

VS1838B Circuit

Figure 5-2 illustrates the VS1838B wired to the Raspberry Pi. Any GPIO pin can be used, but this text uses GPIO 17 for ease of reference. If you choose to use a different GPIO, changes to the source code will be necessary.

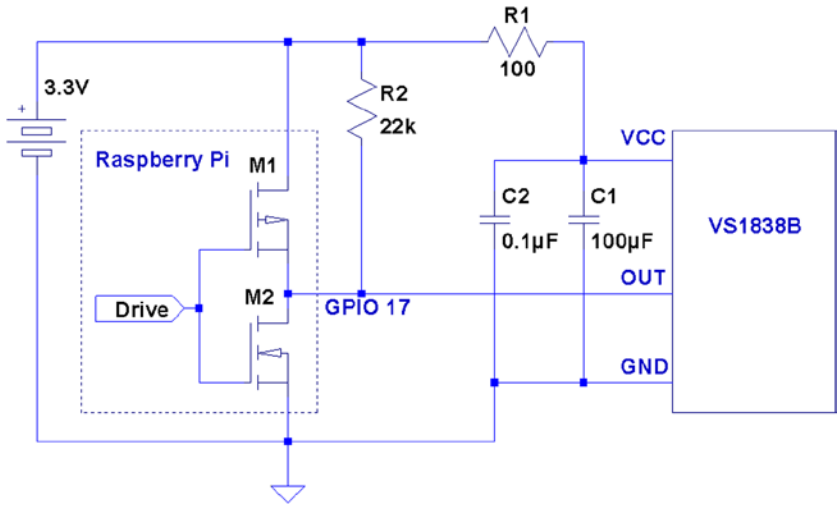


Figure 5-2. *VS1838B wired to the Raspberry Pi using GPIO 17*

The circuit may appear somewhat daunting to students, compared to some of the other projects in this book. The datasheet lists several components as being required: 100 Ω resistor R_1, and capacitors C_1 and C_2. Finally, there is the pull-up resistor R_2, shown here as 22 *k*Ω.

■ **Note** The datasheet simply shows the pull-up as being > 20 kΩ.

If you're breadboarding this in a hurry, you can probably leave out R_1, C_1, and C_2. I wired mine with R_1 but forgot about the capacitors. If you leave out the capacitors, R_1 is not required either. *R1* is not a current-limiting resistor here; R_1 and the capacitors are simply a low-pass filter designed to provide a quieter power supply to the part (which should normally be used). But if you're soldering this up, do include all of the recommended components for best results. Don't leave out the pull-up resistor. R_2 is required.

The IR Receiver

Most IR remote controls today use the 38 kHz carrier frequency on an infrared beam of light. Even if you know that your brand of remote uses a slightly different carrier frequency, the VS1838B may still work. The important point to realize about this part is that it tries to detect the remote control while ignoring other light sources in the room. To discriminate between fluorescent lighting and the remote control, it looks for this 38 kHz carrier signal. When it sees a steady stream of pulses, it can ignore the interference.

The 22 *k*Ω pull-up resistor in the schematic diagram is necessary to pull the Out line up to V_{CC} level, when no 38 kHz beam is seen. (The datasheet block diagram shows the output as a CMOS totem-pole output, but the pull-up suggests open-drain configuration instead.) When the device sees a carrier for a minimum burst of 300 μs, it pulls the Out line low. This line remains driven low as long as the carrier signal is detected. As soon as the carrier is removed for 300 μs or more, the line is pulled high again by the resistor.

Out	Description
High	No 38 kHz carrier seen
Low	38 kHz carrier is detected

Wired as shown, the Raspberry Pi will be able to see the effect of the carrier being turned on and off, many times per second, as it receives remote-control bursts of IR light.

Software

This is where I apologize in advance. No matter which brand of TV or remote control is supported by the software in this chapter, most people will own something *different*. However, if you own a relatively recently produced Samsung TV, the software *might* just work for you out of the box. The software presented in this chapter was developed for the remote control of a Samsung plasma HDTV (Model series 50A400).

If the software doesn't work for you as is, then consider yourself blessed. When you dig into the program and make it work for your remote, you'll come away from the experience knowing much more than when you started.

Signal Components

Here's where it gets fun. While most manufacturers have agreed on the 38 kHz carrier frequency, they haven't agreed on how the signaling works. Most protocols work on the principle of turning bursts of IR on and off, but how that encodes a "key" differs widely.

An informative website (`www.techdesign.be/projects/011/011_waves.htm`) documents a few of the common IR waveforms.[54] The one we're interested in is the Samsung entry, listed as protocol number 8.

Table 5-1 summarizes the technical aspects of the waveforms shown at the website. All times shown are in milliseconds.

Table 5-1. *IR Remote Waveform Times*

Protocol	Brand	Component	High	Low	High
				ms	
2	NEC	Start bit	9	4.5	-
		0 bit	0.56	0.56	-
		1 bit	0.56	1.69	-
		Stop bit	0.56	0.56	-
4	SIRCS	Start bit	2.4	0.6	-
		0 bit	0.6	0.6	-
		1 bit	1.2	0.6	-
5	RC5	Start bit	-	0.889	0.889
		0 bit	-	0.889	0.889
		1 bit	0.889	0.889	-
7	Japan	Start bit	3.38	1.69	-
		0 bit	0.42	0.42	-
		1 bit	0.42	1.69	-
8	Samsung	Start bit	4.5	4.5	-
		0 bit	0.56	0.56	-
		1 bit	0.56	1.69	-
		Stop bit	0.56	0.56	-

The High/Low values shown in the table agree with the website. For our circuit, the signals are *inverted* because of the way that the VS1838B brings the line *low* when a carrier is detected. The logic sense of these signals are documented in Table 5-2 for clarity.

Table 5-2. *Carrier Signals as Seen by the Raspberry Pi GPIO*

Level	GPIO	Meaning
High (1)	Low	Carrier present
Low (0)	High	Carrier absent

The waveform diagrams at the website are pleasant to look at, but the essential ingredients boil down to the timings of three or four waveform components, which are listed in Table 5-3.

Table 5-3. *Waveform Components*

Component	Description
Start bit	Marks the start of a key-code
0 bit	0 bit for the code
1 bit	1 bit for the code
Stop bit	Stop bit (end of code)

Table 5-1 shows that only the NEC and the Samsung signals use a stop bit. In both cases, each stop bit is simply an extra 0 bit added onto the end of the stream.

All protocols use a *special* "start bit" to identify where the code transmission begins. RC5 just uses a 0-bit waveform (in other words, the start and the 0 bits are identical).

A signal component always begins with a burst (seen as a GPIO low) followed by a time of no carrier (GPIO high). The only thing that varies among manufacturers is the timings of these two signal components.

The RC5 protocol is unusual by allowing a start- or 0-bit transmission to begin with no carrier (GPIO high). Only the 1 bit begins with an IR burst followed by no carrier. So if the remote is going from idle to transmission, the first half of the bit cell for the start bit is *unseen*. But after the first transition, to mark the start, the receiver need only expect a transition every 0.889 ms for 0 bits, and double that if the bits are changing state.

Looking at Table 5-1 again, notice that the shortest signal time occurs for type 7 (Japan) with a time of 0.42 ms. The smallest detectable unit of time for the GPIO signal changes approaches 150 µs (0.15 ms) for the Raspberry Pi. But if the Linux kernel is busy with other events, 420 µs events may not be reliably detected. Expect some trouble with that particular protocol. Otherwise, the smallest unit of time shown is 560 µs for the other protocols.

Code Organization

If you experiment, you may find occurrences of other pulses within the IR data stream. For example, the Samsung remote occasionally included a 46.5 ms pulse. Others may do something similar. I believe that these are key repeat signals, which happen when you hold down a remote key.

In the Samsung bit stream, the bits gather into a 32-bit code. Your remote *might* use a different code length, but 32 bits is a convenient storage unit for a key code. For that reason, I expect that you'll find that in other brands as well.

Command-Line Options

The `irdecode` utility program has been designed to take some options. These are listed when `-h` is used:

```
$ ./irdecode -h
Usage : ./irdecode [-d] [-g] [-n] [-p gpio]
where :
 -d           dumps event s
 -g           gnuplot waveforms
 -n           don't invert GPIO input
 -p gpio      GPIO pin to use (17)
$
```

Without any options provided, the utility tries to decode Samsung remote-control codes (some of the output is suppressed in this mode). The `-p` option can be provided to cause the command to use a different GPIO port. In Samsung decode mode, `stderr` receives reports of the key codes. Redirect unit 2 to `/dev/null` if you don't want them.

In this example, we capture the `stderr` output to file `codes.out`. The GPIO port is specified as 17 here, but this is the command's default:

```
$ ./irdecode -p17 2>codes.out
Monitoring GPIO 17 f or changes :

<POWER>
123
<RETURN>
73
<EXIT>

Exit .
$
```

While the program runs, it reports recognized key presses to `stdout`. Special keys are shown in angle brackets, while the numeric digits just print as digits. In this mode, the program exits if it sees an `<EXIT>` key press on the remote. You can also enter `^C` in the terminal session to exit the program.

When the program exits, the `codes.out` file is displayed with the `cat` command:

```
$ cat codes.out
CODE E0E040BF
CODE E0E020DF
CODE E0E0A05F
CODE E0E0609F
CODE E0E0609F
CODE E0E01AE5
CODE E0E030CF
CODE E0E0609F
CODE E0E0B44B
$
```

Dump Mode

When the `-d` option is used, the program runs in *dump mode*. In this mode, the program will report level changes on your selected GPIO pin:

```
$ ./irdecode -d
Monitoring GPIO 17 f or changes :
    30524.573   1
    4.628       0
    4.322       1
    0.696       0
    1.555       1
```

■ **Tip** By default, `irdecode` dumps out a 1 level when the carrier is present. To invert this to match the GPIO level, use the `-n` option.

The left column of numbers is the time in milliseconds, prior to the level change. The number in the right column shows you the level of the GPIO input after the change. In this example, the first event took a long time before it changed (I was picking up the remote). The next change to low (0) occurs only 4.628 ms later, and so on.

This is a good format for getting a handle on the average pulse widths. From this output, you should see pulse widths centered about certain ranges of numbers.

Each line reported is a signal change event. Either the GPIO pin changes to high, or it changes to a low level. When reporting changes, therefore, you should never see two or more lines in a row change to a 0, for example. The reported level should always alternate between 0 and 1.

If, however, you do see repeated highs or lows, *this indicates that the program has missed events*. Events spaced closer together than about 150 µs are not likely to be seen on the Raspberry Pi. Noise and spikes can also cause these kinds of problems.

Gnuplot Mode

Dump mode is great for analyzing pulse widths but it isn't very helpful if you want to visualize the waveform. To produce an output suitable for `gnuplot`, add the `-g` option:

```
$ ./irdecode -dg
Monitoring GPIO 17 f or changes :
  31337.931     1
  31342.528     1
  31342.528     0               4.597
  31342.528     0
  31346.860     0
  31346.860     1               4.332
  31346.860     1
```

```
  31347.594     1
  31347.594     0               0.734
  31347.594     0
  31349.110     0
```

When the `-g` option is used, three lines are produced for each event:

- Time of prior event, with previous state
- Time of current event, with previous state
- Time of current event, with current state, with time lapse in column 3

If `gnuplot` is absent, you can install it on your Raspberry Pi as follows:

```
$ sudo apt-get install gnuplot-x11
```

These data plots can then be read into `gnuplot` to display a waveform. Create a file named `gnuplot.cmd` with these commands in it:

```
set title "IR Remote Waveform"
set xlabel "Time (ms)"
set ylabel "Level"
set autoscale
set yrange [-.1:1.2]
plot "gnuplot.dat" using 1:2 with lines
```

Collect your output into a file named `gnuplot.dat` (or change the file `gnuplot.cmd` to use a different file name). Then run `gnuplot` on the data:

```
$ gnuplot -p gnuplot.cmd
```

Figure 5-3 shows an example plot display. Note that you'll normally have to edit out all but the most interesting lines of data. Otherwise, your plot will be a rather crowded display of vertical lines.

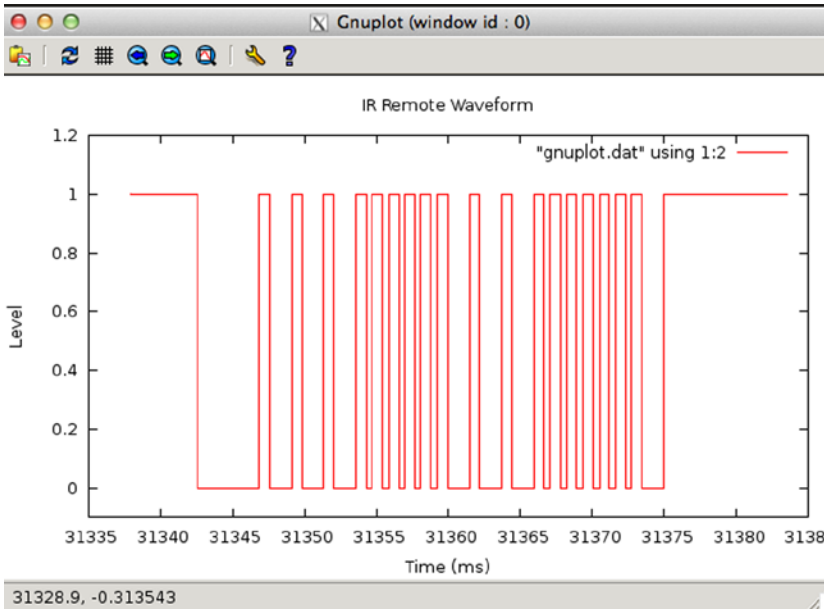


Figure 5-3. *gnuplot waveform of an IR signal*

If running `gnuplot` doesn't pop up a window, you may need to set the `DISPLAY` variable, or run `xhost` on the X-Window server machine. If you are using the Raspberry Pi desktop, this should not be necessary.

The following `xhost` command enables anyone to create a window on your X-Window server:

```
# xhost +
```

The source code for the `irdecode` program is listed here:

```
1    /*************************************************************************
2     * irdecode.c : Read IR remote control on GPIO 17 (GEN0)
3     *************************************************************************/
4    #include <stdio.h>
5    #include <stdlib.h>
6    #include <fcntl.h>
7    #include <unistd.h>
8    #include <string.h>
9    #include <errno.h>
10   #include <signal.h>
11   #include <setjmp.h>
12   #include <assert.h>
13   #include <sys/time.h>
```

```
#include <sys/poll.h>
#include <getopt.h>

static int gpio_inpin = 17;         /* GPIO input pin */
static int is_signaled = 0;         /* Exit program if signaled */
static int gpio_fd = -1;            /* Open file descriptor */

static jmp_buf jmp_exit;

typedef enum {
         gp_export=0,  /* /sys/class/gpio/export */
         gp_unexport,  /* /sys/class/gpio/unexport */
         gp_direction, /* /sys/class/gpio%d/direction */
         gp_edge,      /* /sys/class/gpio%d/edge */
         gp_value      /* /sys/class/gpio%d/value */
} gpio_path_t ;

/*
 *Samsung Remote Codes :
 */
#define IR_POWER     0xE0E040BF
#define IR_0         0xE0E08877
#define IR_1         0xE0E020DF
#define IR_2         0xE0E0A05F
#define IR_3         0xE0E0609F
#define IR_4         0xE0E010EF
#define IR_5         0xE0E0906F
#define IR_6         0xE0E050AF
#define IR_7         0xE0E030CF
#define IR_8         0xE0E0B04F
#define IR_9         0xE0E0708F
#define IR_EXIT      0xE0E0B44B
#define IR_RETURN    0xE0E01AE5
#define IR_MUTE      0xE0E0F00F

static struct  {
        unsigned long   ir_code;   /* IR Code */
        const char      *text;     /* Display text */
} ir_codes[] = {
        { IR_POWER,  "\n<POWER>\n" } ,
        { IR_0,                "0" } ,
        { IR_1,                "1" } ,
        { IR_2,                "2" } ,
        { IR_3,                "3" } ,
        { IR_4,                "4" } ,
        { IR_5,                "5" } ,
        { IR_6,                "6" } ,
        { IR_7,                "7" } ,
```

```
62          { IR_8,             "8" } ,
63          { IR_9,             "9" } ,
64          { IR_EXIT,  "\n<EXIT>\n" } ,
65          { IR_RETURN,  "\n<RETURN>\n" } ,
66          { IR_MUTE,  "\n<MUTE>\n" } ,
67          { 0,                0 }     /* End marker */
68  } ;
69
70  /*
71   * Compute the time difference in milliseconds :
72   */
73  static double
74  msdiff(struct timeval *t1,struct timeval *t0) {
75          unsigned long ut;
76          double ms;
77
78          ms = ( t1->tv_sec - t0->tv_sec ) * 1000.0;
79          if ( t1->tv_usec > t0->tv_usec )
80                  ms += ( t1->tv_usec - t0->tv_usec ) / 1000.0;
81          else {
82                  ut = t1->tv_usec + 1000000UL;
83                  ut -= t0->tv_usec;
84                  ms += ut / 1000.0;
85          }
86          return ms;
87  }
88
89  /*
90   * Create a pathname fo r type in buf.
91   */
92  static const char *
93  gpio_setpath(int pin,gpio_path_t type,char *buf,unsigned bufsiz) {
94          static const char *paths[] = {
95                  "export", "unexport", "gpio%d/direction",
96                  "gpio%d/edge", "gpio%d/value"};
97          int slen;
98
99          strncpy(buf,"/sys/class/gpio/",bufsiz);
100         bufsiz -= (slen = strlen(buf));
101         snprintf(buf+slen,bufsiz,paths[type],pin);
102         return buf;
103 }
104
105 /*
106  * Open /sys/class/gpio%d/value for edge detection :
107  */
```

```
108 static int
109 gpio_open_edge(int pin,const char *edge) {
110         char buf[128];
111         FILE *f;
112         int fd;
113
114         /* Export pin: /sys/class/gpio/export */
115         gpio_setpath(pin gp_export,buf,sizeof buf);
116         f = fopen(buf,"w");
117         assert(f);
118         fprintf(f,"%d\n",pin);
119         fclose(f);
120
121         /* Direction: /sys/class/gpio%d/direction */
122         gpio_setpath(pin,gp_direction,buf,sizeof buf);
123         f = fopen(buf,"w");
124         assert(f);
125         fprintf(f,"in\n");
126         fclose(f);
127
128         /* Edge: /sys/class/gpio%d/edge */
129         gpio_setpath(pin,gp_edge,buf,sizeof buf);
130         f = fopen(buf,"w");
131         assert(f);
132         fprintf(f,"%s\n",edge);
133         fclose(f);
134
135         /* Value: /sys/class/gpio%d/value */
136         gpio_setpath(pin,gp_value,buf,sizeof buf);
137         fd = open(buf,O_RDWR);
138         return fd;
139 }
140
141 /*
142  * Close ( unexport ) GPIO pin :
143  */
144 static void
145 gpio_close(int pin) {
146         char buf[128];
147         FILE *f;
148
149         /* Unexport: /sys/class/gpio/unexport */
150         gpio_setpath(pin,gp_unexport,buf,sizeof buf);
151         f = fopen(buf,"w");
```

```
152         assert(f);
153         fprintf(f,"%d\n",pin);
154         fclose(f);
155 }
156
157 /*
158  * This routine will block until the open GPIO pin has changed
159  * value .
160  */
161 static int
162 gpio_poll(int fd,double *ms) {
163         static char needs_init = 1;
164         static struct timeval t0;
165         static struct timeval t1;
166         struct pollfd polls;
167         char buf[32];
168         int rc, n;
169
170         if ( needs_init ) {
171                rc = gettimeofday(&t0,0);
172                assert(!rc);
173                needs_init = 0;
174         }
175
176         polls.fd = fd;                      /* /sys/class/gpio17/value */
177         polls.events = POLLPRI;             /* Exceptions */
178
179         do     {
180                  rc = poll(&polls,1,-1);    /* Block */
181                  if ( is_signaled )
182                         longjmp(jmp_exit,1);
183         } while ( rc < 0 && errno == EINTR );
184
185         assert(rc > 0);
186
187         rc = gettimeofday(&t1,0);
188         assert(!rc);
189
190         *ms = msdiff(&t1,&t0);
191
192         lseek(fd,0,SEEK_SET);
193         n = read(fd,buf,sizeof buf);                /* Read value */
194         assert(n>0);
195         buf[n] = 0;
196
197         rc = sscanf(buf,"%d",&n) ;
198         assert(rc==1);
199
```

```
200         t0 = t1;                            /* Save for next call */
201         return n;                           /* Return value */
202 }
203
204 /*
205  * Signal handler to quit the program :
206  */
207 static void
208 sigint_handler(int signo) {
209         is_signaled = 1;                    /* Signal to exit program */
210 }
211
212 /*
213  * Wait until the line changes :
214  */
215 static inline int
216 wait_change(double *ms) {
217         /* Invert the logic of the input pin */
218         return gpio_poll(gpio_fd,ms) ? 0 : 1;
219 }
220
221 /*
222  * Wait until line changes to "level" :
223  */
224 static int
225 wait_level(int level) {
226         int v;
227         double ms;
228
229         while ( (v = wait_change(&ms)) != level )
230                 ;
231         return v;
232 }
233
234 /*
235  * Get a 32 bit code from remote control :
236  */
237 static unsigned long
238 getword(void) {
239         static struct timeval t0 = { 0, 0 };
240         static unsigned long last = 0;
241         struct timeval t1;
242         double ms;
243         int v, b, count;
244         unsigned long word = 0;
245
```

```
246 Start: word = 0;
247         count = 0;
248
249         /*
250          * Wait for a space of 46 ms :
251          */
252         do    {
253                 v = wait_change(&ms);
254         } while ( ms < 46.5 );
255
256         /*
257          * Wait for start : 4.5ms high, then 4.5ms low :
258          */
259         for ( v=1;; ) {
260                 if ( v )
261                         v = wait_level(0);
262                 v = wait_level(1);
263                 v = wait_change(&ms);       /* High to Low */
264                 if ( !v && ms >= 4.0 && ms <= 5.0 ) {
265                         v = wait_change(&ms);
266                         if ( v && ms >= 4.0 && ms <= 5.0 )
267                                 break ;
268                 }
269         }
270
271         /*
272          * Get 32 bi t code :
273          */
274         do    {
275                 /* Wait for line to go low */
276                 v = wait_change(&ms);
277                 if ( v || ms < 0.350 || ms > 0.8500 )
278                       goto Start;
279
280                 /* Wait for line to go high */
281                 v = wait_change(&ms);
282                 if ( !v || ms < 0.350 || ms > 2.0 )
283                         goto Start;
284
285                 b = ms < 1.000 ? 0 : 1;
286                 word = (word << 1) | b;
287         } while ( ++count < 32 );
288
289         /*
290          * Eliminate key stutter :
291          */
```

```
292         gettimeofday(&t1,0);
293         if ( word == last && t0.tv_sec && msdiff (&t1,&t0) < 1100.0 )
294                 goto Start;          /* Too soon */
295
296         t0 = t1;
297         fprintf(stderr,"CODE %08lX\n",word);
298         return word;
299 }
300
301 /*
302  * Get text form of remote key :
303  */
304 static const char *
305 getircode(void) {
306         unsigned long code;
307         int kx;
308
309         for (;;) {
310                 code = getword();
311                 for ( kx=0; ir_codes[kx].text; ++kx )
312                         if ( ir_codes[kx].ir_code == code )
313                                 return ir_codes[kx].text;
314         }
315 }
316
317 /*
318  * Main program :
319  */
320 int
321 main(int argc,char **argv) {
322          const char *key;
323          int optch;
324          int f_dump = 0, f_gnuplot = 0, f_noinvert = 0;
325
326          while ( (optch = getopt(argc,argv,"dgnsp:h")) != EOF )
327                  switch ( optch ) {
328                  case 'd' :
329                          f_dump = 1;
330                          break;
331                  case 'g' :
332                          f_gnuplot = 1;
333                          break;
334                  case 'n':
335                          f_noinvert = 1;
336                          break;
337                  case 'p' :
338                          gpio_inpin = atoi(optarg);
```

```
339                         break;
340                 case 'h' :
341                         /* Fall thru */
342                 default :
343 usage :            fprintf (stderr,
344                              "Usage: %s [-d ] [-g ] [-n ] [-p
                               gpio]\n",argv[0]);
345                         fputs("where: \n"
346                               "  -d\t\tdumps events\n"
347                               "  -g\t\tgnuplot waveforms\n"
348                               "  -n\ t \tdon't invert GPIO input \n"
349                               "  -p gpio\tGPIO pin to use (17)\n",
350                               stderr);
351                         exit(1);
352                 }
353
354         if ( gpio_inpin < 0 || gpio_inpin >= 32 )
355                 goto usage;
356
357         if ( setjmp(jmp_exit) )
358                 goto xit;
359
360         signal(SIGINT,sigint_handler);                /* Trap on SIGINT */
361         gpio_fd = gpio_open_edge(gpio_inpin,"both"); /* GPIO input */
362
363         printf("Monitoring GPIO %d for changes:\n",gpio_inpin);
364
365         if ( !f_dump ) {
366                  /*
367                   * Remote control read loop :
368                   */
369                  for (;;) {
370                          key = getircode();
371                          fputs(key,stdout);
372                          if ( !strcmp(key,"\n<EXIT>\n") )
373                                break;
374                          fflush(stdout);
375                  }
376         } else {
377                  /*
378                   * Dump out IR level changes
379                   */
```

```
380                     int v;
381                     double ms, t =0.0;
382
383                     wait_change(&ms);         /* Wait for first change */
384
385                     for (;;) {
386                             v = wait_change(&ms) ^ f_noinvert;
387                             if ( !f_gnuplot )
388                                     printf("%12.3 f\t%d\n",ms,v);
389                             else  {
390                                     printf("%12.3 f\t%d\n",t,v^1);
391                                     t += ms;
392                                     printf("%12.3 f\t%d\n",t,v^1);
393                                     printf("%12.3 f\t%d\t%12.3 f\n",t,v,ms);
394                             }
395                     }
396             }
397
398 xit :   fputs("\nExit.\n",stdout);
399             close(gpio_fd);             /* Close gpio%d/value */
400             gpio_close(gpio_inpin);     /* Unexport gpio */
401             return 0;
402 }
403 /* End irdecode.c */
```

CHAPTER 6

Stepper Motor

A *stepper motor* is a brushless device with multiple windings, where one rotation is divided into several small *steps*. Stepper motors are used when precise positioning is required. Unipolar stepper motors have multiple windings connected to a common connection.

In this chapter, we'll recycle an old floppy-disk stepper motor. Modern stepper motors are smaller and operate at lower voltages. This particular stepper motor presents a good example of the challenges that exist when driving a motor from a 12 V power supply.

Floppy-Disk Stepper Motor

Figure 6-1 shows an old 5.25-inch floppy-disk stepper motor that was sitting on a shelf in my furnace room. Perhaps you have a gem like this in your own junk box.

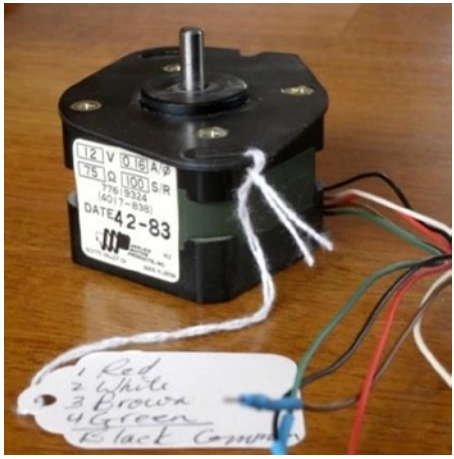


Figure 6-1. *A salvaged 5.25-inch floppy-disk motor*

This particular stepper motor has these markings on it:

12 V	0.16	A/Ø
75 Ω	100	S/R
	Date 42-83	

This motor was clearly marked as a 12 V device. The 0.16 A/Ø marking tells us that each winding (phase Ø) is rated for 160 mA. The following calculation confirms that the winding resistance is 75 Ω, which is consistent with the printed current rating:

$$\begin{aligned} I &= \frac{V}{R} \\ &= \frac{12}{75} \\ &= 160mA \end{aligned}$$

The 100 S/R marking tells us that this motor has 100 steps per revolution. It's really nice when you get all the information you need up front.

Your Junk-Box Motor?

Old 5.25-inch floppy-disk drives are getting scarcer these days. So what about other stepper motors that you might have in your junk box? How can you determine whether you can use one?

The first thing you must check is the type of motor. This chapter focuses on unipolar motors that have three or more step windings with a common connection. The floppy-disk stepper motor that I'm using in this chapter is shown in Figure 6-2. Notice that this motor has four separate windings, labeled L_1 through L_4. These have a common connection to a black wire coming out of the motor. To make this motor step, each winding must be activated in sequence.

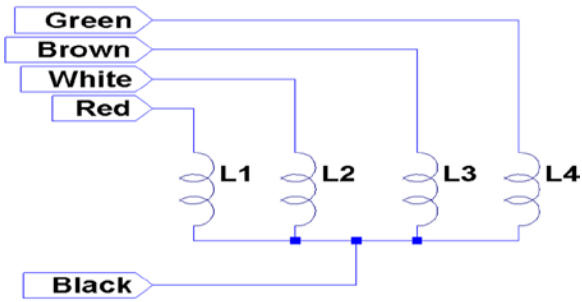


Figure 6-2. *Floppy-disk stepper motor windings*

If you have a stepper motor on hand but don't know much about it, you can test it with a DMM. Measure the DC resistance of the windings between each pair of wires. You won't need to measure every combination, but start a chart something like the following I'll use my motor as an example:

Wire 1	Wire 2	Reading
Black	Red	84 Ω
Red	White	168 Ω
White	Brown	168 Ω
Brown	Black	84 Ω
etc.		

What does this tell you? The lowest readings show 84 Ω (the reading should be 75 Ω for this motor, but my DMM doesn't read low resistances accurately). The other readings are double that. This indicates that each winding should read 84 Ω, and when it doesn't, it means that we are measuring the resistance of two windings in series.

Looking again at the chart, we see that whenever we find an 84 Ω reading, the black wire is common to each. Knowing that the black wire is common to the windings means that all of the other wires should read 84 Ω relative to it. Now you know which wire is the common one.

Some motors you might encounter use two separate split windings. These won't have a wire common to *all* windings. You'll find that some paired wires have infinite resistance (no connection). If this applies, you have a motor that is applicable to the project in Chapter 7.

Another ingredient that you need to check is the DC resistance of each winding. Assuming you already measured this while determining the common wire, perform this calculation:

$$I_{Winding} = \frac{V}{R_{winding}}$$

Let's assume that you think your stepper motor is a 6 V part, or simply that you plan to operate it at 6 V. Assume also that the measured DC resistance of the winding is 40 Ω. What will be the maximum current necessary to drive this motor?

$$I_{Winding} = \frac{6}{40}$$
$$= 150mA$$

This figure is important to the driving electronics. In this chapter, I am using an economical PCB purchased from eBay that uses the ULN2003A driver chip. I'll describe the chip and the PCB in more detail later. The ULN2003A chip has a maximum drive rating of 500 mA. But this figure must be derated by the duty cycle used and the number of simultaneous drivers. If you computed a figure of 300 mA or more, you may need to seek out a more powerful driver.

■ **Note** In addition to stepper motors, the ULN2003A can drive lightbulbs and other loads.

Driver Circuit

Clearly, the GPIO outputs of the Raspberry Pi cannot drive a stepper motor directly. You could build your own driver circuit (or breadboard one) using the ULN2003A chip. I chose instead to buy a PCB from eBay for $2 (with free shipping), which provided the advantage of four LEDs. These light when a winding is activated, which is useful for testing. Figure 6-3 shows the schematic of the PCB that I used.

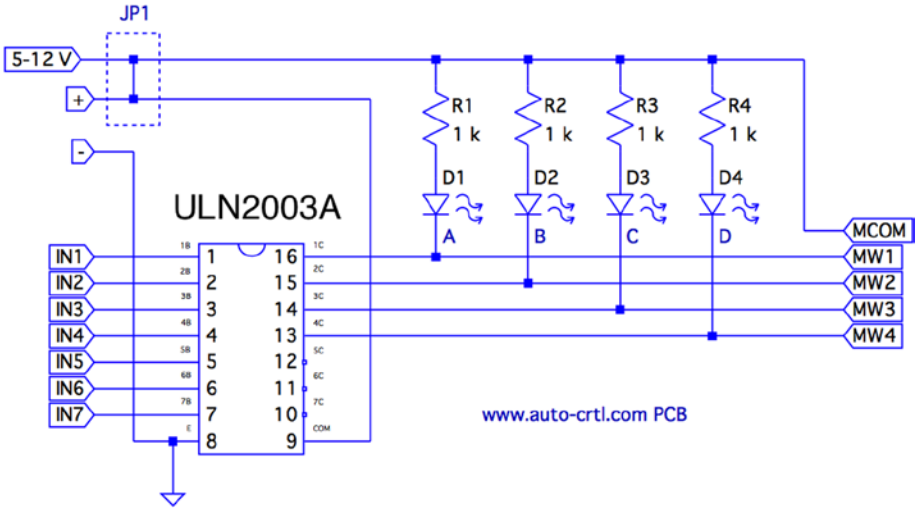


Figure 6-3. *ULN2003A PCB schematic*

The PCB includes two holes that power connections can be soldered into. There are also two pins marked (+) and (-) for a push-on connector.

Beside the power connections is a small jumper with the text *5 – 12 V* under it. This jumper is shown as JP1 in the schematic. You'll normally want to leave the jumper *in*.

The input connections are clearly labeled IN1 through IN7. However, only outputs 1C through 4C are used (outputs for IN1 through IN4). The other ULN2003A outputs 5C through 7C are unconnected. Wires could be carefully soldered to these pins, if you needed additional drivers for lamps, relays, or a second stepper motor.

The LEDs are connected from the (+) side, in series with a 1 *k*Ω current–limiting resistor. The voltage drop $V_{CE(sat)}$ in the ULN2003A ranges from about 0.9 to 1.6 V (use the worst case of 0.9 V). Assuming that the voltage drop is 1.6 V for red LEDs[55] and the maximum of 12 V is applied, each LED conducts about this:

$$\begin{aligned} I_{LED} &= \frac{V_{CC} - V_{CE(sat)} - V_{LED}}{R_{LED}} \\ &= \frac{12 - 0.9 - 1.6}{1000} \\ &= 9.5mA \end{aligned}$$

The LEDs are the main reason the PCB lists a maximum voltage of 12 V. The ULN2003A chip has an absolute maximum V_{CC} voltage of 50 V. If, for example, you need to drive a 24 V stepper motor from an old *8-inch* floppy drive, you can remove jump JP1 to take the LEDs out of the circuit. Then you would supply the +24 V directly to the common wire of the stepper motor itself. If you do this, you'll also want to connect the PCB (+) to the motor's supply. This connects the motor to the COM pin of the ULN2003A, which provides reverse-biased diodes to drain away induced voltages.

When purchased, the PCB included a white socket for connection to the stepper motor. I removed that and replaced it with a soldered-in ribbon cable. These wires connect the driver outputs 1C through 4C to the stepper-motor windings.

The Raspberry Pi will drive pins IN1 through IN4 from the GPIO ports. When a given IN*x* pin is driven high, the Darlington pair of transistors will sink up to 500 mA of current from a positive (motor supply) source to ground.

Darlington Pair

It is tempting to look at the ULN2003A chip as a black box: a signal goes into it, and a bigger one comes out. But when interfacing to voltages higher than the Raspberry Pi's own +3.3 V system, extra caution is warranted. If any of this higher voltage leaks back into the Pi, the GPIO pins will get "cooked" (if not the whole system).

Figure 6-4 shows input 1B being driven high by a GPIO line. This forward-biases Q_2, which in turn biases Q_1. A small amount of current flows in dashed lines from 1B, into the base of Q_2, and then from Q_1 to ground. This small amount of current flow allows a much greater current to flow from the collector of Q_1 to ground. The dashed lines on the right show the motor-winding current flowing from the motor power supply (12 V, for example), through Q_1 to ground through the E terminal.

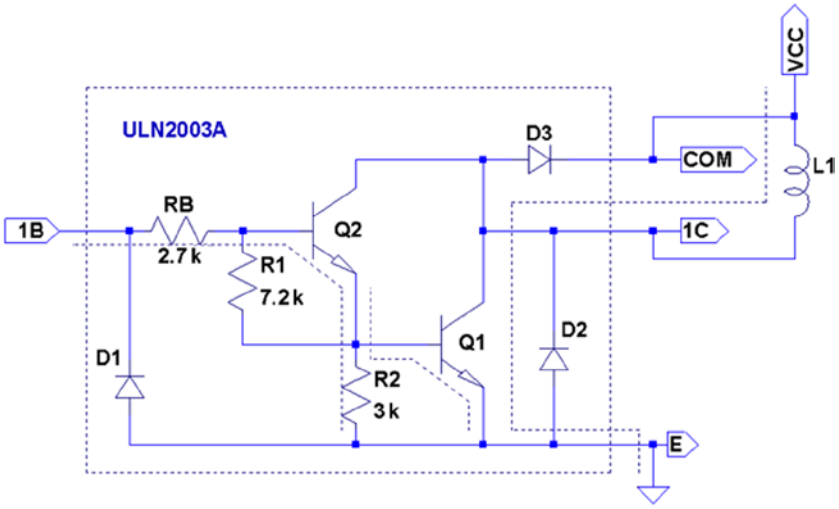


Figure 6-4. *ULN2003A driving a winding*

When the GPIO ceases to drive input 1B as shown in Figure 6-5, the transistors Q_2 and Q_1 turn off. With no more current flowing through L_1, the magnetic field collapses, generating a reverse current. As the field collapses, current flows into terminal 1C, through the diode D_3 and back to the upper side of L_1. In effect, diode D_3 shorts out this generated-back EMF. Diode D_3 is necessary to prevent the rest of the electronics from seeing a high voltage, which can cause damage and disruption.

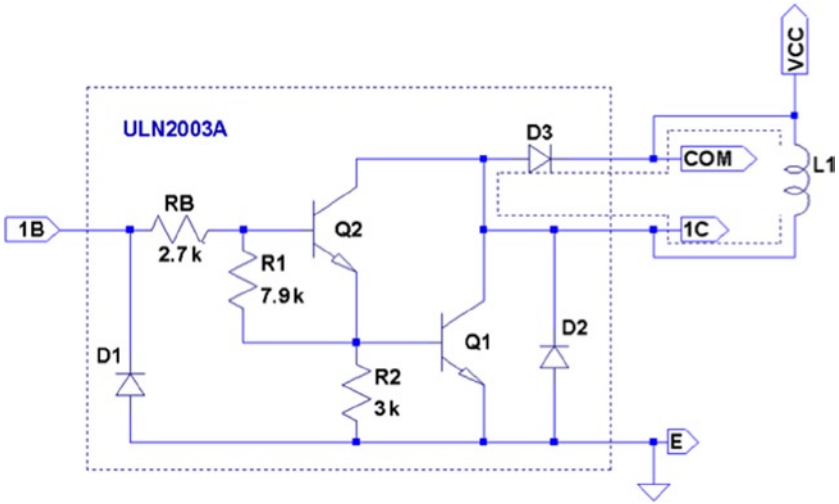


Figure 6-5. *ULN2003A driver turning off*

One side effect of the reverse-biased diode is that it slows down the decay of the magnetic field. As current flows in the reverse direction, the magnetic collapse is resisted. This results in magnetic forces inside the motor, which affect its speed. (This same effect also slows the release of relay contacts.) When greater speed is required, a resistor is sometimes used in series with the diode to limit its effect.

So what about voltage safety of our Raspberry Pi GPIO pins? Reexamine the Darlington pair Q_2 and Q_1. Pins COM and 1C can be as high as 50 V. But current cannot leak through D_3 (from COM) because the diode junction is reverse-biased. Current cannot leak from the collectors of Q_2 and Q_1 (from 1C) into the base circuits because those base-collector junctions are behaving as reverse-biased diodes. The main point of caution is that Q_2 and Q_1 *must remain intact*.

If Q_1 were allowed to overheat, for example, it might break down. If Q_1 or Q_2 breaks down, current will be allowed to flow from its collector into the base circuit, which is connected to the GPIO. Therefore, the breakdown of the driver transistors must be strictly prevented!

Driving the Driver

In this section, we look at the Raspberry Pi (GPIO) interface to the ULN2003A. There are two things we are most interested in here:

- The usual input logic-level interface
- Power-on reset and boot conditions

Input Levels

The output current of the ULN2003A Darlington pair rises as the input voltage rises above the *turn-on* level. We know from the Darlington configuration that there are two base-emitter junctions in the path from input to ground. Therefore, the ULN2003A driver requires a $2 \times V_{BE}$ voltage to forward-bias the pair. If we assume $V_{BE} = 0.6\ V$, we can compute a V_{IL} for the driver as follows:

$$\begin{aligned} V_{IL} &= 2 \times V_{BE} \\ &= 2 \times 0.6 \\ &= 1.2V \end{aligned}$$

Clearly, the Pi GPIO low (0.8 V) easily turns off the ULN2003A input with margin to spare. The datasheets state that a maximum output drive of 300 mA can be achieved with a 3 V input drive signal. The ULN2003A drive characteristics are shown here:

		ULN2003A	
Signal	**Raspberry Pi**	V_I	I_c
V_{OL}	≤ 0.8 V	1.2 V	500 *m*A
		2.4 V	100 *m*A
V_{OH}	≥1.3 V	2.7 V	250 *m*A
		3.0 V	300 *m*A

If we had a TTL signal driving the ULN2003A, we could get closer to the 500 mA maximum drive (interpolating from the characteristics shown). However, for our purposes, we need only 160 mA, so a 3 V drive signal meets the requirements well enough.

■ **Note** TTL levels approach +5V.

Power-on Reset/Boot

The one serious matter that remains is what our circuit will be doing as the Raspberry Pi is reset and is spending time booting up. The maximum ratings of the ULN2003A have to be derated when more than one Darlington pair is operating simultaneously. This is because each driver that is *on* heats up the chip substrate. For this reason, it is highly desirable for the ULN2003A to be "quiet" at reset time and subsequent boot-up. If a boot problem occurs, requiring a lot of time to correct, the drivers could overheat.

This potentially requires that we use GPIO pins that

- Are automatically configured as *inputs* at reset
- Are not configured with high pull-up resistors

Input pins with high pull-up resistors are *potentially* bad news. A high level appearing on ULN2003A inputs might activate drivers. In the worst-case scenario, all inputs become *active*.

Table 6-1 lists the acceptable GPIO pins as well as the reasons that others should be avoided.

Table 6-1. *GPIOs for Motor Control at Reset/Boot Time*

GPIO					
OK		**Bad**	**Reason**	**Bad**	**Reason**
09	23	00	Pull-up high	08	Pull-up high
10	24	01	Pull-up high	14	TXD0
11	25	02	Pull-up high	15	RXD0
12	28†	03	Pull-up high	16	Output
17	29†	04	Pull-up high	27	Output
18	30	05	Pull-up high		
21	31	06	Output		
22		07	Pull-up high		

(†) No pull-up resistor

The pull-up resistance provided by the Broadcom SoC is weak (50 *k*Ω). Because of this, the worst-case input drive, due to the pull-up resistance, is calculated as follows:

$$\begin{aligned} I_I &= \frac{V_{CC}}{R_{pullup}} \\ &= \frac{3.3V}{50K\Omega} \\ &= 66\mu A \end{aligned}$$

The ULN2003A datasheet states that it takes an input drive of 250 *mA* to produce an output current flow of 100 *mA*. *Some* GPIO pins are pulled up by external resistors (GPIO 2 and 3 for SDA and SCL). These GPIO pins should *not* be used as motor drivers, for this reason.

The Darlington pair includes resistances that naturally pull down the input signal (review Figure 6-5). Resistances R_B, R_1, and R_2 are connected in series between the input and ground. This effectively provides a pull-down resistance of approximately 13.6 *k*Ω. If the ULN2003A is attached to a floating input like GPIO 28 or 29, the input voltage will automatically be pulled down as a result (this is desirable here).

Modes of Operation

A unipolar stepper motor may be operated in four modes. The first three of these modes use digital on/off signals to drive each winding. The fourth *micro-stepping* mode requires driving each winding with varying analog signals. Since we are driving with digital GPIO pins, we'll examine only the first three modes.

Wave Drive (Mode 0)

Wave drive mode is the simplest of the modes, in which only one winding of the motor is activated at one time (see Figure 6-6). Each winding is energized in sequence to cause the rotation to occur in full steps. The motor will have significantly less torque than in full-step drive mode and is therefore rarely used.[57]

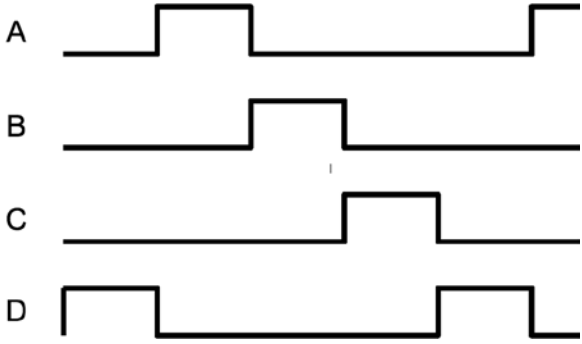


Figure 6-6. *Wave drive (mode 0)*

Full-Step Drive (Mode 1)

Figure 6-7 shows how full-step drive mode operates. Each field is energized in turn like a wave drive, but the next field is activated prior to turning off the prior field. In this way, an overlapping drive is affected in the direction of travel. This is the usual drive method delivering full-rated torque.[58]

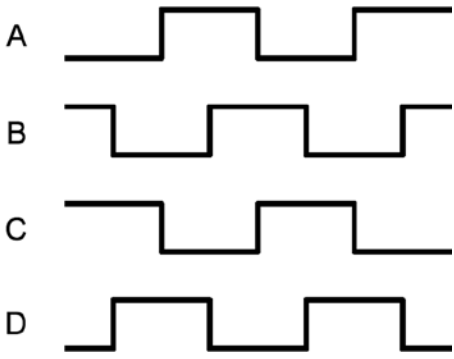


Figure 6-7. *Full-step drive (mode 1)*

Half-Step Drive (Mode 2)

Figure 6-8 illustrates the drive waveforms for half-step drive mode. As in full-step mode, an overlapped drive is applied to the field coils. Unlike full-step mode, the overlap occurs on the first third and the last third of a given coil's drive. For two-thirds of the waveform, there is overlapped drive. In the middle third, only one winding is active.

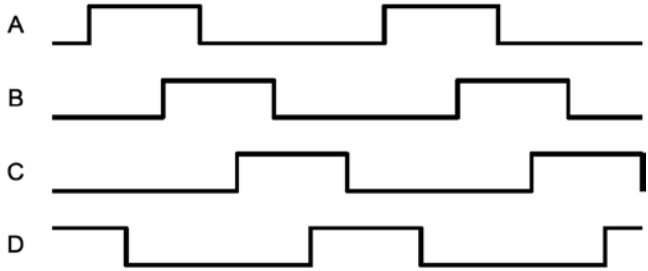


Figure 6-8. *Half-step drive*

This mode provides increased angular resolution but suffers from having less torque (about 70% of full-rated torque).[59]

Software

To demonstrate stepper-motor driving without getting into a complex assignment, the program `unipolar.c` simply positions the shaft of the motor to various hour positions of the clock, based on single-key commands.

With a pointer attached to the shaft of your motor, press 6, and the motor will point at 6 o'clock. Press 3, and the motor figures out that it is quickest to step counterclockwise back to the 3 o'clock position. Press 7, and the motor steps forward to 7 o'clock. All of this, of course, requires that you point the shaft at 12 o'clock before you begin (the motor provides no information to the program about where it is currently pointing).

The program presented uses the GPIO pin assignments in Table 6-2 for driving the stepper motor (your wire colors may differ):

Table 6-2. *GPIO Assignments Used by the Program* `unipolar.c`

GPIO	GENX	P1	Mode	Stepper Wire	ULN2003A	Description
17	GEN0	P1-11	Output	Red	1B	Field A
24	GEN5	P1-18		White	2B	Field B
22	GEN3	P1-15		Brown	3B	Field C
23	GEN4	P1-16		Green	4B	Field D

Figure 6-9 shows how a pointer knob can be used for a pointer. Otherwise, this is your opportunity to get creative.

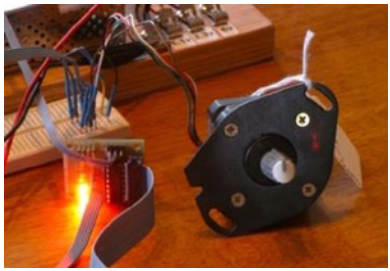


Figure 6-9. *Stepper motor with knob used as a pointer*

At power-on reset and boot time, the selected GPIO lines are all input pins with pull-down resistors. After boot-up, when the program starts and configures its GPIO pins, it will do the following:

1. Configure an output low value for each GPIO (while still an input)
2. Configure the GPIO pin as an output

Step 1 eliminates the possibility of a stepper winding being driven before the software is ready to drive it. If this were not done, a driver could be activated when the GPIO is first configured as an output. Step 2, of course, is necessary to drive the ULN2003A chip. But no glitch occurs in the output when step 1 is performed first.

After the main program has begun, it saves the current terminal settings in `sv_ios` and then sets up a raw mode, permitting single-character I/O interaction (lines 167–173). See Chapter 9 of *Raspberry Pi Hardware Reference* (Apress, 2014) for more information about the serial API.

Lines 175–178 initialize the GPIO lines to drive the stepper-motor field windings. The default stepper-motor mode is configured on line 182, which may be overruled by a command-line argument. The program can also change modes by using keystroke commands.

The remainder of the program is a `while` loop that extends from lines 185–241. It reads a single-character command at line 187 and then dispatches to sections of code in the `switch` statement. The single-character commands are summarized in Table 6-3.

Table 6-3. *Single-Character Commands*

Char	Command	Char	Command
Q	Quit	0	12 o'clock (noon)
<	Slower steps	1	1 o'clock
>	Faster steps	2	
?	Help	…	
H		9	9 o'clock
J	Stepper mode 0	A	10 o'clock
K	Stepper mode 1	B	11 o'clock
L	Stepper mode 2	+/=	Step clockwise
P	Show current position	-	Step counterclockwise
O	Toggle drive on/off		

The < and > commands double or halve the step time interval. This slows and increases the rotational speed, respectively. Stepper modes can be changed using the `J`, `K`, or `L` commands. These reposition the stepper to 12 o'clock prior to changing modes. The digits `0` through `9` and letters `A` and `B` reposition the shaft to point to the hour of the clock.

You can test whether your rotation is properly working by using the + and - keystrokes to step one step clockwise or counterclockwise. Pressing `O` (the letter O, not zero) toggles the drive power on or off for the motor. This is useful for turning off the motor drive when you want to manually reposition the shaft.

The source code used in this program for `gpio_io.c` is provided in Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014), and `timed_wait.c` is provided in Chapter 1. The main source module of interest is `unipolar.c`, which is presented at the end of this chapter.

Testing

Be careful setting up this project because of the voltages involved. One careless wiring error could bring higher voltage into your GPIO pins and fry the Pi. In the following procedures, I refer to the driver PCB (as I used), but this procedure applies equally to breadboarded circuits.

Here is the first part of the setup and checkout procedure:

1. Set up the power to the driver PCB without connecting it to the Raspberry Pi. Leave the motor unconnected also.
2. Make sure that the driver inputs are not connected.
3. Apply the power to the PCB. No LEDs will light if everything is OK. No smoke? Good!

4. Apply +3.3 V one at a time to the driver inputs 1B through 4B (IN1 through IN4 on the PCB) with a wire, which should cause the corresponding LED to light. (These driver inputs will also accept +5 V for testing, if that is what you have available.) If you breadboarded the circuit, consider adding LEDs to each driver output.

5. Measure the voltage at each unconnected driver *input* 1B through 4B (IN1 through IN4). Each should measure 0 V (or very nearly). If you measure anything higher, you have either a wiring error or a bad driver chip. Don't use a defective driver.

If this procedure tests out OK, the next step is to wire up the motor (with PCB still unconnected from the Pi):

1. Put some kind of pointer on the motor shaft (like a pointer knob) and wire up the motor to the PCB driver outputs.

2. Make sure that the COM pin of the driver chip is connected to the + power connection used for the motor (+12 V in my case). This is important for bleeding off the inductive kick that occurs when the motor winding is turned off.

3. Apply power to the PCB and check for smoke. No smoke or crackling sounds means you can proceed to the next step.

4. With the PCB power applied, you should be able to drive each motor winding with +3.3 V applied to individual inputs, as before. If the motor is wired up correctly, it should twitch. If the twitch is not visible, put your hand on the shaft. You should feel it when the winding activates.

The next step is to make sure you wired the windings for the correct sequence. When applying step 4 of the preceding procedure to each winding's driver input, the motor should take one step clockwise. Watch for double steps, or twitches in the reverse direction. As you strobe inputs 1B, 2B, 3B, and 4B (IN1 through IN4) in sequence, the motor should step in an orderly clockwise direction. Reversing that activation sequence should cause the motor to step counterclockwise. Keep your nose alert for smoke or funny smells. Then follow these steps:

1. Measure the inputs of the drivers 1B through 4B one last time, while the motor is connected and all motor voltages are present. Each input should measure near 0 V (due to its internal pull-down resistances).

2. Now power everything off.

3. Make sure there is a ground-wire connection between your Raspberry Pi's ground and the stepper-motor power supply's ground. *Don't try operating without this critical link.*

4. With everything still off, and observing care for static electricity, connect the GPIO pins to each of the ULN2003A driver inputs 1B through 4B (IN1 through IN4).

Now turn everything on and keep alert, just in case. The Raspberry Pi should begin booting with no visible activity on the stepper motor (or LEDs). If there is, you might have a GPIO wiring error. Turn off the stepper-motor power supply if you can and bring the Pi down and recheck.

Assuming all went well, point your motor at 12 o'clock and start the program:

```
$ ./unipolar
```

If the motor struggles or moves erratically when you give it movement commands, you may need to correct the motor wiring. Use the + and - commands to check whether the motor steps properly in one direction.

```
1    /*****************************************************************
2     * unipolar.c : Drive unipolar stepper motor
3     *****************************************************************/
4
5   #include <stdio.h>
6   #include <stdlib.h>
7   #include <fcntl.h>
8   #include <unistd.h>
9   #include <errno.h>
10  #include <math.h>
11  #include <ctype.h>
12  #include <termio.h>
13  #include <sys/mman.h>
14  #include <signal.h>
15  #include <assert.h>
16
17  #include "gpio_io.c"                  /* GPIO routines */
18  #include "timed_wait.c"               /* timed_wait () */
19
20  static const int steps_per_360 = 100; /* Full steps per rotation */
21
22  /*                  GPIO Pins :  A    B    C   D */
23  static const int gpios[] = { 17, 24, 22, 23 };
24
25  static float step_time = 0.1;         /* Seconds */
26  static int drive_mode = 0;            /* Drive mode 0, 1, or 2 */
27  static int step_no = 0;               /* Step number */
28  static int steps_per_r = 100;         /* Steps per rotation */
```

```
29  static int position = 0;    /* Stepper position */
30  static int on_off = 0;      /* Motor drive on/off */
31
32  static int quit = 0;        /* Exit program if set */
33
34  /*********************************************************************
35   * Await so many fractional seconds
36   *********************************************************************/
37  static void
38  await(float seconds) {
39            long sec, usec;
40
41            sec = floor(seconds);               /* Seconds to wait */
42            usec = floor((seconds_sec)*1000000); /* Microseconds */
43            timed_wait(sec,usec,0);             /* Wait */
44  }
45
46  /*********************************************************************
47   * Set motor drive mode
48   *********************************************************************/
49  static void
50  set_mode(int mode) {
51           int micro_steps = mode < 2 ? 1 : 2;
52
53           step_no = 0;
54           drive_mode = mode;
55           steps_per_r = steps_per_360 * micro_steps;
56           printf("Drive mode %d\n",drive_mode);
57  }
58
59  /*********************************************************************
60   * Drive all fields according to bit pattern in pins
61   *********************************************************************/
62  static void
63  drive(int pins) {
64           short x;
65           for ( x=0; x<4; ++x )
66                  gpio_write(gpios [x],pins & (8>>x) ? 1 : 0);
67  }
68
69  /*********************************************************************
70   * Advance motor:
71   *      dir =   -1  Step counter_clockwise
72   *      dir =    0  Turn on existing fields
73   *      dir =   +1  Step clockwise
74   *********************************************************************/
```

```
75  static void
76  advance(int dir) {
77          static int m0drv[] = {8, 4, 2, 1};
78          static int m1drv[] = {9, 12, 6, 3};
79          static int m2drv[] = {9, 8, 12, 4, 6, 2, 3, 1};
80
81          switch ( drive_mode ) {
82          case 0:                     /* Simple mode 0 */
83               step_no = (step_no + dir) & 3;
84               drive(m0drv[step_no]);
85               await(step_time/4.0);
86               break;
87          case 1:                     /* Mode 1 drive */
88               step_no = (step_no + dir) & 3;
89               drive(m1drv[step_no]);
90               await(step_time/6.0);
91               break;
92          case 2:                     /* Mode 2 drive */
93               step_no = (step_no + dir) & 7;
94               drive(m2drv[step_no]);
95               await(step_time/1 2.0);
96               ;
97          }
98
99          on_off = 1;                  /* Mark as drive enabled */
100 }
101
102 /*********************************************************************
103  * Move +/- n steps, keeping track of position
104  *********************************************************************/
105 static void
106 move(int steps) {
107           int movement = steps;
108           int dir = steps >= 0 ? 1 : -1;
109           int inc = steps >= 0 ? -1 : 1;
110
111           for ( ; steps != 0; steps += inc )
112                  advance(dir);
113           position = (position + movement + steps_per_r) % steps_per_r;
114 }
115
116 /*********************************************************************
117  * Move to an hour position
118  *********************************************************************/
```

```
119 static void
120 move_oclock(int hour) {
121         int new_pos = floor((float)hour * steps_per_r/12.0);
122         int diff;
123
124         printf("Moving to %d o'clock.\n",hour);
125
126         if ( new_pos >= position ) {
127                 diff = new_pos - position;
128                 if ( diff <= steps_per_r/2 )
129                         move(diff);
130                 else move(-(position + steps_per_r - new_pos));
131         } else {
132                 diff = position - new_pos;
133                 if ( diff <= steps_per_r/2 )
134                         move(-diff);
135                 else move (new_pos + steps_per_r - position);
136         }
137 }
138
139 /*********************************************************************
140  * Provide usage info :
141  *********************************************************************/
142 static void
143 help(void) {
144    puts("Enter 0-9,A,B for 0_9,10,11 o'clock.\n"
145          " '<' to slow motor speed, \n"
146          " '>' to increase motor speed, \n"
147          " 'J ', 'K' or 'L' for modes 0-2,\n"
148          " '+'/ '-' to step 1 step,\n"
149          " 'O' to toggle drive on/off, \n"
150          " 'P' to show position, \n"
151          " 'Q' to quit.\n");
152 }
153
154 /*********************************************************************
155  * Main program
156  *********************************************************************/
157 int
158 main(int argc,char **argv) {
159          int tty = 0;                  /* Use stdin */
160          struct termios sv_ios, ios;
161          int x, rc;
162          char ch;
163
164          if ( argc >= 2 )
165                  drive_mode = atoi(argv[1]); /* Drive mode 0_2 */
166
```

```
167         rc = tcgetattr(tty,&sv_ios); /* Save current settings */
168         assert(!rc);
169         ios = sv_ios;
170         cfmakeraw(&ios);             /* Make into a raw config */
171         ios.c_oflag = OPOST | ONLCR; /* Keep output editing */
172         rc = tcsetattr(tty,TCSAFLUSH,& ios); /* Put terminal into
                                                    raw mode */
173         assert(!rc);
174
175         gpio_init();                 /* Initialize GPIO access */
176         drive(0);                     /* Turn off output */
177         for ( x=0; x<4; ++x )
178         gpio_config(gpios[x],Output);      /* Set GPIO pin as Output */
179
180         help();
181
182         set_mode(drive_mode);
183         printf("Step time: %6.3f seconds\n",step_time);
184
185         while ( !quit ) {
186                 write(1," : ",2);
187                 rc = read(tty,&ch,1);     /* Read char */
188                 if ( rc != 1 )
189                        break;
190                 if ( islower(ch) )
191                        ch = toupper(ch);
192
193                 write(1,&ch,1);
194                 write(1,"\n",1);
195
196                 switch ( ch ) {
197                 case 'Q':           /* Quit */
198                       quit = 1;
199                       break;
200                 case '<' :          /* Go slower */
201                       step_time *= 2.0;
202                       printf ("Step time : %6.3 f seconds \n",
                          step_time);
203                       break;
204                 case '>':           /* Go faster */
205                       step_time /= 2.0;
206                       printf ("Step time: %6.3 f seconds \n",
                          step_time);
207                       break;
208                 case '?':           /* Provide help */
209                 case 'H':
210             help ();
```

```
211             break;
212                 case 'J':           /* Mode 0 */
213                 case 'K':           /* Mode 1 */
214                 case 'L':           /* Mode 2 */
215                       move_oclock(0);
216                       set_mode((int) ch - (int) 'J');
217                       break;
218                 case 'A':           /* 10 o'clock */
219                 case 'B':           /* 11 o'clock */
220                       move_oclock ((int) ch - (int) 'A'+10);
221                       break;
222                 case 'O':           /* Toggle on/ off drive */
223                       on_off ^= 1;
224                       if ( !on_off )
225                              drive(0);   /* Turn off motor drive */
226                       else advance(0);    /* Re_assert motor drive */
227                       break;
228                 case '+':        /* Advance +1 */
229                 case '=':        /* Tread '=' as '+' for convenience */
230                 case '-':        /* Counter clock_wise 1 */
231                       move(ch == '-' ? -1 : 1);
232                       /* Fall thru */
233                case 'P':           /* Display Position */
234                       printf("Position: %d of %d\n",position,
                          steps_per_r);
235                       break;
236                default:            /* 0 to 9'oclock */
237                       if ( ch >= '0' && ch <= '9' )
238                              move_oclock((int) ch - (int) '0');
239                       else write (1,"???\n",4);
240                 }
241         }
242
243         puts("\nExit.");
244
245         drive(0);
246         for ( x=0; x<4; ++x )
247             gpio_config(gpios[x],Input); /* Set GPIO pin as Input */
248
249         tcsetattr(tty,TCSAFLUSH,&sv_ios); /* Restore terminal mode */
250         return 0;
251 }
252
253 /* End unipolar.c */27.5.  SOFTWARE
```

CHAPTER 7

76 The H-Bridge Driver

One of the challenges of driving DC electric motors is that they sometimes need the capability to operate in reverse. To do this, the current flow must be reversed. Arranging for this requires additional hardware.

The H-Bridge driver can be used to drive a reversible DC motor *or* a bipolar stepper motor (also LEDs, as covered in Chapter 10 of *Raspberry Pi Hardware Reference* [Apress, 2014]). Unlike the unipolar motor, the field windings of a bipolar stepper motor require reversible current flow to operate. This chapter demonstrates the utility of the H-Bridge driver, using a bipolar stepper motor.

The L298 Driver

The L298 integrated circuit implements a convenient H-Bridge driver circuit. An H-Bridge can be built from discrete components, but integrated circuits are more convenient for lower-current applications. Figure 7-1 shows the block diagram for the L298 driver IC. You can see the *H* composed from the driver transistors Q_1 through Q_4, and the driven motor in the center (in this case, a DC motor).

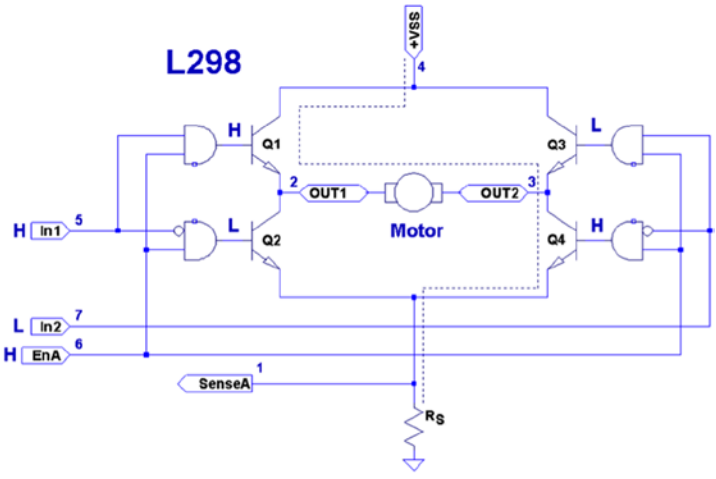


Figure 7-1. *L298 full-bridge driver*

The motor in the figure is driven when Q_1 and Q_4 are turned on. Q_2 and Q_3 are kept off when the other transistors are on. If Q_1 and Q_2 were allowed to be on at the same time, a short circuit would exist from V_{SS} to ground. The *and* logic gates driving these transistors prevent this.

Returning to Figure 7-1, with Q_1 and Q_4 on, the current flows through the motor from left to right. Turning all transistors off results in no current flow. Turning Q_3 and Q_2 on causes the current to flow from V_{SS} to ground, passing this time through the motor from right to left. By controlling pairs of transistors, current can be made to flow in one direction or the other.

Sensing Resistor

When used, the sensing resistor R_S is a low-resistance resistor for sensing how much current flows through the motor (the datasheet suggests a *non-wire-wound* resistance of $R_S = 0.5\ \Omega$). As current flow increases, the voltage V_{RS} across the resistor increases. When the motor stalls, for example, V_{RS} will exceed a certain threshold voltage, allowing protective circuitry to turn the drivers (and thus the motor) off. In this chapter, we will simply wire the sense pins to ground and omit the protective circuitry for simplicity.

Enable A and B

The L298 is a dual-bridge driver, with units A and B. Figure 7-1 shows only unit A. The enable inputs EnA and EnB enable or disable the drive to units A and B, respectively. Without a high signal on the enable input, no current will flow through the bridge, no matter what the other input signals are. The enable input can be used by the protective circuitry to disable the motor outputs, should the V_{RS} voltage rise too high. Otherwise, the enable inputs can be tied to the logic high or controlled by the microprocessor.

Inputs In1 and In2

Each half of the dual-bridge driver has a pair of logic inputs. They are In1 and In2 for bridge A, and In3 and In4 for bridge B. We'll focus on bridge A.

When the enable EnA pin is enabled, the In1 and In2 inputs have the following results for the motor drive:

In1	In2	Q1	Q2	Q3	Q4	Motor Current
0	0		On		On	No current flow
0	1		On	On		Right to left
1	0	On			On	Left to right
1	1	On		On		No current flow

A simple way to think about this is that one input must be high, while the other is low for the motor drive. The direction is selected by the input that is high.

Protection Diodes

No inductive driver circuit is complete without protective diodes. When the applied voltage is suddenly removed from the motor coil, the magnetic field collapses, producing an electric current. Recall in Chapter 6 that the reverse-biased diode was used to bleed off the inductive kick in the unipolar motor drive.

Figure 7-2 shows the L298 with the external protective diodes wired in (these are not included in the IC). If the current flow was as shown in the earlier block diagram, the sudden off would cause the current to flow through diodes D_3 and D_2. The SGS-Thomson Microelectronics datasheet specifies that these should be 1A fast-recovery diodes ($t_{rr} \leq 200\ ns$). A slow-reacting diode can allow the voltage to spike into the surrounding circuit.

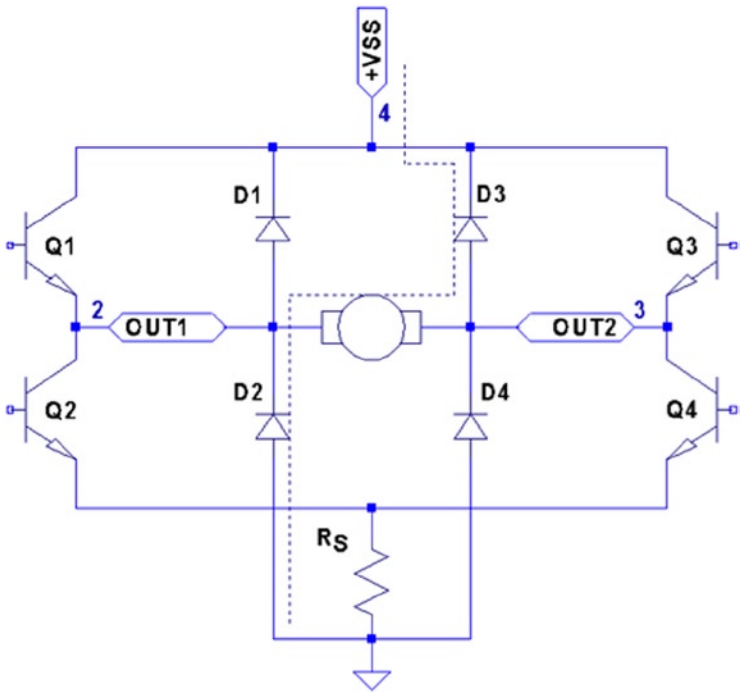


Figure 7-2. *L298 with protective diodes*

L298 PCB

You could build your own L298 driver circuit, but with the availability of PCBs around $4 on eBay, you'd have to have a good reason to bother. Figure 7-3 shows the unit that I purchased and used for this project.

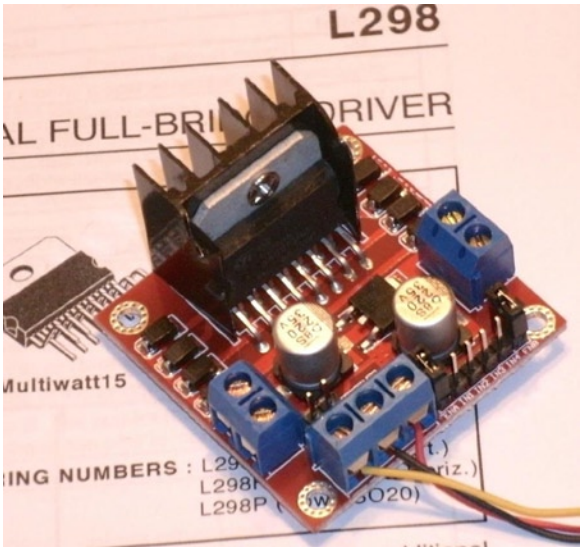


Figure 7-3. *L298 driver PCB*

■ **Note** I purchased this PCB as an eBay Buy It Now offer with free shipping.

The PCB has three power connections:

- V_S, which is labeled as +12 V (yellow wire in the photo)
- Gnd (black wire)
- V_{SS}, which is labeled as +5 V (red wire)

This particular PCB has a jumper (removed in Figure 7-3), with its two pins visible just above the power-connection block and below the round capacitor. With the jumper installed, an onboard regulator supplies V_{SS} with +5 V from the V_S (+12 V) input. The regulated +5 V is also available for external circuitry at the block connector (where the red wire is shown).

When the motor (V_S) voltage is higher than 12 V, it is best to remove the jumper and supply the +5 V into the block instead. The reason for this is that the linear regulator must dissipate additional heat from the higher input voltage. I am using a salvaged power supply with both a +5 V supply and a +16 V supply, so the jumper was removed.

To the right of the power-input block are header connection pins as follows:

+5V					+5V
EnA	In1	In2	In3	In4	EnB

The EnA and EnB connections have jumpers installed to enable both driver units (tying the enable A and B inputs up to the +5 V supply). If you don't need to control the enable inputs, leave the jumpers in. Otherwise, remove them and then use the edge pins for inputs to enables A and B.

The pins In1 through In4 are the inputs to the bridge drivers (see In1 and In2 in Figure 7-1).

The remaining connections are two blocks with paired connections:

- OUT1 and OUT2, bridge connections for unit A
- OUT3 and OUT4, bridge connections for unit B

You don't have to install any protective diodes, since they are already included on the PCB. Price and convenience were the reasons I chose to buy the PCB. If you breadboard the driver instead, be sure to wire in the fast-acting protection diodes, since these are not included in the IC.

Driving from GPIO

Of course, before we attach the inputs of these drivers to the GPIO pins of the Raspberry Pi, we need to be certain that the voltage levels are safe and that the interface logic levels work.

The L298 IC has the following power requirements:

Symbol	Parameter	Min	Typ	Max	Unit
V_S	Supply voltage (pin 4)	V_{IH} + 2.5		46	Volts
V_{SS}	Logic supply voltage (pin 9)	4.5	5	7	Volts

From this, we see that the motor side (V_S) can operate up to 46 V. The logic side, however, must have a minimum of 4.5 V. In other words, the L298 driver operates at 5V TTL levels.

■ **Note** Be sure to remove the regulator jumper when using high voltages.

But we've seen this kind of problem before, in Chapter 6. There we were still able to drive the ULN2003A safely from the GPIO outputs at 3 V levels. So let's check the signal requirements of GPIO outputs vs. L298 inputs:

GPIO		L298	
Signal	Volts	Volts	Signal
V_{OL}	$\leq 0.8\ V$	$\leq 1.5\ V$	V_{IL}
V_{OH}	$\geq 1.3\ V$	$\geq 2.3\ V$	V_{IH}

If you look carefully at the chart, there is a dodgy area where the GPIO output can be as low as $V_{OH} \geq 1.3\ V$ and still be in spec *as far as the Raspberry Pi is concerned*. We see that the L298 considers signals $V_{IL} \leq 1.5V$ as a *low*. Worse, only voltages $\geq 2.3\ V$ are considered high by the L298. The good news is that the L298 input current is very low:

		L298			
Symbol	**Parameter**	**Test Conditions**	**Typ**	**Max**	**Unit**
I_{IH}	High-voltage input current	$V_I = H \leq V_{SS} - 0.6\ V$	30	100	*mA*

The input current necessary to drive the L298 input high is a maximum of 100 μA. The lowest configured output drive capability of a GPIO pin is 2 mA. The L298 input current requirement is thus only 5% of the minimum current drive available. If the GPIO pin had to drive a 2 mA signal, its output voltage might be as low as 1.3 V. But having to supply only 100 μA of signal current means that the GPIO voltage should be almost as high as it can go.

For this reason, it is not that unreasonable to expect the GPIO output voltage to be near 3 V (allowing for a drop from the +3.3 V supply). However, we must allow for variation in the +3.3 V power supply as well. If the supply is within the standard range of +3.125 to +3.465 V, and we allow a GPIO output drop of, say, 0.3 V due to the output transistor R_{on}, then the unloaded GPIO output voltage could be as low as 3.135 – 0.3 = 2.835 *V*. This is only 0.535 V above the minimum $V_{IH} = 2.3\ V$ that we need for the L298. This is cutting things rather close, but sufficient for hobby and educational use (for products that are sold, you would want a greater margin for error). If this remains a concern for a project build, external pull resistors to +3.3 V can be added.

The DMM Check

The final word is the voltage measurement of the L298 chip's inputs. You must make certain there is no pull-up resistor to +5 V on the PCB. The datasheet doesn't indicate that any L298 chip internal pull-up resistors exist. But seeing is believing, so don't skip this check. A purchased PCB is more likely to contain pull-up resistors than not.

Without attaching it to the Pi, supply the circuit with +5 V for its logic (the motor supply need not be applied). When using the onboard regulator, supply the +12 V to the +VS input instead. Then check the voltage appearing at the EnA, EnB, In1, In2, In3, and In4 inputs. When measured, there should be nearly no voltage present (with respect to ground). If you read +5 V instead, the PCB likely has provided a pull-up resistor somewhere. For the enable inputs, jumpers may need to be removed. Do not wire these inputs to the Raspberry Pi until these inputs have passed this check. Anything measured less than 0.6 V is probably OK. Measurements higher than this probably mean a defective driver IC or a wiring error.

If you are supplying the L298 logic from a separate +5 V supply, it is a good idea to perform one more test with the +12 V (or higher) motor supply applied. The measured voltage at each input pin should remain as before, near zero. Anything else suggests a bad PCB or defective L298 chip leaking current into the inputs.

Bipolar Stepper Modes

Before we look at the schematic and software, let's review how the bipolar stepper motor works. There are three basic modes of operation for a *bipolar* stepper motor:

- Wave drive, one-phase-on drive
- Wave drive, two-phase-on drive
- Half-step drive

One-Phase-On Mode

Figure 7-4 shows the first two of four possible drive states for wave drive, one phase on. Each winding is energized in turn for the first two steps. The final two steps energize the same two windings in sequence except that the current polarity is reversed. In other words, the south pole of the rotor follows the positive input polarity (as wired in the figure). In this mode, there are a total of four steps.

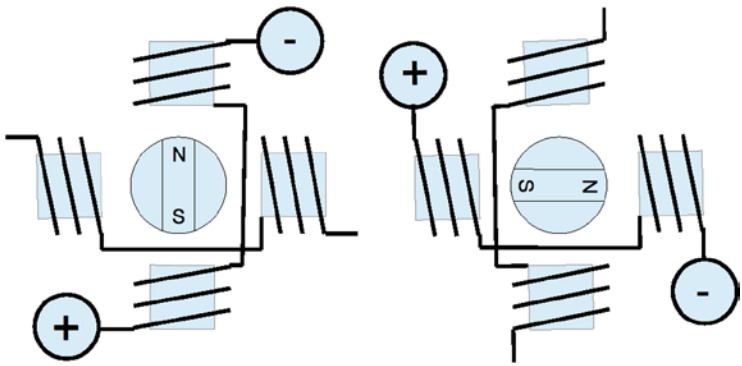


Figure 7-4. *Wave drive, one phase on*

This simple mode of operation suffers from the loss of precision that the half-step drive has and lacks the torque of two-phase-on mode.

Two-Phase-On Mode

Wave drive, two-phase-on mode energizes both windings for each step. This is where the extra torque comes from. Figure 7-5 shows two of the four possible steps for this mode. Notice how the south pole centers itself between two poles, as it follows the two positive polarities. Like the one-phase mode, there are only four possible steps.

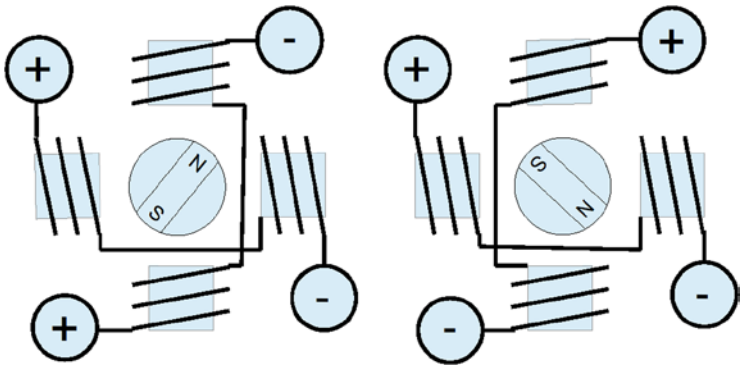


Figure 7-5. *Wave drive, two phase on*

While this mode lacks the precision of half-step mode (next), it does enjoy the extra torque advantage over all three modes.

Half-Step Mode

In half-step mode, a combination of the two prior modes is used. First, only one winding is energized to point the rotor at the winding's pole (like one-phase mode). Then the next pole is energized while keeping the prior winding energized. In this way, the rotor moves a half step between the two poles, as with two-phase mode. Finally, the previous winding is turned off, producing another half step. The precision is increased to a total of eight steps in this manner.

This is clearly the most precise of the three modes. While it lacks some of the torque of two-phase mode, it has on average more torque than one-phase mode.

In all of these modes, it is necessary to first pass current through the windings in one direction, and then later in the reverse direction. This allows the bipolar stepper motor to be built with less wire than the unipolar motor. In the unipolar design, only one or two of the four center-tapped windings are used at one time. Consequently, the bipolar motor is cheaper to manufacture and lighter in weight.

Figure 7-6 illustrates my test setup. At the left is a power supply that I rescued from a discarded piece of equipment. To the right of the Raspberry Pi station, I have the L298 PCB wired up to the power and the Pi's GPIO pins. The remaining four wires go from the drive PCB to the bipolar stepper motor (I left some sort of shaft attachment to the motor, to make the rotation more visible).

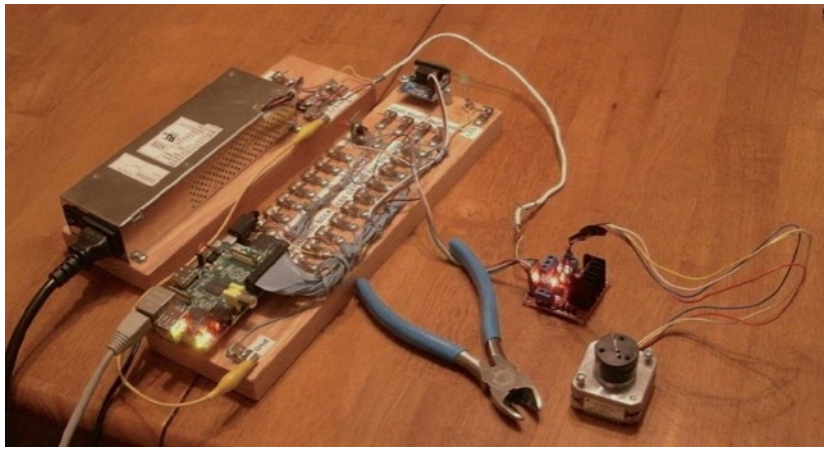


Figure 7-6. *My bipolar stepper motor setup*

Choosing Driving GPIOs

Recall from Chapter 6's Table 6-1 that some GPIO pins are more suitable than others for motor controls. While the Raspberry Pi is booting up, we don't want driver circuits and motors running amok. It is best that the motor remains disabled until the Pi boots up and the motor-controlling software takes proper control.

When using the L298, we can take one of two design approaches:

- Tie enable inputs high, but choose *motor-safe* GPIO pins for the driver inputs.
- Drive the enable inputs from a *motor-safe* GPIO and configure the other GPIO pins after boot-up.

The first option does not use the enable inputs at all. For that, you must make sure that all In GPIO pins are safe for motor control at boot time. The disadvantage is that all *four* input controls need to be taken from the *safe* GPIO pool. If you need to drive more than one motor, your options start to become limited.

The second approach uses motor-safe GPIO pin(s) on the *two* enable inputs of the L298 driver. This way, the enable inputs are pulled down during the boot-up process, disabling the motor controls, regardless of the state of the In pins. This gives you flexibility to choose any other GPIO pins for use for the In signals. This is the approach adopted for this chapter's project. (Note that you can tie the enable pins together so that only one safe GPIO pin is required to drive the enable input.) Because a bipolar stepper motor needs a bridge driver for each of its two windings, we'll use both bridge driver units provided by the L298 IC.

The enable inputs for the two windings can be ganged together and driven by one GPIO pin. This, of course, increases the load on the GPIO output, but at a worst case of 200 *mA*, the driving voltage requirements will be easily met.

Project Schematic

Figure 7-7 shows the schematic for the bipolar motor driver. If you are using a purchased PCB, the only important details are the connections to it. The schematic, however, helps us visualize all the separate components involved.

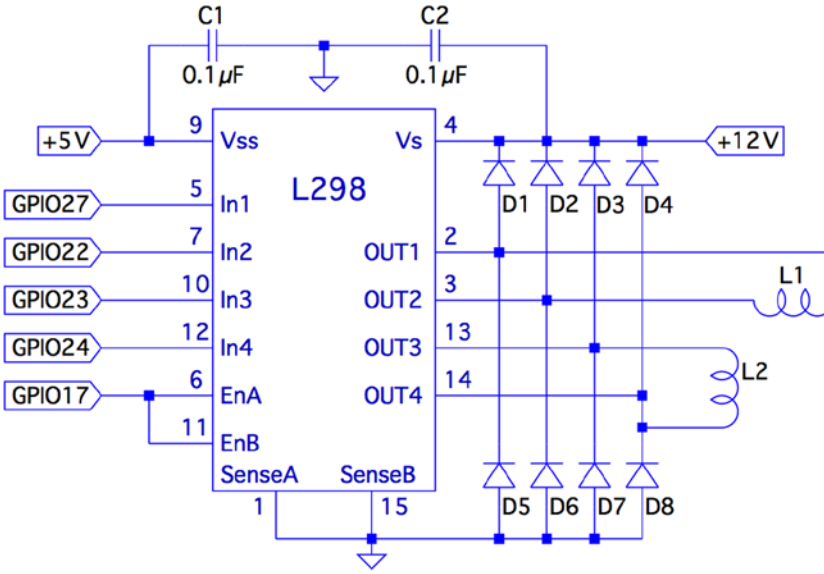


Figure 7-7. *L298 schematic*

In this circuit, the enable inputs A and B have been tied together so that only GPIO 17 needs to be allocated to drive it.

Junk-Box Motors

If you've been an electronics hobbyist for a while, you likely have a bipolar motor in your junk box. If not, salvage one from an old 3.5-inch floppy disk. Its seek motor will likely be a bipolar stepper. Another source of stepper motors is an old flat-top scanner.

Bipolar motors are easier to figure out than unipolar motors. There are only four wires, and they operate in pairs. To identify the pairs, simply take resistance readings. A low reading will identify one pair of wires. Once that pair is identified, the remaining two wires should be the second pair and read similarly. Make sure there is no connection between the windings. They should be electrically isolated from each other.

Program Operation

The program used in this chapter is named `bipolar.c` and is listed at the end of the chapter. The program is designed similarly to the unipolar program in Chapter 6. The bipolar program, however, does not do clock positioning, but instead operates in free-running mode when instructed to do so.

The program starts in one-phase mode, but the stepper-motor mode can be changed with any of the following single-character commands:

Character	Command
1	Wave mode, one phase
2	Wave mode, two phase
3	Half-step mode

Entering a mode command will automatically stop the motor if it is in free-running mode.

To test your motor connections, these single-step commands are available:

Character	Command
+	Single step clockwise
-	Single step counterclockwise

The + command steps the motor one step clockwise, while the – (minus) key steps the motor counterclockwise. If your motor turns the wrong way, you can fix your wiring after testing it.

Similarly, use these single-step commands to make sure your motor is wired up correctly. In one-phase mode (the default), the motor should step equally with each + or - step command. If not, one of the two pairs needs its connections reversed.

The free-running commands (and Quit) are listed here:

Character	Command
F	Forward (free running)
R	Reverse (free running)
S	Stop
>	Go faster (halve the step time)
<	Go slower (double the step time)
Q	Quit

Entering F starts the motor running, in the forward (clockwise) direction. To speed it up, press > while it is running, or prior to starting it. Pressing the same direction command F toggles the motor off again. Alternatively, S is available to stop the motor if that seems more intuitive. The R command starts the motor in the reverse direction. Pressing R again stops it. Direction can be changed while the motor is running. This tests how well it recovers when operated at higher speeds.

Program Internals

This program requires the use of a thread to run the motor in free-running mode. This design allows the main program to continue to read user commands from the keyboard while supplying the motor with stepping commands. The user can change the stepping speed, reverse the motor, or stop the motor.

The main user input dispatch loop is in the main program (lines 230 to 305). The threaded code resides in lines 125 to 140. Unless the free-running F or R commands are in effect, the thread blocks in line 131, waiting for a command. Once a command is received, the loop in lines 133 to 136 keeps the motor stepping, until the main loop sets the stop flag.

The `mutex` and `cond` variables (lines 36 and 37) provide a simple arrangement to implement a queue from the main thread to the free-running thread. The queue `get` function is implemented in lines 105 to 119. The code must first successfully lock the `mutex` in line 109. Once that is accomplished, the `while` loop in lines 111 and 112 is executed. If the `cmd` variable is still zero, this indicates that no command has been queued. When that happens, `pthread_cond_wait()` in line 112 is executed. This unlocks the `mutex` and blocks the execution of the program. Control blocks until the `cond` variable is signaled in line 158. When control returns from `pthread_cond_wait(3)`, the kernel has relocked the `mutex`.

Queuing the command occurs in the routine `queue_cmd()` (lines 146 to 159). After locking the `mutex` (line 149), the `while` loop checks whether the `cmd` variable is nonzero. If it is, this indicates that the motor thread has not received the last command yet, and control blocks in the `pthread_cond_wait()` call (line 152). Again, when control blocks, the kernel releases the `mutex`. The `cond` variable is signaled from line 117, when the command is taken off the one-element queue.

The stepping functions are performed by the routine `step()` in lines 73 to 91. The motor drive is disabled in line 86 so the GPIO signals can be changed (line 87). Once the new GPIO output settings are established, the drive to the motor is enabled in line 88.

If you choose to use different GPIO pins for this project, change the constant declarations in lines 23 to 27.

```
1   /*************************************************************************
2    * bipolar.c : Drive a bipolar stepper motor
3    *************************************************************************/
4
5   #include <stdio.h>
6   #include <stdlib.h>
7   #include <fcntl.h>
8   #include <unistd.h>
9   #include <errno.h>
```

```
10  #include <math.h>
11  #include <ctype.h>
12  #include <termio.h>
13  #include <sys/mman.h>
14  #include <pthread.h>
15  #include <assert.h>
16
17  #include "gpio_io.c"                  /* GPIO routines */
18  #include "timed_wait.c"               /* timed_wait() */
19
20  /*
21   * GPIO definitions :
22   */
23  static const int g_enable    = 17;  /* L298 EnA and EnB */
24  static const int g_in1   = 27;      /* L298 In1 */
25  static const int g_in2   = 22;      /* L298 In2 */
26  static const int g_in3   = 23;      /* L298 In3 */
27  static const int g_in4   = 24;      /* L298 In4 */
28
29  static volatile int stepper_mode = 0;      /* Stepper mode - 1 */
30  static volatile float step_time = 0.1;     /* Step time in seconds */
31
32  static volatile char cmd = 0;       /* Thread command when nonzero */
33  static volatile char stop = 0;      /* Stop thead when nonzero */
34  static volatile char stopped = 0;   /* True when thread has stopped */
35
36  static pthread_mutex_t mutex;       /* For inter-thread locks */
37  static pthread_cond_t cond;         /* For inter-thread signaling */
38
39  /*
40   * Await so many fractional seconds
41   */
42  static void
43  await(float seconds) {
44          long sec, usec;
45
46          sec = floor(seconds);               /* Seconds to wait */
47          usec = floor((seconds-sec)*1000000); /* Microseconds */
48          timed_wait(sec,usec,0);             /* Wait */
49  }
50
51  /*
52   * Enable/Disable drive to the motor
53   */
54  static inline void
```

```
55  enable(int enable) {
56          gpio_write(g_enable, enable);
57  }
58
59  /*
60   * Drive the appropriate GPIO outputs :
61   */
62  static void
63  drive(int L1L2) {
64          gpio_write(g_in1, L1L2&0x08);
65          gpio_write(g_in2, L1L2&0x04);
66          gpio_write(g_in3, L1L2&0x02);
67          gpio_write(g_in4, L1L2&0x01);
68  }
69
70  /*
71   * Take one step in a direction :
72   */
73  static void
74  step(int direction) {
75          static const int modes[3][8] = {
76                  { 0b1000, 0b0010, 0b0100, 0b0001 },      /* Mode 1 */
77                  { 0b1010, 0b0110, 0b0101, 0b1001 },      /* Mode 2 */
78                  { 0b1000, 0b1010, 0b0010, 0b0110, 0b0100, 0b0101,
                      0b0001, 0b1001 }
79          } ;
80          static int stepno = 0;            /* Last step no.*/
81          int m = stepper_mode < 2 ? 4 : 8; /* Max steps for mode */
82
83          if ( direction < 0 )
84                  direction = m - 1;
85
86          enable(0);                          /* Disable motor */
87          drive(modes[stepper_mode][stepno]); /* Change fields */
88          enable(1);                          /* Drive motor */
89
90          stepno = (stepno+direction) % m; /* Next step */
91  }
92
93  /*
94   * Set the stepper mode of operation :
95   */
96  static inline void
```

```
97  set_mode(int mode) {
98            enable(0);
99            stepper_mode = mode;
100 }
101
102 /*
103  * Take a command off the input queue
104  */
105  static char
106  get_cmd(void) {
107           char c;
108
109           pthread_mutex_lock(&mutex);
110
111           while ( !cmd )
112                   pthread_cond_wait(&cond,&mutex);
113
114           c = cmd;
115           cmd = stop = 0;
116           pthread_mutex_unlock(&mutex);
117           pthread_cond_signal (&cond); /* Signal that cmd is taken */
118
119           return c;
120 }
121
122 /*
123  * Stepper controller thread :
124  */
125 static void *
126 controller(void * ignored) {
127           int command;
128           int direction;
129
130           for ( stopped = 1; ; ) {
131                   command = get_cmd();
132                   direction = command == 'F' ? 1 : -1;
133
134                   for ( stopped = 0; !stop; ) {
135                           step(direction);
136                           await(step_time);
137                   }
138                   stopped = 1;
139           }
140           return 0;
141 }
142
143 /*
```

```
144  * Queue up a command for the controller thread :
145  */
146 static void
147 queue_cmd( char new_cmd) {
148
149         pthread_mutex_lock(&mutex); /* Gain exclusive access */
150
151         /* Wait until controller grabs and zeros cmd */
152         while ( cmd )
153                 pthread_cond_wait(&cond ,&mutex);
154
155         cmd = new_cmd;                  /* Deposit new command */
156
157         pthread_mutex_unlock(&mutex);  /* Unlock */
158         pthread_cond_signal(&cond);    /* Signal that cmd is there */
159 }
160
161 /*
162  * Stop the current operation :
163  */
164 static void
165 stop_cmd(void) {
166          for ( stop = 1; !stopped; stop = 1 )
167                  await(0.100);
168 }
169
170 /*
171  * Provide usage info :
172  */
173 static void
174 help(void) {
175           puts("Enter :\n"
176                    "  1 - One phase mode\n"
177                    "  2 - Two phase mode\n"
178                    "  3 - Half step mode\n"
179                    "  R - Toggle Reverse (counter-clockwise)\n"
180                    "  F - Toggle Forward (clockwise)\n"
181                    "  S - Stop motor\n"
182                    "  + - Step forward\n"
183                    "  - - Step backwards\n"
184                    "  > - Faster step times \n"
185                    "  < - Slower step times \n"
186                    "  ? - Help\n"
187                    "  Q - Quit\n " ) ;
188 }
189
190 /*
```

```
191  * Main program
192  */
193 int
194 main(int argc,char **argv) {
195          pthread_t tid;    /* Thread id */
196          int tty = 0;      /* Use stdin */
197          struct termios sv_ios, ios;
198          int rc, quit;
199          char ch, lcmd = 0;
200
201          rc = tcgetattr (tty,&sv_ios);    /* Save current settings */
202          assert(!rc);
203          ios = sv_ios;
204          cfmakeraw(&ios);          /* Make into a raw config */
205          ios.c_oflag = OPOST | ONLCR; /* Keep output editing */
206          rc = tcsetattr(tty,TCSAFLUSH,&ios); /* Put into raw mode */
207          assert(!rc);
208
209          /*
210           * Initialize and configure GPIO pins :
211           */
212          gpio_init();
213          gpio_config(g_enable,Output);
214          gpio_config(g_in1,Output);
215          gpio_config(g_in2,Output);
216          gpio_config(g_in3,Output);
217          gpio_config(g_in4, Output);
218
219          enable(0);                   /* Turn off output */
220          set_mode(0);                 /* Default is one phase mode */
221
222          help();
223
224          pthread_mutex_init(&mutex,0);     /* Mutex for inter-thread
             locking */
225          pthread_cond_init(&cond,0);  /* For inter-thread signaling */
226          pthread_create(&tid,0,controller,0); /* The thread itself */
227
228          /*
229           * Process single-character commands :
230           */
231          for ( quit=0; !quit; ) {
232                  /*
233                   * Prompt and read input char :
234                   */
235                  write(1,": ",2);
```

```
236                 rc = read(tty,&ch,1);
237                 if ( rc != 1 )
238                         break;
239                 if ( islower (ch) )
240                         ch = toupper(ch);
241
242                 write(1,&ch,1);
243                 write(1,"\n",1);
244
245                 /*
246                  * Process command char :
247                  */
248                 switch ( ch ) {
249                 case '1' :    /* One phase mode */
250                         stop_cmd();
251                         set_mode(0);
252                         break;
253                 case '2' :    /* Two phase mode */
254                         stop_cmd();
255                         set_mode(1);
256                         break;
257                 case '3' :    /* Half step mode */
258                         stop_cmd();
259                         set_mode(2);
260                         break;
261                 case '<' :    /* Make steps slower */
262                         step_time *= 2.0;
263                         printf("Step time is now %.3f ms\n",step_
                            time*1000.0);
264                         break;
265                 case '>' :    /* Make steps faster */
266                         step_time /= 2.0;
267                         printf("Step time is now %.3f ms\n",step_
                            time*1000.0);
268                         break;
269                 case 'F' :   /* Forward : run motor */
270                         if ( !stopped && lcmd != 'R' ) {
271                              stop_cmd();       /* Stop due to toggle */
272                                 lcmd = 0;
273                         } else  {
274                    op_cmd();       /* Stop prior to change direction */
275                                 queue_cmd(lcmd='F');
276                         }
277                         break;
278                 case 'R' :    /* Reverse : run motor */
```

```
279                         if ( !stopped && lcmd != 'F' ) {
280                                 stop_cmd();
281                                 lcmd = 0;
282                         } else  {
283                                 stop_cmd();
284                                 queue_cmd(lcmd='R');
285                         }
286                         break ;
287                 case 'S' :      /* Just stop */
288                         stop_cmd();
289                         break;
290                 case '+' :      /* Step clockwise */
291                 case '=' :      /* So we don't have to shift for + */
292                         stop_cmd();
293                         step(1);
294                         break;
295                 case '-' :      /* Step counterclockwise */
296                         stop_cmd();
297                         step(-1);
298                         break;
299                 case 'Q' :      /* Quit */
300                         quit = 1;
301                         break;
302                 default :       /* Unsupported */
303                         stop_cmd();
304                         help();
305                 }
306         }
307
308         stop_cmd();
309         enable(0);
310
311         puts("\nExit.");
312
313         tcsetattr(tty,TCSAFLUSH,&sv_ios); /* Restore terminal mode */
314         return 0;
315 }
316
317 /* End bipolar.c */
```

CHAPTER 8

Remote-Control Panel

Because of the Raspberry Pi's small size and low cost, it is an attractive platform for remote-sensing applications. A remote station might need to sense control panel switches or push button events. This electronic problem sounds simple until you discover that switches and buttons suffer from *contact bounce*.

The remaining challenge resides on the software side. When your sensing stations are *remote,* some kind of local software console needs to exist. In fact, your console may monitor several remote Raspberry Pis. Then add redundant consoles, or consoles in multiple locations. Each of these has the ability to monitor *and* control the same remote devices. It doesn't take long before the problem becomes complex.

This chapter's project aims to solve two problems:

- Debouncing a switch or push button (hardware)
- Controlling remote consoles (software)

Let's first examine the contact bounce problem.

Switched Inputs

One of the aggravations of dealing with push buttons and switches in an electronic computing environment is that contacts *bounce*. When you close a switch or push a button, the contacts can bounce a thousand times before they settle and produce a stable contact. A modern computer might see thousands of on/off transitions before the contacts stabilize.

This is not only a nuisance for software design, but also wasteful of the CPU. Each time the signal from the switch changes state, the CPU must be interrupted to make note of this event and pass the information on to the interested software (for example, GPIO change events). The software must then apply algorithms to smooth out these pulses and arrive at a conclusion when the switch is fully on, or fully off. This is all very ugly and messy!

The same problem happens in reverse when contacts release. Thousands of pulses are delivered to the CPU as the contacts slowly release and alternate between being in contact and being disconnected.

There are several ways to reduce or eliminate the problem. One approach is to apply a flip-flop ahead of the GPIO pins, as shown in Figure 8-1. One end of a SPDT switch is wired to the flip-flop reset input, while the other is wired to the set input. In this manner, a single pulse on either end changes the flip-flop state and keeps it stable.

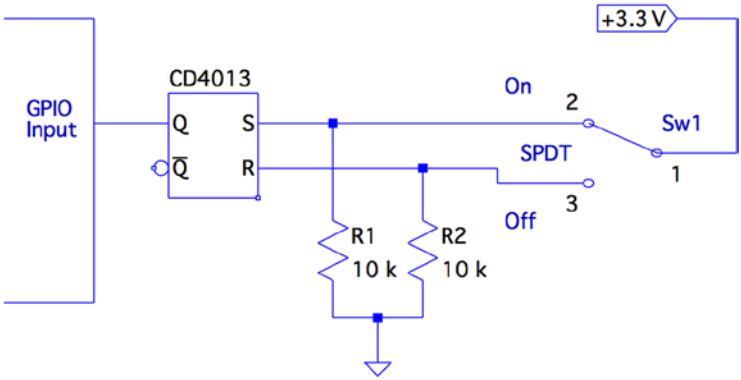


Figure 8-1. *Using a flip-flop for debouncing*

When the switch is releasing one contact, there is no change in the flip-flop output. After the arm has flown through its switching arc, the opposite contact eventually starts to bounce at the end of its swing. At this point, it takes only a single pulse to change the output of the flip-flop to its new state. After that, it remains constant.

The pull-down resistors R_1 and R_2 are necessary because the CMOS inputs would otherwise float when the switch arm disconnects from the switch's contacts. While disconnected, the resistors pull the input voltage down to ground potential.

The CD4013

The CD4013 is a CMOS part that is able to operate from +3 V and up. The pinout for the CD4013 is provided in Figure 8-2. The supply voltage V_{DD} is applied to pin 14, with pin 7 (V_{SS}) performing as the ground return. From the pinout diagram, you can see that this is a dual flip-flop IC, with pins labeled for units 1 and 2.

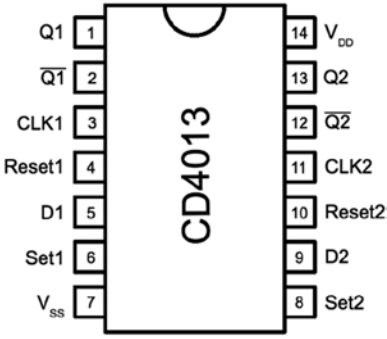


Figure 8-2. *The CD4013 pinout*

The datasheet for this part from various manufacturers shows the V_{IL} and V_{IH} levels when V_{DD} = +5 *V* (and higher). The values shown for V_{OH} for each V_{DD} are all listed at a value of V_{DD} – 0.5 *V*. Extrapolating from that, I have assumed V_{OH} = 3.3 – 0.5 = 2.8 *V* in the following table. The V_{OL} is listed as 0.05 *V* for all V_{DD} values listed, so we'll assume the same for 3.3 *V*.

The following table compares the Raspberry Pi GPIO logic levels with those of the CD4013 chip operating at +3.3 V.

Raspberry Pi, GPIO		CD4013, V_{DD} = +3.3 *V*	
Parameter	**Volts**	**Volts**	**Parameter**
V_{IL}	≤ 0.8 *V*	≤0.05 *V*	V_{OL}
V_{IH}	≥ 1.3 *V*	≥ 2.8 *V*†	V_{OH}

†Derived from a National Semiconductor datasheet

From Figure 8-1, recall that we are using the flip-flop output Q to drive a GPIO input. The flip-flop's V_{OL} is much lower than the maximum value for V_{IL}, so that works well. Additionally, from the table, notice that the V_{OH} level of the CD4013 output is well above the minimum required for V_{IH} for the GPIO input as well. From this signal comparison, we can conclude that the CD4013 part should play very nice with the Pi when powered from 3.3 V.

■ **Caution** Unused CMOS *inputs* should not be left unconnected. If an unused input has no contribution to your design, ground it. If you must have the input in a high state, wire it directly to the +3.3 V supply. No limiting resistor is required, since a CMOS input draws no current. Likewise, do not omit R_1 and R_2, shown in Figure 8-1. Unused CMOS *outputs*, however, can be left unconnected.

Unused CMOS inputs should not be left to float. In the presented flip-flop circuit, the following unused pins will be grounded:

Pin	Function	Wired to	Notes
3	Clock 1	Ground	Not used
5	Data 1	Ground	Not used
8	Set 2	Ground	If FF2 not used
9	Data 2	Ground	Not used
10	Reset 2	Ground	If FF2 not used
11	Clock 2	Ground	Not used

If the second flip-flop is used, simply ground unused pins 9 and 11. Otherwise, unused pins 8 and 10 should also be grounded. With two flip-flops in the CD4013, you could debounce two switches/buttons.

Testing the Flip-Flop

After wiring up the CD4013 circuit, you can do a preliminary test before hooking it up to your Pi. Simply apply +3.3 V to the circuit and measure the voltage on pin 1 (Q_1). When you throw the switch from one position to the next, the output of Q_1 should follow.

Hooked up to the Pi, you can test the circuit with the `evinput` program that is developed in Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014). You can choose any suitable GPIO input, or one that you configured for input. Consult that book also for a list of GPIOs that boot up in input mode. I chose to use GPIO 22 (GEN3):

```
$ ./evinput 22
Monitoring for GPIO input changes :

GPIO 22 changed :   0
GPIO 22 changed :   1
GPIO 22 changed :   0
GPIO 22 changed :   1
GPIO 22 changed :   0
^C
$
```

Here the switch was initially off (Q_1 reads low). Then I threw the switch on, and then off, on, and then off again. Notice that there are no intervening glitches or other contact bounce events.

If you have a microswitch available with SPDT contacts, you can wire it as a push button. Push it on, release it, push it on again, and release again. The Raspberry Pi will read nice clean events without any contact bounce. That's how we like it on the software side!

The LED

Figure 8-3 shows the wiring for the LED. The resistor R_1 was chosen to provide a red LED, about 8 mA. If you're using a lower-powered LED, you can increase the resistance of R_1. Students may want to refer to Chapter 10 of *Raspberry Pi Hardware Reference* (Apress, 2014) for the procedure on how to calculate the resistance for R_1.

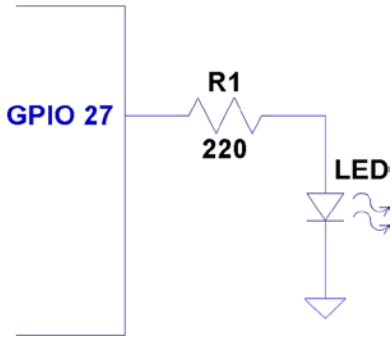


Figure 8-3. *Sensor LED hookup*

ØMQ

Some open source projects are just too good not to use. ØMQ is one of them. It exists to solve a difficult problem close to our hearts. Using this library, we can have each Raspberry Pi act as a *publisher* of information for the multiple software consoles acting as *subscribers*.

To allow multiple consoles to control each Pi sensing station, each sensing station also becomes a *subscriber* to the console *publishers*. In effect, we have many-to-many communication in a tidy software API, thanks to ØMQ.

■ **Note** For interesting reading, a nice overview of ØMQ is available here: `http://zguide.zeromq.org/page:all`.

Performing Installation

The download and installation of ØMQ is almost painless for the Raspberry Pi. Simply allow some time for the compile, which might take a while (step 3):

1. `wget http://download.zeromq.org/zeromq-3.2.2.tar.gz`
2. `./configure  -prefix=/usr/local`
3. `make`
4. `make check` (optional)
5. `make install`

If you also want C++ support for ØMQ, you can perform the following additional steps (we'll use only the C API in this chapter):

1. `git clone https://github.com/zeromq/cppzmq.git`
2. `cd cppzmq`
3. `sudo cp zmq.hpp /usr/local/include/`

Compiling and Linking

When compiling source code using ØMQ, you need to specify only the directory where the include files were installed:

- `-I /usr/local/include`

For linking, you need the following linker options:

- `-L/usr/local/lib -lzmq`
- `-Wl,-R/usr/local/lib`

The last option tells the executable where to find the ØMQ shared libraries at runtime. Exclude that option when linking on the Mac (or use the provided makefile `target mac_console`).

```
$  make
gcc -c -Wall -O0 -g -I/usr/local/include -Wall -O0 -g sensor.c -o sensor.o
gcc sensor.o -o sensor -L/usr/local/lib -lzmq -lncurses -Wl, -R/usr/local/lib
sudo chown root ./sensor
sudo chmod u+s ./sensor
gcc -c -Wall -O0 -g -I/usr/local/include -Wall -O0 -g console.c -o console.o
gcc -console.o -o console -L/usr/local/lib -lzmq -lncurses -Wl,
-R/usr/local/lib
```

Sensing Station Design

Our Raspberry Pi sensing station will use the CD4013 flip-flop circuit to debounce one switch or SPDT push button. The Pi station will also consist of one LED that will be controlled by the multiple software consoles.

If you need to imagine some kind of use case, imagine that the Raspberry Pi is controlling a jail cell door. The guard who wants to open a door pushes a microswitch button to show `SW1=On` on the remote consoles (as a request indication). After the monitoring agents check their video monitor, one of them agrees to honor the request by entering `1` on the console (which lights the LED) to open the jail cell door. Pressing `0` closes the latch again (turns off the LED).

The great thing about using ØMQ for networking is that you can do the following:

- Run `./sensor` with no consoles running
- Run any number of `./console` (or `./mac_console`) programs without the sensor running yet
- Run as many consoles as you like
- Bring down consoles anytime you like

With a little homework and extra effort, you could monitor multiple sensors as well. That was avoided here, to keep the example as simple as possible.

Sensing Station Program

The sensing station (Raspberry Pi) is started as follows:

```
$ ./sensor
```

The station runs quietly until terminated (it can be shut down from a console).

While it runs, it periodically broadcasts (publishes) updates to the consoles with the current status of SW_1 and *LED*. This is necessary because a console may be offline when the last switch or LED change occurs.

Whenever SW_1 changes, a broadcast is immediately sent with its new status `sw1:%d`, where `%d` is a `1` when the switch is on, and otherwise, a `0`.

The LED is changed only at the command of the console program. When the sensor program receives a console message of the form `led:%d` (over the network), the LED is turned on or off, according to the value of `%d` (`1` or `0`). Once the LED is changed, however, it is rebroadcasted to all consoles, so that the other consoles can see that this has changed.

Finally, if the console sends `stop:` to the sensor, the sensor program shuts down and exits. Pressing `^C` in its terminal session will also terminate it.

Console Program

The console program should be compilable for any Linux or Mac OS X platform. If you use the downloaded makefile, use the target `mac_console` when building it on Mac OS X:

```
$ make mac_console
```

For the Raspberry Pi or any other Linux distribution, you can build the program simply as follows:

```
$ make
```

You'll need the ncurses development library installed, in addition to ØMQ:

```
# apt-get install libncurses5-dev
```

To run the console program, simply launch it with the optional hostname as the first command-line argument (the default is `localhost`):

```
$ ./console 192.145.200.14      # Raspberry Pi by IP no.
```

Mac users will use the following:

```
$ ./mac_console myrasp          # Raspberry Pi by hostname
```

Figure 8-4 shows the appearance of the console when it first starts up. The `???` show that the console does not yet know the status of the switch or LED. Beside the command-line input, it also shows `Online?`, indicating that it does not yet know whether the sensor is online. As soon as one message is received, that changes to `ONLINE`.

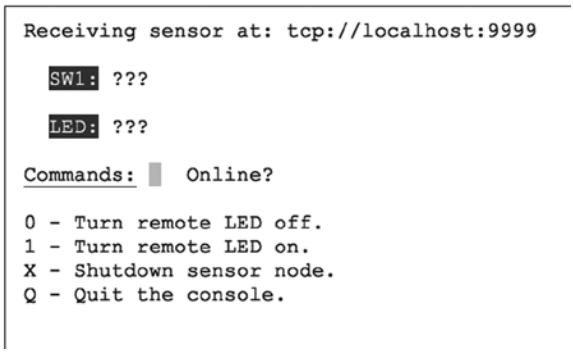


Figure 8-4. *Console at startup*

Console Commands

The console commands are all single-character commands and are displayed on the screen. Typing `0` turns off the LED on the sensor, and typing `1` turns it on. Typing `q` or `Q` quits the console.

Typing `x` or `X` terminates the sensor program. (It would not be good to have this option on a real jail cell control).

Sensor Source Code

Every attempt was made to keep these listings short. But despite these attempts, the code is a bit "winded" for this simple-minded task. The important thing here is the basic concept and how to leverage it in your own more sophisticated designs.

Except for the use of pthreads and ØMQ, not much is new in the source code. Consequently, I'll just provide some highlights.

The `sensor.c` main program gets everything started, by opening the GPIO files (input and output), opening the ØMQ sockets, and creating two threads. The main thread is contained within the main program, within the `for` loop starting at line 298. The loop simply pulls console commands from the ØMQ socket `console` at line 299 and then acts upon them.

There are only two supported console commands:

`led:%d`: Change LED status

`stop:`: Shut down the `./sensor` program

Line 286 of the main program creates the `SW1_monitor_thread`. This thread is located in lines 211 to 223. It uses the `poll(2)` system call in the routine `gpio_poll()`, to determine when the switch setting changes. This GPIO input is coming from Q_1 of the flip-flop, which is connected to either a switch or a microswitch push-button.

Program execution blocks at line 216, until the switch changes state. Then the status of the switch is captured in `rc` and relayed to all interested consoles by calling the routine `publish_SW1()`.

The remaining thread is launched in the main program from line 289. It runs in lines 228 through 237. It is a very small loop, which simply updates the consoles every 3 seconds, with the current status of the LED and SW_1. This is necessary so that consoles that are restarted can eventually know the current state of these items.

The `mutex_lock()` and `mutex_unlock()` routines are designed to guard against two threads using the same ØMQ resources at the same time. Doing so would cause program aborts.

The ØMQ library supports a routine named `zmq_poll()`, which would have simplified things if it could have been used. Unfortunately, it supports only `ZMQ_POLLIN` for input. Our switch change driver requires the use of `poll(2)`'s `POLLPRI` event, so `zmq_poll()` will not support us there.

```
1     /*****************************************************************
2      * sensor.c - Sense SW1, send to console (and take LED cmd from console)
3      *****************************************************************/
4
5    #include <stdio.h>
6    #include <stdlib.h>
7    #include <unistd.h>
8    #include <string.h>
9    #include <fcntl.h>
10   #include <assert.h>
11   #include <poll.h>
12   #include <pthread.h>
13
14   #include <zmq.h>
15
16   static const char *service_sensor_pub =  "tcp ://*:9999";
17   static const char *service_sensor_pull = "tcp ://*:9998";
18
```

```
19   static void *context = 0;   /* ZMQ context */
20   static void *publisher = 0; /* Publishing socket */
21   static void *console = 0;   /* Pull socket */
22
23   static int SW1 = 0;         /* Switchstatus */
24   static int LED = 0;         /* LED status */
25   static int stop = 0;        /* Nonzero when shutting down */
26
27   static int gp_SW1 = 22;     /* GPIO 22 (input) */
28   static int gp_LED = 27;     /* GPIO 22 (output) */
29   static int fd_SW1 = -1;     /* Open fd for SW1 */
30
31   #include "mutex.c"
32
33   /*
34    * Publish the LED setting to the console(s)
35    */
36  static void
37  publish_LED(void) {
38              char buf [256];
39              size_tn;
40              int rc;
41
42      n = sprintf(buf,"led:%d",LED);
43      mutex_lock();
44      rc = zmq_send(publisher,buf,n,0);
45      assert(rc!=-1);
46      mutex_unlock();
47  }
48
49   /*
50    * Publish the switch setting to the console(s)
51    */
52  static void
53  publish_SW1(void) {
54      char buf[256];
55      size_t n;
56      int rc;
57
58      n = sprintf(buf,"sw1:%d",SW1);
59
60      mutex_lock();
61      rc = zmq_send(publisher,buf,n,0);
62      assert(rc!=-1);
63      mutex_unlock();
64  }
65
```

```
typedef enum {
        gp_export = 0,  /* /sys/class/gpio/export */
        gp_unexport,    /* /sys/class/gpio/unexport */
        gp_direction,   /* /sys/class/gpio%d/direction */
        gp_edge,        /* /sys/class/gpio%d/edge */
        gp_value        /* /sys/class/gpio%d/value */
} gpio_path_t;

 /*
  * Internal : Create a pathname for type in buf.
  */
 static const char *
 gpio_setpath(int pin,gpio_path_t type,char *buf,unsigned bufsiz) {
    static const char *paths [] = {
            "export", "unexport", "gpio%d/ direction",
            "gpio%d/edge", "gpio%d/value" };
    intslen;

    strncpy(buf,"/sys/class/gpio/",bufsiz);
    bufsiz -= (slen == strlen(buf));
    snprintf(buf+slen,bufsiz,paths[type],pin);
    return buf;
 }

 /*
  * Open/sys/class/gpio%d/value for edge detection :
  */
 static int
 gpio_open_edge(int pin,const char *edge) {
    char buf[128];
    FILE *f;
    int fd;

    /* Export pin : /sys/class/gpio/export */
    gpio_setpath(pin,gp_export,buf,sizeof buf);
    f = fopen(buf,"w");
    assert(f);
    fprintf(f,"%d\n",pin);
    fclose(f);

    /* Direction : /sys/class/gpio%d/direction */
    gpio_setpath(pin,gp_direction,buf,sizeof buf);
    f = fopen(buf,"w");
    assert(f);
    fprintf(f,"in\n");
    fclose(f);

```

```
113     /* Edge : /sys/class/gpio%d/edge */
114     gpio_setpath(pin, gp_edge,buf,sizeof buf);
115     f = fopen(buf,"w");
116     assert(f);
117     fprintf(f,"%s\n",edge);
118     fclose(f);
119
120     /* Value : /sys/class/gpio%d/value */
121     gpio_setpath(pin,gp_value,buf,sizeof buf);
122     fd = open(buf,O_RDWR);
123     return fd;
124  }
125
126  /*
127   * Open/sys/class/gpio%d/value for output :
128   */
129  static int
130  gpio_open_output(int pin) {
131     char buf[128];
132     FILE *f;
133     int fd;
134
135     /* Export pin : /sys/class/gpio/export */
136     gpio_setpath(pin,gp_export,buf,sizeof buf);
137     f = fopen(buf,"w");
138     assert(f);
139     fprintf(f,"%d\n",pin);
140     fclose(f);
141
142     /* Direction : /sys/class/gpio%d/direction */
143     gpio_setpath(pin,gp_direction,buf,sizeof buf);
144     f = fopen(buf,"w");
145     assert(f);
146     fprintf(f,"out\n");
147     fclose(f);
148
149     /* Value : /sys/class/gpio%d/value */
150     gpio_setpath(pin,gp_value,buf,sizeof buf);
151     fd = open(buf,O_WRONLY);
152     return fd;
153  }
154
155  /*
156   * Close (unexport) GPIO pin :
157   */
```

```
158 static void
159 gpio_close(int pin) {
160    char buf [128];
161    FILE *f ;
162
163    /* Unexport : /sys/class/gpio/unexport */
164    gpio_setpath(pin,gp_unexport,buf,sizeof buf);
165    f = fopen(buf,"w");
166    assert(f);
167    fprintf(f,"%d\n",pin);
168    fclose(f);
169 }
170
171 /*
172  * This routine will block until the open GPIO pin has changed
173  * value.
174  */
175 static int
176 gpio_poll(int fd) {
177    struct poll fd_polls;
178    char buf[32];
179    int rc, n;
180
181    polls.fd = fd;              /* /sys/class/gpio17/value */
182    polls.events = POLLPRI;     /* Exceptions */
183
184    do  {
185          rc = poll (&polls,1, -1);       /* Block */
186    } while ( rc < 0 && errno == EINTR );
187
188    assert(rc > 0);
189
190    lseek(fd,0,SEEK_SET);
191    n = read(fd,buf,sizeof buf);   /* Read value */
192    assert(n>0);
193    buf[n] = 0;
194
195    rc = sscanf(buf,"%d",&n);
196    assert(rc==1);
197    return; /* Return value */
198 }
199
200 /*
201  * Write to the GPIO pin
202  */
```

```
203 static void
204 gpio_write(int fd,int dbit) {
205    write(fd,dbit ? "1\n" : "0\n",2);
206 }
207
208 /*
209  * Monitor switch changes on GPIO
210  */
211 static void *
212 SW1_monitor_thread(void *arg) {
213    int rc;
214
215    while ( !stop ) {
216         rc = gpio_poll(fd_SW1);       /* Watch for SW1 changes */
217        if ( rc < 0 )
218            break;
219        SW1 = rc;
220        publish_SW1();
221    }
222    return 0;
223 }
224
225 /*
226  * Periodic broadcast to consoles thread
227  */
228 static void *
229 console_thread(void *arg) {
230
231    while ( !stop ) {
232        sleep(3);
233        publish_SW1();
234        publish_LED();
235    }
236    return 0;
237 }
238
239 /*********************************************************************
240  * Main thread : read switch changes and publish to console (s)
241  *********************************************************************/
242 int
243 main(int argc,char **argv) {
244    pthread_t tid;
245    int rc = 0;
246    char buf[256];
247    int fd_LED = -1;          /* GPIO 27 */
248
```

```
249     mutex_init();
250
251     /* Open GPIO for LED */
252     fd_LED = gpio_open_output(gp_LED);
253     if ( fd_LED < 0 ) {
254         printf("%s : Opening GPIO %d for output.\n",
255             strerror (errno),gp_LED);
256         return 1;
257     }
258
259     /* Open GPIO for SW1 */
260     fd_SW1 = gpio_open_edge(22,"both"); /* GPIO input */
261     if ( fd_SW1 < 0 ) {
262         printf("%s: Opening GPIO %d for input.\n",
263             strerror(errno),gp_SW1);
264         return 1;
265     }
266
267     context = zmq_ctx_new();
268     assert(context);
269
270     /* Create a ZMQ publishing socket */
271     publisher = zmq_socket(context,ZMQ_PUB);
272     assert(publisher);
273     rc = zmq_bind(publisher,service_sensor_pub);
274     assert(!rc);
275
276     /* Create a console PULL socket */
277     console = zmq_socket(context, ZMQ_PULL);
278     assert(console);
279     rc = zmq_bind(console,service_sensor_pull);
280     assert(rc != -1);
281
282     SW1 = 0;
283     publish_SW1();
284     publish_LED();
285
286     rc = pthread_create(&tid,0,SW1_monitor_thread,0);
287     assert(!rc);
288
289     rc = pthread_create(&tid,0,console_thread,0);
290     assert(!rc);
291
292     /*
293      * In this thread, we "pull" console commands :
294      *
```

```
295      * led:n change state of LED
296      * stop: shutdown the sensor
297      */
298     for (;;) {
299         rc = zmq_recv(console,buf,sizeof buf -1,0);
300         if ( rc > 0 ) {
301             buf[rc] = 0;
302             if ( !strncmp(buf,"led:",4) ) {
303                 /* LED command from console */
304                 buf[rc] = 0;
305                 sscanf(buf,"led:%d",&LED);
306                 gpio_write(fd_LED,LED);
307                 publish_LED();
308             }
309             if ( !strncmp(buf,"stop:",5) ) {
310                 stop = 1;
311                 break;
312             }
313         }
314     }
315
316     mutex_lock();
317     zmq_close(console);
318     console = 0;
319
320     rc = zmq_send(publisher,"off: " 4,0);
321     assert(rc !=-1);
322     sleep(3);
323     zmq_close(publisher);
324     publisher = 0;
325
326     gpio_close(gp_SW1);
327     gpio_close(gp_LED);
328     mutex_unlock();
329
330     return 0;
331 }
332
333 /* End sensor.c */
```

Console Source Code

The console program is an ncurses-based program. It provides the user with a full-screen display without the complexity of programming a GUI program (an exercise left to the interested reader).

The main program initiates curses mode in lines 204 through 207. Prior to that, the ØMQ library is used to subscribe to the sensor's published data in lines 184 through 196. Notice that when subscribing, you *must* indicate what subscriptions you want. Not setting any `ZMQ_SUBSCRIBE` options will result in no messages being received.

Lines 198 to 202 initiate a push connection to the sensor, so commands may be delivered from the console to the sensor. Note that all running consoles will also establish this connection. Any console can control the sensor.

The main console loop from lines 226 through 243 receives the subscribed messages and displays them on the console. That's all it does.

The `command_center` thread is shown in lines 112 to 161. It simply reads a keystroke in line 125 and then dispatches the command in line 132.

The ncurses library is not thread safe, so mutex locking is used to prevent more than one thread from attempting to use that library simultaneously.

```
1   /*************************************************************************
2    * console.c - Raspberry Pi Sensor Console
3    *************************************************************************/
4
5   #include <stdio.h>
6   #include <stdlib.h>
7   #include <unistd.h>
8   #include <string.h>
9   #include <assert.h>
10  #include <pthread.h>
11  #include <curses.h>
12
13  #include <zmq.h>
14
15  #include "mutex.c"
16
17  static char*host_name = "local host"; /* Default host name */
18  static char service_sensor_pub[128];  /* Service name for sensor */
19  static char service_sensor_pull[128]; /* Service name for sensor's cmds
*/
20
21  static void *context = 0;             /* ZMQ context object */
22  static void *subscriber = 0;          /* Subscriber socket */
23  static void *console = 0;             /* Push socket */
24
25  static int SW1 = -1;                  /* Known status of SW1 */
26  static int LED = -1;                  /* Known status of LED */
27
28  /*
29   * Post the status of SW1 to the console screen
30   */
```

```
31  static void
32  post_SW1(void) {
33
34      mutex_lock();        /* Lock for shared curses access */
35      attrset(A_REVERSE);
36      mvprintw(3,4,"SW1:");
37      attrset(A_NORMAL);
38      move (3,9);
39      if ( SW1 < 0 ) {
40          addstr("???");
41      } else {
42          if ( SW1 ) {
43              attrset(A_BOLD);  /* Blink when switch on */
44              addstr("On ");
45          } else {
46              attrset(A_NORMAL);
47              addstr("Off");    /* SW1 is off */
48          }
49      }
50      attrset(A_NORMAL);
51      if ( SW1 >= 0 || LED >= 0 )
52          mvprintw(7,15,"ONLINE ");
53      move(7,12);
54      refresh();
55      mutex_unlock();           /* Done with curses */
56  }
57
58   /*
59    * Post LED status to console screen
60    */
61  static void
62  post_LED(void) {
63
64      mutex_lock();            /* Lock shared curses access */
65      attrset(A_REVERSE);
66      mvprintw(5,4,"LED:");
67      attrset(A_NORMAL);
68      move(5,9);
69
70      if ( LED < 0 ) {
71          addstr("???");
72      } else {
73          if ( LED ) {
74              attrset(A_BOLD);
75              addstr("On ")     /* LED is now on */
76          } else {
```

```
77              attrset(A_NORMAL);
78              addstr("Off");    /* LED is now off */
79          }
80      }
81
82      attrset(A_NORMAL);
83      if ( SW1 >= 0 || LED >= 0 )
84          mvprintw(7,15,"ONLINE ");
85      move(7, 12);
86      refresh();
87      mutex_unlock();            /* Release hold on curses */
88  }
89
90  /*
91   * Post online status to screen
92   */
93  static void
94  post_offline(void) {
95
96      SW1 = -1;
97      LED = -1;
98
99      mutex_lock();              /* Lock for shared curses access */
100     attrset(A_REVERSE|A_BLINK);
101     mvprintw(7,15,"OFFLINE");
102     refresh();
103     mutex_unlock();           /* Done with curses */
104
105     post_LED();
106     post_SW1();
107 }
108
109 /*
110  * Main console thread for command center
111  */
112 static void *
113 command_center(void *ignored) {
114     int rc;
115
116     post_LED();            /* Post unknown LED status */
117     post_SW1();            /* Post unknown SW1 status */
118
119     for (;;) {
120         mutex_lock();      /* Lock curses */
121         move (7,12);       /* Move cursor to command point */
122         refresh();
123         mutex_unlock();    /* Release curses*/
124
```

```
125         rc = getch();      /* Wait for keystroke */
126
127         mutex_lock();      /* Lock curses */
128         mvaddch(7,12,rc);  /* Echo character that was typed */
129         refresh();
130         mutex_unlock();    /* Release curses */
131
132         switch ( rc ) {
133         case '0' :
134             /* Tell sensor to turn off LED */
135             rc = zmq_send(console,"led : 0",5,0);
136             assert(rc !=-1);
137             break;
138         case '1' :
139             /* Tell sensor to turn on LED */
140             rc = zmq_send(console,"led: 1",5,0);
141             assert(rc!=-1);
142             break ;
143         case'x' :
144         case'X' :
145             rc = zmq_send(console,"stop :",5,0);
146             assert(rc!=-1);
147             break;
148         case 'q' :
149         case 'Q' :
150             /* Quit the command console */
151             sleep(1);
152             clear();
153             refresh();
154             endwin();
155             exit(0);
156             break;
157         default :
158             ;
159         }
160     }
161 }
162
163 /*
164  * Main thread : init/receive published SW1/LED status updates
165  *
166  * Specify the IP number or hostname of the sensor on the command
167  * line as argument one : $ ./console myrasp
168  */
169 int
```

```
170 main(int argc,char **argv) {
171     char buf[1024];
172     int rc;
173     pthread_t tid;
174 
175     if ( argc > 1 )
176         host_name = argv[1];
177     sprintf(service_sensor_pub,"tcp://%s:9999",host_name);
178     sprintf(service_sensor_pull,"tcp://%s:9998",host_name);
179 
180     mutex_init();
181     context = zmq_ctx_new();
182     assert(context);
183 
184     subscriber = zmq_socket(context,ZMQ_SUB);
185     assert(subscriber);
186 
187     rc = zmq_connect(subscriber,service_sensor_pub);
188     if (rc == -1) perror("zmq_connect\n");
189     assert(rc!=-1);
190 
191     rc = zmq_setsockopt(subscriber,ZMQ_SUBSCRIBE,"sw1:", 4);
192     assert(rc!=-1);
193     rc = zmq_setsockopt(subscriber,ZMQ_SUBSCRIBE,"led:", 4);
194     assert(rc!=-1);
195     rc = zmq_setsockopt(subscriber,ZMQ_SUBSCRIBE, "off:",4);
196     assert(rc!=-1);
197 
198     console = zmq_socket(context,ZMQ_PUSH);
199     assert(console);
200 
201     rc = zmq_connect(console, service_sensor_pull);
202     assert(!rc);
203 
204     initscr();
205     cbreak();
206     noecho();
207     nonl();
208 
209     clear();
210     box(stdscr,0,0);
211     move(1,2);
212     printw("Receiving sensor at: %s",service_sensor_pub);
213 
214     attrset(A_UNDERLINE);
215     mvaddstr(7,2,"Commands:");
216     attrset(A_NORMAL);
```

```
217     mvaddstr(9,2,"0 - Turn remote LED off.");
218     mvaddstr(10,2,"1 - Turn remote LED on.");
219     mvaddstr(11,2,"X - Shutdown sensor node.");
220     mvaddstr(12,2,"Q - Quit the console.");
221     mvprintw(7,15,"Online ?");
222
223     rc = pthread_create(&tid,0,command_center,0);
224     assert(!rc);
225
226     for(;;) {
227         rc = zmq_recv(subscriber,buf,sizeof buf - 1,0);
228         assert(rc >= 0 && rc < sizeof buf -1);
229         buf[rc] = 0;
230
231         if ( !strncmp(buf,"off:",4) )
232             post_offline();
233
234         if ( !strncmp(buf,"sw1:",4) ) {
235             sscanf(buf,"sw1:%d",&SW1);
236             post_SW1();
237         }
238
239         if ( !strncmp(buf,"led:",4) ) {
240             sscanf(buf,"led:%d",&LED);
241             post_LED();
242         }
243     }
244
245     return 0;
246 }
247
248 /* console.c */
```

```
1  /*********************************************************************
2   * Mutex . c
3   *********************************************************************/
4
5  static pthread_mutex_t mutex;
6
7  static void
8  mutex_init(void) {
9       int rc = pthread_mutex_init(&mutex, 0);
10      assert(!rc);
11 }
12
```

```
13  static void
14  mutex_lock(void) {
15      intrc = pthread_mutex_lock(&mutex);
16      assert(!rc);
17  }
18
19  static void
20  mutex_unlock(void) {
21      int rc = pthread_mutex_unlock(&mutex);
22      assert(!rc);
23  }
24
25  /* End mutex.c */
```

CHAPTER 9

Pulse-Width Modulation

This chapter explores pulse-width modulation (PWM) using the Raspberry Pi. PWM is applied in motor control, light dimming, and servo controls, to name a few examples. To keep the hardware simple and the software small enough to read, we're going to apply PWM to driving an analog meter in this chapter.

While the CPU percent-busy calculation used here is a bit cheesy, it is simple and effective for our demonstration. The meter deflection will indicate how busy your Raspberry Pi's CPU is. We'll demonstrate this using a hardware and software PWM solution.

Introduction to PWM

The GPIO output signal is a digital signal that may be only on or off. You can program it to deliver only 3 V or 0 V. Consequently, there is no means for the software to ask the GPIO to deliver 1 or 2 V. Despite this limitation, an analog meter can be driven from a digital output using PWM.

PWM is a technique that works on the principle of averaging the signal. If the signal is on for 10% of the total cycle, then when the signal is averaged out, the result is an analog 10% of the two digital extremes. If the highest voltage produced by the GPIO output is 3.3 V, a repeating digital signal that is only *on* for 75% of that cycle produces an average voltage that's determined as follows:

$$V_{avg} = 3.3 \times 0.75$$
$$= 2.475V$$

If the GPIO output signal was high only 10% of the time, the averaged result is V_{avg} = 0.33 V. The on time as a percentage of the total cycle time is known as the *duty cycle*.

Obviously, there is an averaging aspect to all of this. If you applied the 10% signal to the probes of an oscilloscope, you'd see a choppy digital-looking signal. The duty cycle may be there, but the averaging effect is not.

The averaging effect is accomplished in several ways. In a lightbulb, the element is heated up by the on pulses but does not cool immediately, so its brightness reflects the averaged current flow. A DC motor does not immediately stop when the current is withdrawn, because the rotational inertia keeps the rotor spinning. A meter's pointer does not immediately move back to zero when the current is removed. All of these physical effects have an averaging effect that can be exploited.

PWM Parameters

PWM involves modulating the width of the pulse. But the pulse's width is one aspect relative to a whole cycle. Defining a PWM signal requires three parameters:

- Frequency (or period) of the cycle
- The time period that the signal is on
- The time period that the signal is off

It is tempting to think that the cycle time is unimportant. But consider a cycle lasting 10 seconds, where the signal is on for 1 second and off for the remaining 9 (10%). Apply that signal to a meter, and the needle will show 100% for 1 second and zero for the remaining time. Clearly the cycle is too long for the meter's movement to average out.

If you produce a software-derived PWM signal, a high-frequency rate will average well on the meter movement. But the amount of CPU effort expended is also needlessly high, wasting computing power. Planning the operating frequency is an important aspect of PWM. Hardware PWM peripherals also have design frequency limits that must be considered.

The remaining two parameters form the *duty* in *duty cycle*, and are often expressed as a fraction:

$$\frac{N}{M}$$

The denominator M = 100 when we talk of percentages. However, M may be any integer that divides the complete cycle into equal units of time. The value N defines the number of units that the PWM device is to be *on*. The remaining M – N step represents the *off* time.

PWM Hardware Peripheral

The Raspberry Pi makes one hardware PWM peripheral available to the user. It is available on GPIO 18 (GEN1), but you must give up one of the audio channels to use it (or both, if you consider that the clock is also reconfigured for PWM clock rates). If your application does not use audio, the peripheral makes a great resource for effortlessly delivering fast and relatively clean pulse waveforms. And all this without having your software even "think" about it. If you don't need to change the duty cycle, you can set up the peripheral and let it run free on its own.

PWM Software

The servo folks would be wringing their hands at the thought of only one PWM signal. Fortunately, the Pi is quite capable of generating more PWM signals if you can accept a little jitter in the signal output and a little CPU overhead (about 6% of the CPU for each thread-driven PWM signal, in nonturbo mode). While separate processes could be used to generate multiple PWM signals, this is best accomplished in one process using threads. The `softpwm` program at the end of this chapter demonstrates this.

Meter Circuit

Figure 9-1 shows the circuit used for this chapter's CPU percent meter. The resistor R1 = 3.3 kΩ when you use a 1 mA meter movement.

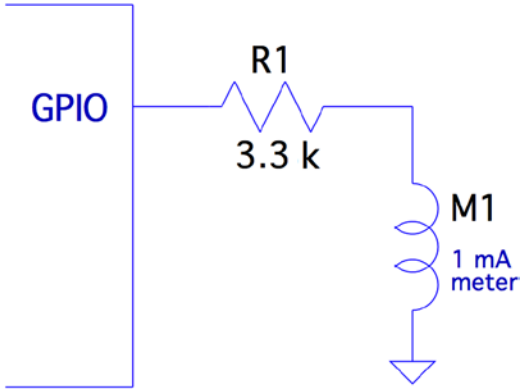


Figure 9-1. *PWM-driven meter*

If you know the current-handling capability for the meter you would like to use, you can calculate the resistance needed as follows:

$$R_1 = \frac{V}{I_m}$$

where:

- V is the voltage (3.3 V) at the GPIO pin.
- I_m is the current for your meter movement.

If your meter is known to use a 100 μA movement, for example, the series-dropping resistor would work out to be the following:

$$R_1 = \frac{3.3}{0.0001}$$
$$= 33K\Omega$$

For all projects in this book, I encourage you to substitute and try parts that you have on hand. You may have a junk-box meter somewhere that you can use. Don't use automotive ammeters, since they will usually have a shunt installed. Almost any voltmeter or meter with a sufficiently sensitive movement can be used. The limit is imposed by the GPIO output pin, which supports up to 8 mA (unless reconfigured).

If you don't know its movement sensitivity, start with high resistances and work down (try lowest currents first). With care, you can sort this out without wrapping the needle around the pin.

pwm Program

The program software `pwm` is listed at the end of this chapter. To facilitate discussion, I'll show excerpts of it here. The hardware example driven by `pwm.c` is the nastier of the two programs presented. This is due to the difficulty of programming the PWM hardware registers and the clock-rate registers.

The main program invokes `pwm_init()`, which gains access to the Pi's peripherals in much the same way that the other examples did in `gpio_init()`. The same `mmap()` techniques are used for access to the PWM and CLK control registers.

Whether operating `pwm` to just set the PWM peripheral or to use the CPU percent-busy function, the PWM frequency must be set by the function `pwm_frequency()`:

```
static int
pwm_frequency(float freq) {
   ...
```

This function stops the clock that is running and computes a new integer divisor. After disabling the clock, a little sleep time is used to allow the clock peripheral to stop. The maximum clock rate appears to be 19.2 MHz. To compute the divisor, the following calculation is used:

$$I_{div} = \frac{19200000}{f}$$

where:

- I_{div} is the computed integer divisor.
- f is the desired PWM frequency.

The range of the resulting I_{div} is checked against the peripheral's limits. The value of I_{div} is then forced to remain in range, but the return value is `-1` or `+1` depending on whether the frequency is under or over the limits.

```
idiv = (long)( clock_rate / (double) freq );
if ( idiv < 1 ) {
    idiv = 1;               /* Lowest divisor */
    rc = -1;
} else if ( idiv >= 0x1000 ) {
    idiv = 0xFFF;           /* Highest divisor */
    rc = +1;
}
```

Once that is calculated, the value of I_{div} is loaded:

```
ugclk[PWMCLK_DIV] = 0x5A000000 | ( idiv << 12 );
```

Finally, the clock source is set to use the oscillator, and the clock is enabled:

```
ugclk[PWMCLK_CNTL] = 0x5A000011;
```

After this, GPIO 18 is configured for ALT function 5, to gain access to the PWM peripheral:

```
INP_GPIO(18);                   /* Set ALT = 0 */
SET_GPIO_ALT(18,5);             /* Or in '5' */
```

The way the `SET_GPIO_ALT()` macro is defined requires that the `INP_GPIO()` macro be used first. The `INP_GPIO()` macro clears the ALT function bits so that `SET_GPIO_ALT()` can *or* in the new bits (the value 5, in this case).

The remaining steps ready the PWM peripheral:

```
pwm_ctl->MODE1 = 0;             /* PWM mode */
pwm_ctl->RPTL1 = 0;
pwm_ctl->SBIT1 = 0;
pwm_ctl->POLA1 = 0;
pwm_ctl->USEF1 = 0;
pwm_ctl->MSEN1 = 0;             /* PWM mode */
pwm_ctl->CLRF1 = 1;
```

Now, at this point, the PWM peripheral is almost ready to go. It needs the ratio $\frac{N}{M}$ and then to be enabled. This is done in the routine `pwm_ratio()`:

```
static void
pwm_ratio(unsigned n,unsigned m) {
   ...
```

This function allows the $\frac{N}{M}$ ratio be changed without having to fully reinitialize the other aspects, including the clock. With our CPU percent-busy function, this ratio will be changing often.

```
pwm_ctl->PWEN1 = 0;             /* Disable */

*pwm_rng1 = m;
*pwm_dat1 = n;
```

After initialization, the PWM peripheral is already disabled. But the first step here disables it, because it may be running when the ratio is being changed. The following pair of statements put the value of M into the PWM register `RNG1`, while N goes into the `DAT1` register.

A few more statements check for errors and reset if necessary (these may not be strictly necessary). Then the following two statements provide a short pause and re-enable the PWM peripheral:

```
usleep(10);             /* Pause  */
pwm_ctl->PWEN1 = 1;     /* Enable */
```

That covers the interesting aspects of the hardware PWM control.

Hardware PWM Set Command

When program `pwm` is provided with command-line arguments, it simply sets up and starts the PWM peripheral. The command takes up to three arguments:

```
$ ./pwm N [M] [ F ]
```

where:

- `N` is the N in the PWM ratio.
- `M` is the M in the PWM ratio.
- `F` is the frequency required.

Once the command is started with these parameters, the PWM peripheral is started and the program exits:

```
$ . /pwm 40 100 1000
PWM set for 40/100, frequency 1000.0
$
```

If you have an oscilloscope available, you can attach probes to GPIO 18 and the ground to see a 40% PWM signal. If you attach the meter circuit of Figure 9-1, it should read near 40% of the full deflection. Figure 9-2 shows my milliampere meter showing nearly 40% (the deflection reading is nearly 0.4). The DMM in the background is measuring the +3.3 V supply voltage, which is showing good voltage regulation.

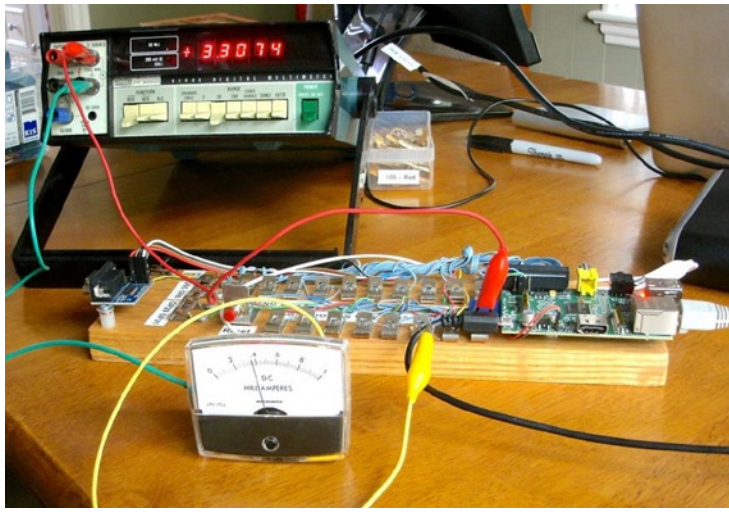


Figure 9-2. *A milliampere meter showing 40% deflection*

To get a more accurate reading, you could put a potentiometer or Trimpot in series with a lower-valued resistor and adjust for full deflection (with GPIO set to high).

Alternatively, you could take a voltage reading of the GPIO output when set to high and calculate the 1% resistor value needed. At the time I took the photo for Figure 9-2, I measured 3.275 V when the GPIO was set high while supplying current to the milliampere meter (through a 3.3 kΩ 10% resistor). Using that for the basis for calculations, you could use a 3.24 kΩ 1% resistor.

Hardware Based CPU Percent-Busy Display

The same `pwm` command can be used as a CPU percent-busy command when started with no command-line arguments:

```
$ ./pwm
CPU Meter Mode:
1.4%
```

The percent of CPU that is busy will be repeatedly shown on the same console line. Simultaneously, the hardware PWM ratio is being changed. This will cause the meter deflection to indicate the current CPU percent-busy reading. The `pwm` command itself requires about 0.6% CPU, so you will never see the meter reach zero.

The CPU percent is determined in a cheesy manner, but it is simple and good enough for this demonstration.

```
for (;;) {
    pipe = popen("ps -eo pcpu|sed 1d","r");
    for ( total=0.0; fgets(buf,sizeof buf,pipe); ) {
        sscanf(buf,"%f",&pct);
        total += pct;
    }
    pclose(pipe);
    printf("\r%.1f%%    ",total);
    fflush(stdout);
    pwm_ratio(total,100);
    usleep(300000);
}
```

In this section of code, we open a piped command to `ps`, with options to report the percent of CPU used by each process. The `sed` command deletes the header line from the `ps` command output.

The `for` loop reads each line, totaling the percent of CPU used. Occasionally, the total exceeds 100% because of timing and other roughness in the calculations.

Once the CPU percent total is known, the function `pwm_ratio()` is called to alter the ratio, thus changing the position of the meter's indicator.

```
1  /************************************************************************
2   * pwm. c - PWM example program
3   ************************************************************************/
4
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <unistd.h>
8  #include <fcntl.h>
9  #include <sys/mman.h>
10 #include <errno . h>
11 #include <string . h>
12
13 #define BCM2835_PWM_CONTROL 0
14 #define BCM2835_PWM_STATUS  1
15 #define BCM2835_PWM0_RANGE  4
16 #define BCM2835_PWM0_DATA   5
17
18 #define BCM2708_PERI_BASE    0x20000000
19 #define BLOCK_SIZE    (4*1024)
20
21 #define GPIO_BASE     (BCM2708_PERI_BASE + 0x200000)
22 #define PWM_BASE      (BCM2708_PERI_BASE + 0x20C000)
23 #define CLK_BASE      (BCM2708_PERI_BASE + 0x101000)
24
```

```
25 #define PWMCLK_CNTL     40
26 #define PWMCLK_DIV      41
27
28 static volatile unsigned *ugpio    = 0;
29 static volatile unsigned *ugpwm    = 0;
30 static volatile unsigned *ugclk    = 0;
31
32 statics struct S_PWM_CTL {
33         unsigned     PWEN1 : 1;
34         unsigned     MODE1 : 1;
35         unsigned     RPTL1 : 1;
36         unsigned     SBIT1 : 1;
37         unsigned     POLA1 : 1;
38         unsigned     USEF1 : 1;
39         unsigned     CLRF1 : 1;
40         unsigned     MSEN1 : 1;
41 } volatile *pwm_ctl = 0;
42
43 static struct S_PWM_STA {
44         unsigned     FULL1 : 1;
45         unsigned     EMPT1 : 1;
46         unsigned     WERR1 : 1;
47         unsigned     RERR1 : 1;
48         unsigned     GAPO1 : 1;
49         unsigned     GAPO2 : 1;
50         unsigned     GAPO3 : 1;
51         unsigned     GAPO4 : 1;
52         unsigned     BERR : 1;
53         unsigned     STA1 : 1;
54 } volatile *pwm_sta = 0;
55
56 static volatile unsigned *pwm_rng1 = 0;
57 static volatile unsigned *pwm_dat1 = 0;
58
59 #define INP_GPIO(g) *( ugpio+((g )/10)) &= ~(7<<(((g)%10)*3))
60 #define SET_GPIO_ALT(g,a) \
61     *(ugpio+(((g)/10))) |= (((a)<=3?(a)+4:((a)==4?3:2))<<(((g)%10)*3))
62
63 /*
64  * Establish the PWM frequency :
65  */
66 static int
67 pwm_frequency(float freq) {
68      const double clock_rate = 19200000.0;
69      long idiv;
70      int rc = 0;
71
```

```
72      /*
73       * Kill the clock :
74       */
75      ugclk[PWMCLK_CNTL] = 0x5A000020;   /* Kill clock */
76      pwm_ctl->PWEN1 = 0;                /* Disable PWM */
77      usleep(10);
78
79      /*
80       * Compute and set the divisor:
81       */
82      idiv = (long)( clock_rate / (double)freq );
83      if ( idiv < 1 ) {
84          idiv = 1;                      /* Lowest divisor */
85          rc = -1;
86      } else if ( idiv >= 0x1000 ) {
87          idiv = 0xFFF;                  /* Highest divisor */
88          rc = +1;
89      }
90
91      ugclk[PWMCLK_DIV] = 0x5A000000 | ( idiv << 12 );
92
93      /*
94       * Set source to oscillator and enable clock :
95       */
96      ugclk[PWMCLK_CNTL] = 0x5A000011;
97
98      /*
99       *  GPIO 18 is PWM, when set to Alt Func 5 :
100      */
101     INP_GPIO(18);                 /* Set ALT = 0 */
102     SET_GPIO_ALT(18,5);           /* Or in '5 ' */
103
104     pwm_ctl->MODE1 = 0;           /* PWM mode */
105     pwm_ctl->RPTL1 = 0;
106     pwm_ctl->SBIT1 = 0;
107     pwm_ctl->POLA1 = 0;
108     pwm_ctl->USEF1 = 0;
109     pwm_ctl->MSEN1 = 0;           /* PWM mode */
110     pwm_ctl->CLRF1 = 1;
111     return rc ;
112 }
113
114 /*
115  * Initialize GPIO/PWM/CLK Access
116  */
```

```
117 static void
118 pwm_init() {
119     int fd;
120     char *map;
121
122     fd = open("/dev/mem",O_RDWR|O_SYNC); /* Needs root access */
123     if ( fd < 0 ) {
124         perror("Opening /dev/mem");
125         exit(1);
126     }
127
128     map = (char *)mmap(
129         NULL,                   /* Any address */
130         BLOCK_SIZE,             /* # of bytes */
131         PROT_READ|PROT_WRITE,
132         MAP_SHARED,             /* Shared */
133         fd,                     /* /dev/mem */
134         PWM_BASE                /* Offset to GPIO */
135     );
136
137     if ( (long)map == -1L ) {
138         perror("mmap(/dev/mem)");
139         exit(1);
140     }
141
142     /* Access to PWM */
143     ugpwm = (volatile unsigned *)map;
144     pwm_ctl = (struct S_PWM_CTL *) &ugpwm[BCM2835_PWM_CONTROL];
145     pwm_sta = (struct S_PWM_STA *) &ugpwm[BCM2835_PWM_STATUS];
146     pwm_rng1 = &ugpwm[BCM2835_PWM0_RANGE];
147     pwm_dat1 = &ugpwm[BCM2835_PWM0_DATA];
148
149     map = (char *)mmap(
150         NULL,                   /* Any address */
151         BLOCK_SIZE,             /* # of bytes */
152         PROT_READ|PROT_WRITE,
153         MAP_SHARED,             /* Shared */
154         fd,                     /* /dev/mem */
155         CLK_BASE                /* Offset to GPIO */
156     );
157
158     if ( (long )map == -1L ) {
159         perror("mmap(/dev/mem)");
160         exit(1);
161     }
162
```

```
163     /* Access to CLK */
164     ugclk = (volatile unsigned *)map;
165
166     map = (char *)mmap(
167         NULL,                   /* Any address */
168         BLOCK_SIZE,             /* # of bytes */
169         PROT_READ|PROT_WRITE,
170         MAP_SHARED,             /* Shared */
171         fd,                     /* /dev/mem */
172         GPIO_BASE               /* Offset to GPIO */
173     );
174
175     if ( (long)map == -1L ) {
176         perror("mmap(/dev/mem)");
177         exit(1);
178           }
179
180     /* Access to GPIO */
181     ugpio = (volatile unsigned *)map;
182
183     close(fd);
184 }
185
186 /*
187  * Set PWM to ratio N/M, and enable it :
188  */
189 static void
190 pwm_ratio(unsigned n,unsigned m) {
191
192     pwm_ctl->PWEN1 = 0;           /* Disable */
193
194     *pwm_rng1 = m;
195     *pwm_dat1 = n;
196
197     if ( !pwm_sta->STA1 ) {
198         if ( pwm_sta->RERR1 )
199             pwm_sta->RERR1 = 1;
200             if ( pwm_sta->WERR1 )
201                 pwm_sta->WERR1 = 1;
202                 if ( pwm_sta->BERR )
203                     pwm_sta->BERR = 1;
204     }
205
206     usleep(10);                   /* Pause */
207     pwm_ctl->PWEN1 = 1; /* Enable */
208 }
209
```

```
/*
 * Main program :
 */
int
main(int argc,char **argv) {
   FILE *pipe;
   char buf[64];
   float pct, total;
   int n, m = 100;
   float f = 1000.0;

   if ( argc > 1 )
       n = atoi(argv[1]);
   if ( argc > 2 )
       m = atoi(argv[2]);
   if ( argc > 3 )
       f = atof(argv[3]);
   if ( argc > 1 ) {
       if ( n > m || n < 1 || m < 1 || f < 586.0 || f > 19200000.0 ) {
           fprintf(stderr,"Value error: N=%d , M=%d , F=%.1f \n",n,m,f);
           return 1;
       }
   }

   pwm_init();

   if ( argc > 1 ) {
       /* Start PWM */
       pwm_frequency(f);
       pwm_ratio(n,m);
       printf("PWM set for %d/%d, frequency %.1f \n",n,m,f);
   } else {
       /* Run CPU Meter */
       puts("CPU Meter Mode : ");
       for (;;) {
           pipe = popen("ps -eo pcpu | sed 1d","r");
           for ( total =0.0; fgets(buf,sizeof buf,pipe); ) {
               sscanf(buf,"%f",&pct);
               total += pct;
           }
           pclose(pipe);
           printf("\r%.1f%%",total);
           fflush(stdout);
           pwm_ratio(total,100);
           usleep(300000);
        }
   }

```

```
258     return 0 ;
259  }
260
261  /* End pwm.c */
```

Software PWM Program

The program `softpwm` works from the command line very similarly to the hardware PWM program `pwm`. One difference, however, is that the software PWM requires that the program continue to run to maintain the signal. The hardware program can exit and leave the PWM peripheral running.

The design of the program differs in that a thread is used for each PWM signal being maintained. With a little bit of work, the `softpwm.c` module could be formed into a PWM software library. The data type `PWM` is created with the same idea as the stdio `FILE` type:

```
typedef struct {
        int         gpio;     /* GPIO output pin */
        double      freq;     /* Operating frequency */
        unsigned    n;        /* The N in N/M */
        unsigned    m;        /* The M in N/M */
        pthread_t   thread;   /* Controlling thread */
        volatile char         chgf;   /* True when N/M changed */
        volatile char         stopf;  /* True when thread to stop */
} PWM;
```

The comments identify the purpose of the structure object members. The last two members are flags that are used to control the thread.

The function `pwm_open()`, establishes the GPIO line and the PWM frequency, and returns the `PWM` control block. Note that no thread is started just yet:

```
PWM *
pwm_open(int gpio,double freq) {
    PWM *pwm = malloc(sizeof *pwm);

    pwm->gpio = gpio;
    pwm->freq = freq;
    pwm->thread = 0;
    pwm->n = pwm->m = 0;
    pwm->chgf  = 0;
    pwm->stopf = 0;

    INP_GPIO(pwm->gpio);
    OUT_GPIO(pwm->gpio);
    return pwm;
}
```

The reverse of open is the pwm_close() call. Here the thread is instructed to stop (stopf=1), and if there is a thread running, a join with the thread is performed. The join causes the caller to block until the thread itself has ended. Then the PWM structure is freed, completing the close operation.

```
void
pwm_close(PWM *pwm) {
        pwm->stopf = 1;
        if ( pwm->thread )
            pthread_join(pwm->thread,0);
        pwm->thread = 0;
        free(pwm);
}
```

The software PWM signal starts when the ratio is established by a call to pwm_ratio():

```
void
pwm_ratio(PWM *pwm,unsigned n,unsigned m) {
        pwm->n = n <= m ? n : m;
        pwm->m = m;
        if ( !pwm->thread )
            pthread_create(&pwm->thread,0,soft_pwm,pwm);
        else
            pwm->chgf = 1;
}
```

This call establishes the values for N and M. Then if no thread is currently running, one is created with the thread's ID saved in the PWM structure. If the thread is already running, we simply point out to the thread that the $\frac{N}{M}$ values have changed so that it can adapt to it at the cycle's end.

The function soft_pwm() is the software PWM engine itself. The pthread_create() call passes the PWM structure into the call as a void *arg, which is used by the function to access the PWM structure. The entire procedure is an outer and inner loop. The outer loop runs as long as the stopf flag is zero. Then the floating-point period variables fperiod, percent, and ontime are calculated.

From there, the inner loop continues until either the chgf or stopf flag variables become nonzero. If the stopf becomes nonzero, both loops are exited. Once the thread function exits, the thread ends. The thread resources are reclaimed in the pwm_close() call when it joins.

```
static void *
soft_pw(void *arg) {
PWM *pwm = (PWM *)arg;
double fperiod, percent, ontime;
```

```
while ( !pwm->stopf ) {
    fperiod = 1.0 / pwm->freq;
    percent = (double) pwm->n / (double)pwm->m;
    ontime = fperiod * percent;
    for ( pwm->chgf=0; !pwm->chgf && !pwm->stopf; ) {
        gpio_write(pwm->gpio,1);
        float_wait(ontime);

        gpio_write(pwm->gpio,0);
        float_wait(fperiod-ontime);
    }
}

return 0;
}
```

One final note about the `PWM` structure members concerns the use of the C keyword `volatile`. Both `chgf` and `stopf` structure members are declared `volatile` so that the compiler will generate code that will access these values every time they are required. Otherwise, compiler optimization may cause the generated code to reuse values held in registers. This would cause the thread to not notice a change in these values, which are critical.

```
volatile char           chgf;           /* True when N/M changed */
volatile char           stopf;          /* True when thread to stop */
```

How Many PWMs?

The design of the preceding PWM software routines is such that you can open as many `PWM` instances as you require. The limiting factors are as follows:

- Number of free GPIO output lines
- CPU resource utilization

On a nonturbo mode Raspberry Pi, the code shown seems to require approximately 6% CPU for each soft PWM created. (The CPU utilization rises with frequency, however.) This leaves you with a certain latitude in the number of PWM signals you generate.

Running the Software PWM Command

To generate a fixed software PWM signal on GPIO 22 (GEN3), run the command like this:

```
$ ./ softpwm 60 100 2000
PWM set for 60 / 100 , frequency 2000.0 (for 60 seconds )
```

Obviously, the PWM signal is present for only as long as the `softpwm` program continues to run.

Software Based CPU Percent-Busy Display

Without command-line arguments, the `softpwm` command defaults to being a CPU percent-busy driver. It drives pin GPIO 22 (GEN3), which when attached to a meter as shown in Figure 9-1, will display CPU utilization.

```
$  ./softpwm
CPU  Meter  Mode :
6.5%
```

Press ^C after the fascination of the CPU meter wears off.

```
1  /*************************************************************************
2   * softpwm.c Software PWM example program
3   *************************************************************************/
4
5  #include <stdio.h>
6  #include <stdlib.h>
7  #include <unistd.h>
8  #include <fcntl.h>
9  #include <sys/mman.h>
10 #include <errno.h>
11 #include <string.h>
12 #include <math.h>
13 #include <pthread.h>
14
15 #include "gpio_io.c"
16
17 typedef struct {
18          int             gpio;   /* GPIO out put pin */
19          double          freq;   /* Operating frequency */
20          unsigned        n;      /* The N in N/M */
21          unsigned        m;      /* The M in N/M */
22          pthread_t       thread; /* Controlling thread */
23          volatile char   chgf;   /* True when N/M changed */
24          volatile char   stopf;  /* True when thread to stop */
25 } PWM;
26
27 /*
28  * Timed wait from a float
29  */
30 static void
31 float_wait(double seconds) {
32      fd_set mt ;
33      struct timeval time out;
34      int rc;
35
```

```
36      FD_ZERO(&mt);
37      timeout.tv_sec = floor(seconds);
38      timeout.tv_usec = floor((seconds - floor(seconds)) * 1000000);
39
40      do  {
41          rc = select(0,&mt,&mt,&mt,&timeout);
42      } while ( rc < 0 && time out.tv_sec && timeout.tv_usec );
43 }
44
45 /*
46  * Thread performing the PWM function :
47  */
48 static void *
49 soft_pwm(void *arg) {
50      PWM *pwm = (PWM *)arg;
51      double fperiod, percent, ontime;
52
53      while ( !pwm >stopf ) {
54          fperiod = 1.0 / pwm->freq;
55          percent = (double ) pwm->n / (double) pwm->m;
56          ontime = fperiod * percent ;
57          for ( pwm->chgf =0; !pwm->chgf && !pwm->stopf; ) {
58              gpio_write (pwm->gpio,1);
59              float_wait(ontime);
60
61              gpio_write(pwm->gpio,0);
62              float_wait(fperiod ontime);
63          }
64      }
65
66      return 0;
67 }
68
69 /*
70  * Open a soft PWM object:
71  */
72 PWM *
73 pwm_open(int gpio,double freq) {
74      PWM *pwm = malloc(sizeof *pwm);
75
76      pwm->gpio = gpio;
77      pwm->freq = freq;
78      pwm->thread = 0;
79      pwm->n = pwm->m = 0;
80      pwm->chgf = 0;
81      pwm->stopf = 0;
82
```

```
83      INP_GPIO(pwm->gpio);
84      OUT_GPIO(pwm->gpio);
85      return pwm;
86 }
87
88 /*
89  * Close the soft PWM object:
90  */
91 void
92 pwm_close(PWM *pwm) {
93      pwm->stopf = 1;
94      if ( pwm->thread )
95          pthread_join(pwm->thread,0);
96          pwm->thread = 0;
97          free(pwm);
98 }
99
100 /*
101  * Set PWM Ratio:
102  */
103 void
104 pwm_ratio(PWM *pwm,unsigned n,unsigned m) {
105     pwm->n = n <= m ? n : m;
106     pwm->m = m;
107     if ( !pwm->thread )
108         pthread_create(&pwm->thread,0,soft_pwm,pwm);
109     else pwm->chgf = 1;
110 }
111
112 /*
113  * Main program:
114  */
115 int
116 main(int argc,char **argv) {
117     int n, m = 100;
118     float f = 1000.0;
119     PWM *pwm;
120     FILE *pipe;
121     char buf[64];
122     float pct, total;
123
124     if ( argc > 1 )
125         n = atoi(argv[1]);
126     if ( argc > 2 )
127         m = atoi(argv[2]);
```

```
128     if ( argc > 3 )
129         f = atof(argv[3]);
130     if ( argc > 1 ) {
131         if ( n > m || n < 1 || m < 1 || f < 586.0 || f > 19200000.0 ) {
132             fprintf(stderr,"Value error: N=%d, M=%d, F=%.1f \n",n,m,f);
133             return 1;
134         }
135     }
136
137     gpio_init();
138
139     if ( argc > 1 ) {
140         /* Run PWM mode */
141         pwm = pwm_open(22,1000.0);       /* GPIO 22 (GEN3) */
142         pwm_ratio(pwm,n,m) ;                / * n% , Start it */
143
144         printf("PWM set for %d/%d, frequency %.1f "
             "(for 60 seconds)\n",n,m,f);
145
146         sleep(60);
147
148         printf("Closing PWM..\n");
149         pwm_close(pwm);
150     } else {
151         /* Run CPU Meter */
152         puts("CPU Meter Mode: ");
153
154         pwm = pwm_open(22,500.0);  /* GPIO 22 (GEN3) */
155         pwm_ratio(pwm,1,100);      / * Start at 1%  */
156
157         for (;;) {
158             pipe = popen("ps -eo pcpu | sed 1d","r");
159             for ( total = 0.0 ; fgets(buf,sizeof buf,pipe); ) {
160                 sscanf(buf,"%f ",&pct);
161                 total += pct;
162             }
163             pclose(pipe);
164
165             pwm_ratio(pwm,total,100);
166
167             printf("\r%.1f%%        ",total);
168             fflush (stdout) ;
169
```

```
            usleep(300000);
        }
    }

    return 0;
}

/ * End softpwm.c */
```

APPENDIX A

Glossary

AC
Alternating current

Amps
Amperes

ATAG
ARM tags, though now used by boot loaders for other architectures

AVC
Advanced Video Coding (MPEG-4)

AVR
Wikipedia states that "it is commonly accepted that AVR stands for Alf (Egil Bogen) and Vegard (Wollan)'s RISC processor."

BCD
Binary-coded decimal

Brick
To accidently render a device unusable by making changes to it

CEA
Consumer Electronics Association

cond
Condition variable

CPU
Central processing unit

CRC
Cyclic redundancy check, a type of hash for error detection

CVT
Coordinated Video Timings standard (replaces GTF)

daemon
A Unix process that services requests in the background

DC
Direct current

DCD
RS-232 data carrier detect

DCE
RS-232 data communications equipment

Distro
A specific distribution of Linux software

DLNA
Digital Living Network Alliance, whose purpose is to enable sharing of digital media between multimedia devices

DMM
Digital multimeter

DMT
Display Monitor Timing standard

DPI
Display Pixel Interface (a parallel display interface)

DPVL
Digital Packet Video Link

DSI
Display Serial Interface

DSR
RS-232 data set ready

DTE
RS-232 data terminal equipment

DTR
RS-232 data terminal ready

ECC
Error-correcting code

EDID
Extended display identification data

EEPROM
Electrically erasable programmable read-only memory

EMMC
External mass media controller

Flash
Similar to EEPROM, except that large blocks must be entirely rewritten in an update operation

FFS
Flash file system

FIFO
First in, first out

FSP
Flash storage processor

FTL
Flash translation layer

FUSE
Filesystem in Userspace (File system in USErspace)

GNU
GNU is not Unix

GPIO
General-purpose input/output

GPU
Graphics processing unit

GTF
Generalized Timing Formula

H.264
MPEG-4 Advanced Video Coding (AVC)

H-Bridge
An electronic circuit configuration that allows voltage to be reversed across the load

HDMI
High-Definition Multimedia Interface

HID
Human interface device

I2C
Two-wire interface invented by Philips

IC
Integrated circuit

IDE
Integrated development environment

IR
Infrared

ISP
Image Sensor Pipeline

JFFS2
Journalling Flash File System 2

LCD
Liquid-crystal display

LED
Light-emitting diode

mA
Milliamperes, a measure of current flow

MCU
Microcontroller unit

MMC
MultiMedia Card

MISO
Master in, slave out

MOSI
Master out, slave in

MTD
Memory technology device

mutex
Mutually exclusive

NTSC
National Television System Committee (analog TV signal standard)

PAL
Phase Alternating Line (analog TV signal standard)

PC
Personal computer

PCB
Printed circuit board

PLL
Phase-locked loop

PoE
Power over Ethernet (supplying power over an Ethernet cable)

POSIX
Portable Operating System Interface (for Unix)

pthreads
POSIX threads

PWM
Pulse-width modulation

Pxe
Preboot execution environment, usually referencing booting by network

RAM
Random-access memory

RI
RS-232 ring indicator

RISC
Reduced instruction set computer

RH
Relative humidity

ROM
Read-only memory

RPi
Raspberry Pi

RS-232
Recommended standard 232 (serial communications)

RTC
Real-time clock

SBC
Single-board computer

SD
Secure Digital Association memory card

SDIO
SD card input/output interface

SDRAM
Synchronous dynamic random-access memory

SoC
System on a chip

SMPS
Switched-mode power supply

SPI
Serial Peripheral Interface (bus)

Stick parity
Mark or space parity, where the bit is constant

TWI
Two-wire interface

UART
Universal asynchronous receiver/transmitter

USB
Universal Serial Bus

V3D
Video for 3D

VAC
Volts AC

VESA
Video Electronics Standards Association

VFS
Virtual file system

VNC
Virtual Network Computing

V_{SB}
ATX standby voltage

YAFFS
Yet Another Flash File System

APPENDIX B

Power Standards

The following table references the standard ATX power supply voltages, regulation (tolerance), and voltage ranges.[15]

The values listed here for the +5 V and +3.3 V supplies are referenced in Chapter 2 of *Raspberry Pi Hardware Reference* (Apress, 2014) as a basis for acceptable power supply ranges. When the BroadCom power specifications become known, they should be used instead.

Supply (Volts)	Tolerance		Minimum	Maximum	Ripple (Peak to Peak)
+5 V	±5%	± 0.25 V	+4.75 V	+5.25 V	50 mV
-5 V	±10%	±0.50 V	–4.50 V	–5.50 V	50 mV
+12 V	±5%	±0.60 V	+11.40 V	+12.60 V	120 mV
-12 V	±10%	±1.2 V	–10.8 V	–13.2 V	120 mV
+3.3 V	±5%	±0.165 V	+3.135 V	+3.465 V	50 mV
+5 V_{SB}	±5%	±0.25 V	+4.75 V	+5.25 V	50 mV

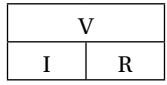
APPENDIX C

Electronics Reference

The experienced electronic hobbyist or engineer will already know these formulas and units well. This reference material is provided as a convenience for the student or beginning hobbiest.

Ohm's Law

Using the following triangle, cover the unknown property to determine the formula needed. For example, if current (I) is unknown, cover the I, and the formula $\frac{V}{R}$ remains.



Power

Power can be computed from these formulas:

$$P = I \times V$$
$$P = I^2 \times R$$
$$P = \frac{V^2}{R}$$

Units

The following chart summarizes the main metric prefixes used in electronics.

	Name	Prefix	Factor
Multiples	mega	M	10^{6}
	kilo	k	10^{3}
	milli	m	10^{-3}
	micro	μ	10^{-6}
Fraction	nano	n	10^{-9}
	pico	p	10^{-12}

APPENDIX D

ARM Compile Options

For ARM platform compiles, the following site makes compiler option recommendations: http://elinux.org/RPi_Software.

The site states the following:

- The gcc compiler flags that produce the most optimal code for the Raspberry Pi are as follows:
  - `-Ofast -mfpu=vfp -mfloat -abi=hard -march=armv6zk -mtune=arm1176jzf-s`
- For some programs, `-Ofast` may produce compile errors. In these cases, `-O3` or `-O2` should be used instead.
- `-mcpu=arm1176jzf-s` can be used in place of `-march=armv6zk -mtune=arm1176jzf-s`.

APPENDIX E

Mac OS X Tips

This appendix offers a couple of tips pertaining to Raspberry Pi SD card operations under Mac OS X. Figure E-1 shows an SD card reader and a built-in card slot being used.

Figure E-1. *USB card reader and MacBook Pro SD slot*

The one problem that gets in the way of working with Raspberry Pi images on SD cards is the automounting of partitions when the card is inserted. This, of course, can be disabled, but the desktop user will find this inconvenient. So you need a way to turn it off, when needed.

Another problem that occurs is determining the OS X device name for the card. When copying disk images, you need to be certain of the device name! Both of these problems are solved using the Mac `diskutil` command (found in `/usr/sbin/diskutil`).

Caution Copying to the wrong device on your Mac can destroy all of your files. Be afraid!

Before inserting your SD cards, do the following:

```
$ diskutil list
/dev/disk0
#:                TYPE NAME                    SIZE       IDENTIFIER
0:      GUID_partition_scheme                 *750.2 GB   disk0
1:      EFI                                    209.7 MB   disk0s1
2:      Apple_HFS Macintosh HD                 749.3 GB   disk0s2
3:      Apple_Boot Recovery HD                 650.0 MB   disk0s3
```

Check the mounts:

```
$ mount
/dev/disk0s2 on / (hfs, NFS exported, local, journaled)
...
```

Insert the SD card:

```
$ diskutil list
/dev/disk0
#:                TYPE NAME                    SIZE       IDENTIFIER
0:      GUID_partition_scheme                 *750.2 GB   disk0
1:      EFI                                    209.7 MB   disk0s1
2:      Apple_HFS Macintosh HD                 749.3 GB   disk0s2
3:      Apple_Boot Recovery HD                 650.0 MB   disk0s3
/dev/disk1
#:                TYPE NAME                    SIZE       IDENTIFIER
0:      FDisk_partition_scheme                *3.9 GB     disk1
1:      Windows_FAT_32                         58.7 MB    disk1s1
2:      Linux                                  3.8 GB     disk1s2
```

Unmount any automounted partitions for `disk1`:

```
$ diskutil unmountDisk /dev/disk1
Unmount of all volumes on disk1 was successful
$
```

Likewise, insert the destination SD card and use `diskutil` to get its device name (mine was `/dev/disk2`). Unmount all file systems that may have been automounted for it (`diskutil unmountDisk`).

At this point, you can perform a file system image copy:

```
$ dd if=/dev/disk1 of=/dev/disk2 bs=1024k
3724+0 records in 3724+0 records out
3904897024 bytes transferred in 2571.524357 secs (1518515 bytes/sec)
$
```

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This book is dedicated to the memory of my father, Charles Wallace Gay, who passed away this year. He didn't remember it when we discussed it last, but he was responsible for sparking my interest in electronics at an early age. He had brought home from his used-car business two D cells, a piece of blue automotive wire, and a flashlight bulb. After showing me how to hold them together to complete the circuit and light the bulb, I was hooked for life.

I am also indebted to my family for their patience. Particularly my wife Jacqueline, who tries to understand why I need to do the things I do with wires, solder, and parts arriving in the mail. I am glad for even grudging acceptance because I'm not sure that I could give up the thrill of moving electrons in some new way. Sometimes hobby electronics projects have no real justification beyond "because we can!"

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About the Author

Warren W. Gay started out in electronics at an early age, dragging discarded TVs and radios home from public school. In high school he developed a fascination for programming the IBM 1130 computer, which resulted in a career plan change to software development. After attending Ryerson Polytechnical Institute, he has enjoyed a software developer career for more than 30 years, programming mainly in C/C++. Warren has been programming Linux since 1994 as an open source contributor and professionally on various Unix platforms since 1987.

Before attending Ryerson, Warren built an Intel 8008 system from scratch before there were CP/M systems and before computers got personal. In later years, Warren earned an advanced amateur radio license (call sign VE3WWG) and worked the amateur radio satellites. A high point of his ham radio hobby was making digital contact with the Mir space station (U2MIR) in 1991.

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About the Technical Reviewer

Stewart Watkiss graduated from the University of Hull, United Kingdom, with a master's degree in electronic engineering. He has been a fan of Linux since first installing it on a home computer during the late 1990s. While working as a Linux system administrator, he was awarded Advanced Linux Certification (LPIC 2) in 2006 and created the Penguin Tutor web site to help others learning Linux and working toward Linux certification (www.penguintutor.com).

Stewart is a big fan of the Raspberry Pi. He owns several Raspberry Pi computers that he uses to help to protect his home (Internet filter), provide entertainment (XBMC), and teach programming to his two children. He also volunteers as a STEM ambassador, going into local schools to help support teachers and teach programming to teachers and children

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