Experimenting with Raspberry Pi

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

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Shelve in Computer Hardware/General
User level: Intermediate–Advanced

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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 Gerbboard 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.
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.

![DHT11 sensor](image)

*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).

![DHT11 circuit](image)

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.

![DHT11 data bit](image)

**Figure 1-4.** *DHT11 data bit*

Each data bit starts with a transition to low, lasting for 50 $\mu$s. The final transition to low after the last bit also lasts for 50 $\mu$s. 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 $\mu$s 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.

![DHT11 data format](image)

**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 &mu;s
- 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 waveform 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 &mu;s. 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 &mu;s, 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

\[
\frac{330}{50} = 6.6 \text{reads / &mu}s
\]

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

\[
\frac{130}{50} = 2.6 \text{reads / &mu}s
\]
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 \( C_{\text{low}} \)).
2. Compute an adjustment bias \( B \) based on \( B = \frac{C_{\text{low}}}{D} \), where \( D \) is some fixed divisor.
3. Compute a new count \( K = B + C_{\text{high}} \), where \( C_{\text{high}} \) is the number of times the line was read as high.
4. If the count value \( K > C_{\text{low}} \), 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.
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.

Table 1-1. Bias Test Results

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

```c
/* dht11.c: Direct GPIO access reading DHT11 humidity and temp sensor. */
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <unistd.h>
#include <errno.h>
#include <setjmp.h>
#include <sys/mman.h>
#include <signal.h>

#include "gpio_io.c" /* GPIO routines */
#include "timed_wait.c" /* timed_wait() */

static const int gpio_dht11 = 22; /* GPIO pin */
static jmp_buf timeout_exit; /* longjmp on timeout */
static int is_signaled = 0; /* Exit program if signaled */

/* Signal handler to quit the program: */
static void
sigint_handler(int signo) {
    is_signaled = 1; /* Signal to exit program */
}

/* Read the GPIO line status: */
static inline unsigned
gread(void) {
    return gpio_read(gpio_dht11);
}
```
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 */
static unsigned rbyte(void) {
    unsigned x, u = 0;
    for ( x=0; x<8; ++x )
        u = (u << 1) | rbit();
    return u;
}

/*
  * Read 32 bits of data + 8 bit checksum from the
  * DHT sensor. Returns relative humidity and
  * temperature in Celsius when successful. The
  * function returns zero if there was a checksum
  * error.
  */
static int rsensor(int *relhumidity, int *celsius) {
    unsigned char u[5], cs = 0, x;
    for ( x=0; x<5; ++x ) {
        u[x] = rbyte();
        if ( x < 4 )        /* Only checksum data..*/
            cs += u[x];   /* Checksum */
    }
    if ( (cs & 0xFF) == u[4] ) {
        *relhumidity = (int)u [0];
        *celsius = (int)u [2];
        return 1;
    }
    return 0;
}

/*
  * Main program:
  */
int main(int argc, char **argv) {
    int relhumidity = 0, celsius = 0;
    int errors = 0, timeouts = 0, readings = 0;
    unsigned wait;
    signal(SIGINT,sigint_handler); /* Trap on SIGINT */
    gpio_init();                    /* Initialize GPIO access */
    gpio_config(gpio_dht11, Input); /* Set GPIO pin as Input */
for (;;)
{
  if ( setjmp(timeout_exit) ) { /* Timeouts go here */
    if ( is_signaled ) { /* SIGINT? */
      break; /* Yes, then exit loop */
    }
  }
  if ( rsensor(&relhumidity,&celsius) )
    printf("RH %d%% Temp %d C Reading %d\n", relhumidity, celsius,++readings);
  else fprintf(stderr, " (Error # %d)\n", ++errors);
}

gpio_config(gpio_dht11,Input); /* Set pin to input mode */

puts("\nProgram exited due to SIGINT: \n");
printf("Last Read: RH %d%% Temp %d C, %d errors, "%d timeouts, %d readings \n",
  relhumidity, celsius, errors, timeouts, readings);
return 0;

/* End dht11.c */
static void timed_wait(long sec, long usec, long early_usec)
{
    FD_ZERO(&mt);
    struct timeval timeout;
    int rc;
    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.
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:

\[ I_{VDD} = \frac{P}{V_{DD}} \]

\[ = \frac{0.7}{3.3} \]

\[ = 212 mA \]
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 $V_{DD} = +3.3\,\text{V}$, the input low voltage is calculated as follows:

$$V_{IL_{\text{max}}} = 0.2 \times V_{DD}$$
$$= 0.2 \times 3.3$$
$$= 0.66\,\text{V}$$

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:

$$V_{IH_{\text{min}}} = 0.8 \times V_{DD}$$
$$= 0.8 \times 3.3$$
$$= 2.64\,\text{V}$$

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 $V_{IL_{\text{max}}}$ and $V_{IH_{\text{min}}}$ 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:

$$V_{OL_{\text{max}}} = 0.6\,\text{V}$$
$$V_{OH_{\text{min}}} = V_{DD} - 0.7\,\text{V}$$
$$= 3.3 - 0.7$$
$$= 2.7\,\text{V}$$
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 \( \text{RESET} \) must remain active (low) for a minimum of 1 \( \mu \text{s} \). The device resets and places outputs into the high-impedance mode within a maximum of 1 \( \mu \text{s} \).

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 \( \text{RESET} \) and \( \text{INT} \) 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](image)

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 \( \text{RESET} \) and \( \text{INT} \) are optional connections. The \( \text{RESET} \) line can be eliminated if you never plan to force a hardware reset of the slaves (tie to \( V_{\text{DD}} \) through a 10 K resistor). Usually the power-on reset is sufficient. The \( \text{INT} \) 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 \( \text{INT} \) 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 \( \text{INT} \) signal, with a corresponding increase in signal lines.

Each MCP23017 chip has two interrupt lines, named \( \text{INT}_A \) and \( \text{INT}_B \). 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 \( \text{INT} \) line is required.

On the Raspberry Pi end, the GPIO pin used for the \( \text{RESET} \) 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 \( \text{INT} \) 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:

\[
R_{\text{pullup}} = \frac{+3.3V}{2mA} = 1650\Omega
\]

A 2.2 k\( \Omega \) 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 0000000000000000
10: 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).
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 2-1. MCP23017 Register Addresses

<table>
<thead>
<tr>
<th>Register</th>
<th>A</th>
<th>B</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IODIRx</td>
<td>0x00</td>
<td>0x01</td>
<td>I/O direction</td>
</tr>
<tr>
<td>IPOLx</td>
<td>0x02</td>
<td>0x03</td>
<td>Input polarity</td>
</tr>
<tr>
<td>GPINTENx</td>
<td>0x04</td>
<td>0x05</td>
<td>Interrupt on change control</td>
</tr>
<tr>
<td>DEFVALx</td>
<td>0x06</td>
<td>0x07</td>
<td>Default comparison value</td>
</tr>
<tr>
<td>INTCONx</td>
<td>0x08</td>
<td>0x09</td>
<td>Interrupt control</td>
</tr>
<tr>
<td>IOCONx</td>
<td>0x0A</td>
<td>0x0B</td>
<td>Configuration</td>
</tr>
<tr>
<td>GPPUx</td>
<td>0x0C</td>
<td>0x0D</td>
<td>Pull-up configuration</td>
</tr>
<tr>
<td>INTFx</td>
<td>0x0E</td>
<td>0x0F</td>
<td>Interrupt flags</td>
</tr>
<tr>
<td>INTCAPx</td>
<td>0x10</td>
<td>0x11</td>
<td>Interrupt captured value</td>
</tr>
<tr>
<td>GPIOx</td>
<td>0x12</td>
<td>0x13</td>
<td>General-purpose I/O</td>
</tr>
<tr>
<td>OLATx</td>
<td>0x14</td>
<td>0x15</td>
<td>Output latch</td>
</tr>
</tbody>
</table>
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 \( \text{INTA} \) equivalent to \( \text{INTB} \). 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 \( \text{INTA} \) pin as an open-drain pin. This allows multiple MCP23017 devices to share the same interrupt line. Use a pull-up resistor on the \( \text{INT} \) 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.

### Table 2-2. \texttt{IOCON} Register

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

<table>
<thead>
<tr>
<th>GPIO</th>
<th>Address</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0x0A</td>
<td>These access a shared register</td>
</tr>
<tr>
<td>B</td>
<td>0x0B</td>
<td></td>
</tr>
</tbody>
</table>

These access a shared register
OLATx Register

GPIO pins are all configured as inputs after a power-on reset (or use of \texttt{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 \texttt{0x00} to both OLATA and OLATB.

<table>
<thead>
<tr>
<th>OLATx Register</th>
<th>GPIO</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit 7 6 5 4 3 2 1</td>
<td>0 A</td>
<td>0x14</td>
</tr>
<tr>
<td>R Y Y Y Y Y Y Y B</td>
<td></td>
<td>0x15</td>
</tr>
<tr>
<td>W Y Y Y Y Y Y Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reset</td>
<td></td>
<td>0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

**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 KΩ 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.

<table>
<thead>
<tr>
<th>GPPUx Register</th>
<th>GPIO</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit 7 6 5 4 3 2 1</td>
<td>0 A</td>
<td>0x0C</td>
</tr>
<tr>
<td>R Y Y Y Y Y Y Y B</td>
<td></td>
<td>0x0D</td>
</tr>
<tr>
<td>W Y Y Y Y Y Y Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reset</td>
<td></td>
<td>0 0 0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>DEFVALx Register</th>
<th>GPIO Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>A 0x06</td>
</tr>
<tr>
<td>R</td>
<td>B 0x07</td>
</tr>
<tr>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Reset</td>
<td></td>
</tr>
</tbody>
</table>

DEFVALx Bit Value

<table>
<thead>
<tr>
<th>Bit Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Interrupt when input not 0</td>
</tr>
<tr>
<td>1</td>
<td>Interrupt when input not 1</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>INTCONx Register</th>
<th>GPIO Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>A 0x08</td>
</tr>
<tr>
<td>R</td>
<td>B 0x09</td>
</tr>
<tr>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Reset</td>
<td></td>
</tr>
</tbody>
</table>

INTCONx Bit Value

<table>
<thead>
<tr>
<th>Bit Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Input compared against its previous value</td>
</tr>
<tr>
<td>1</td>
<td>Input compared against DEFCONx bit value</td>
</tr>
</tbody>
</table>
**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.

<table>
<thead>
<tr>
<th>Bit</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
<th>GPIO Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>B 0x03</td>
</tr>
<tr>
<td>W</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Reset</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>Bit</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
<th>GPIO Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>B 0x01</td>
</tr>
<tr>
<td>W</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Reset</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>GPINTENx Register</th>
<th>GPIO</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>R</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>W</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Reset</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>INTFx Register</th>
<th>GPIO</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>R</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>W</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Reset</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**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 \( \text{INT A} \) is linked to \( \text{INT B} \), both INTCAPA and INTCAPB must be read to clear the interrupt (or read the GPIOx registers).

<table>
<thead>
<tr>
<th>INTCAPx Register</th>
<th>GPIO</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>W</td>
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<td>N</td>
<td>N</td>
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<tr>
<td>Reset</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**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 \( \text{INT A} \) is linked to \( \text{INT B} \), 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.

<table>
<thead>
<tr>
<th>GPIOx Register</th>
<th>GPIO</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
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<td>3</td>
<td>2</td>
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<tr>
<td></td>
<td>1</td>
<td>0</td>
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<tr>
<td>R</td>
<td>Y</td>
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<td>Reset</td>
<td>X</td>
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<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

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### 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:

```c
#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 GPPU 6
#define INTF 7
#define INTCAP 8
#define GPIO 9
#define OLAT 10
#define MCP_REGISTER(r,g) (((r) <<1)|(g)) /* For I2C routines */

static unsigned gpio_addr = 0x20;  /* MCP23017 I2C Address */
static const int gpio_inta = 17;   /* GPIO pin for INTA connection */
static int is_signaled = 0;        /* Exit program if signaled */

#include "sysgpio.c"

/* Signal handler to quit the program : */
static void sigint_handler(int signo) {
    is_signaled = 1;        /* Signal to exit program */
}

/* Write to MCP23017 A or B register set: */
static int mcp23017_write(int reg,int AB,int value) {
    unsigned reg_addr = MCP_REGISTER(reg,AB);
    int rc;
    rc = i2c_write8(gpio_addr,reg_addr,value);
    return rc;
}

/* Write value to both MCP23017 register sets : */
static void mcp23017_write_both(int reg,int value) {
    mcp23017_write(reg,GPIOA,value); /* Set A */
    mcp23017_write(reg,GPIOB,value); /* Set B */
}

/* Read the MCP23017 input pins (excluding outputs, 16-bits) : */
static unsigned mcp23017_inputs(void) {
    unsigned reg_addr = MCP_REGISTER(GPIO,GPIOA);

    return i2c_read16(gpio_addr,reg_addr) & 0xF0F0;
}

/* Write 16 bits to outputs */
static void mcp23017_outputs(int value) {
    unsigned reg_addr = MCP_REGISTER(GPIO,GPIOA);

    i2c_write16 (gpio_addr,reg_addr,value & 0x0F0F);
}

/* Read MCP23017 captured values (16–bits): */
static unsigned mcp23017_captured(void) {
    unsigned reg_addr = MCP_REGISTER(INTCAP,GPIOA);

    return i2c_read16(gpio_addr,reg_addr) & 0xF0F0;
}

/* Read interrupting input flags (16–bits) : */
static unsigned mcp23017_interrupts(void) {
    unsigned reg_addr = MCP_REGISTER(INTF,GPIOA);

    return i2c_read16(gpio_addr,reg_addr) & 0xF0F0;
}

/* Configure the MCP23017 GPIO Extender : */
static void mcp23017_init(void) {
    int v, int_flags;

    mcp23017_write_both(IOCON,0b01000100); /* MIRROR=1,ODR=1 */
    mcp23017_write_both(GPINTEN,0x00); /* No interrupts enabled */
mcp23017_write_both(DEFVAL,0x00);    /* Clear default value */
mcp23017_write_both(OLAT,0x00);      /* OLATx=0 */
mcp23017_write_both(GPPU,0b11110000); /* 4–7 are pull up */
mcp23017_write_both(IPOL,0b00000000); /* No inverted polarity */
                                      /* 4–7 inputs, 0–3 outputs */
mcp23017_write_both(IODIR,0b11110000);
146        mcp23017_write_both(INTCON,0b00000000); /* Cmp to previous */
mcp23017_write_both(_GPIOINTEN,0b11110000); /* Int on changes */

/* Loop until all interrupts are cleared:
   
   do    {
        int flags = mcp23017_interrupts();
        if ( int_flags != 0 ) {
            v = mcp23017_captured();
            printf(" Got change %04X values %04X\n",int_flags,v);
        }
        } while ( int_flags  != 0x0000 && !is_signaled );

/* Copy input bit settings to outputs :
 */
static void
post_outputs(void) {
    int inbits = mcp23017_inputs(); /* Read inputs */
    int outbits = inbits >> 4;      /* Shift to output bits */
    mcp23017_outputs(outbits);      /* Copy inputs to outputs */
    printf(" Outputs: %04X\n",outbits);
}

/*Main program : 
 */
int
main(int argc,char **argv) {
    int int_flags, v;
    int fd;

    signal(SIGINT,sigint_handler); /* Trap on SIGINT */
    i2c_init(node);                /* Initialize for I2C */
    mcp23017_init();              /* Configure MCP23017 @ 20 */
    fd = gpio_open_edge(gpio_inta); /* Configure INTA pin */

puts("Monitoring for MCP23017 input changes :\n");
post_outputs(); /* Copy inputs to outputs */
do {
    gpio_poll(fd); /* Pause until an interrupt */
    int_flags = mcp23017_interrupts();
    if ( int_flags ) {
        v = mcp23017_captured();
        printf(" Input change: flags %04X values %04X\n",
                int_flags,v);
        post_outputs();
    }
} while ( !is_signaled ); /* Quit if ^C' d */
fputc('\n', stdout);

i2c_close(); /* Close I2C driver */
close(fd); /* Close gpio17/value */
gpio_close(gpio_inta); /* Unexport gpio17 */
return 0;

/* 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).

```c
/* 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;
```

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Chapter 2

■ MCP23017 GPIO extender

```c
    buf[0] = (unsigned char)reg;
    buf[1] = (unsigned char)(( value >> 8 ) & 0xFF);
    buf[2] = (unsigned char)(value & 0xFF);

    iomsgs[0].addr = (unsigned)addr;
    iomsgs[0].flags = 0; /* Write */
    iomsgs[0].buf = buf;
    iomsgs[0].len = 3;

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

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

```c
    int
    i2c_read8(int addr,int reg) {
        struct i2c_rdwr_ioctl_data msgset;
        struct i2c_msg iomsgs[2];
        unsigned char buf[1], rbuf[1];
        int rc;

        buf[0] = (unsigned char)reg;

        iomsgs[0].addr = iomsgs[1].addr = (unsigned)addr;
        iomsgs[0].flags = 0; /* Write */
        iomsgs[0].buf = buf;
        iomsgs[0].len = 1;

        iomsgs[1].flags = I2C_M_RD; /* Read */
        iomsgs[1].buf = rbuf;
        iomsgs[1].len = 1;

        msgset.msgs = iomsgs;
        msgset.nmsgs = 2;

        rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
        return rc < 0 ? -1 : ((int)(rbuf[0]) & 0x0FF);
```
/* Read 16- bits of data from peripheral : */

int i2c_read16(int addr, int reg) {
    struct i2c_rdwr_ioctl_data msgset;
    struct i2c_msg iomsgs[2];
    unsigned char buf[1], rbuf[2];
    int rc;

    buf[0] = (unsigned char)reg;
    iomsgs[0].addr = iomsgs[1].addr = (unsigned)addr;
    iomsgs[0].flags = 0; /* Write */
    iomsgs[0].buf = buf;
    iomsgs[0].len = 1;

    iomsgs[1].flags = I2C_M_RD;
    iomsgs[1].buf = rbuf; /* Read */
    iomsgs[1].len = 2;

    msgset.msgs = iomsgs;
    msgset.nmsgs = 2;

    if ( (rc = ioctl(i2c_fd, I2C_RDWR, &msgset)) < 0 )
        return -1;
    return (rbuf[0] << 8) | rbuf[1];
}

/* Open I2C bus and check capabilities : */
static void i2c_init(const char *node) {
    int rc;

    i2c_fd = open(node, O_RDWR); /* Open driver /dev/i2s-1 */
    if ( i2c_fd < 0 ) {
        perror("Opening /dev/i2s-1");
        puts("Check that the i2c dev & i2c-bcm2708 kernel modules "
             "are loaded.");
        abort();
    }

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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 INTA 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. */

/**
   * Open /sys/class/gpio%d/value for edge detection :
   */

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" 
    }
    int slen;
    strncpy(buf,"/sys/class/gpio/",bufsz);
    bufsiz -= (slen = strlen(buf));
    snprintf(buf+slen,bufsz,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);
}

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/* 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);

/* Edge: /sys/class/gpio%d/edge */
gpio_setpath(pin, gp_edge, buf, sizeof buf);
f = fopen(buf, "w");
assert(f);
fprintf(f, "falling\n");
fclose(f);

/* Value: /sys/class/gpio%d/value */
gpio_setpath(pin, gp_value, buf, sizeof buf);
fd = open(buf, O_RDWR);
return fd;
}

/* Close (unexport) GPIO pin: */
static void
gpio_close(int pin) {
    char buf[128];
    FILE *f;

    /* Unexport: /sys/class/gpio/unexport */
gpio_setpath(pin, gp_unexport, buf, size of buf);
f = fopen(buf, "w");
assert(f);
fprintf(f, "%d\n", pin);
fclose(f);
}

/* This routine will block until the open GPIO pin has changed
* value. This pin should be connected to the MCP23017 /INTA
* pin. */
static int
gpio_poll(int fd) {
    unsigned char buf[32];
    struct pollfd polls;
    int rc;
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 ^C received */
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

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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 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 1  1 1 1 0 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 INTA 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 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 I2C 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 $3 \times 90 = 270$ 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:

$$T = t_{\text{addr}} + t_{\text{register}} + t_{\text{INTFA}} + t_{\text{INTFB}} + t_{\text{register}} + t_{\text{GPIOA}} + t_{\text{GPIOB}}$$
$$= 7 \times 90$$
$$= 0.630 \text{ms}$$

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.
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>
<thead>
<tr>
<th>User-Interface Features</th>
<th>Bits</th>
<th>Data</th>
<th>Hardware/Chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>C Button</td>
<td>1</td>
<td>Boolean</td>
<td>Membrane switch</td>
</tr>
<tr>
<td>Z button</td>
<td>1</td>
<td>Boolean</td>
<td>Membrane switch</td>
</tr>
<tr>
<td>X-Y joystick</td>
<td>8x2</td>
<td>Integers</td>
<td>30 kΩ potentiometers</td>
</tr>
<tr>
<td>X, Y, and Z accelerometer</td>
<td>10x3</td>
<td>Integers</td>
<td>ST LIS3L02 series</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Table 3-2. Nunchuck Cable Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCL</td>
</tr>
<tr>
<td>+3.3 V</td>
</tr>
</tbody>
</table>

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.*
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.

![Nunchuk with wire ends](image)

**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:

```bash
$ 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

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. 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:

<table>
<thead>
<tr>
<th>Write</th>
<th>Pause</th>
<th>Write</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>55</td>
<td>FB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Byte</th>
<th>Bits</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Analog stick x axis value</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Analog stick y axis value</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>X acceleration bits 9:2</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Y acceleration bits 9:2</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Z acceleration bits 9:2</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>Z button pressed (active low)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>C button pressed (active low)</td>
</tr>
<tr>
<td>3:2</td>
<td></td>
<td>X acceleration bits 1:0</td>
</tr>
<tr>
<td>5:4</td>
<td></td>
<td>Y acceleration bits 1:0</td>
</tr>
<tr>
<td>7:6</td>
<td></td>
<td>Z acceleration bits 1:0</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Write</th>
<th>Pause</th>
<th>Read 6 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>-</td>
<td>01 02 03 04 05 06</td>
</tr>
</tbody>
</table>

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”
- “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:

```c
#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:

```bash
$ 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:

```c
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:

```c
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

<table>
<thead>
<tr>
<th>Macro</th>
<th>From Header File input.h[3]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV_SYN</td>
<td></td>
<td>Event synchronization/separation</td>
</tr>
<tr>
<td>EV_KEY</td>
<td></td>
<td>Key/button state changes</td>
</tr>
<tr>
<td>EV_REL</td>
<td></td>
<td>Relative axis mouse-like changes</td>
</tr>
<tr>
<td>EV_ABS</td>
<td></td>
<td>Absolute axis mouse-like changes</td>
</tr>
<tr>
<td>EV_MSC</td>
<td></td>
<td>Miscellaneous events</td>
</tr>
<tr>
<td>EV_SW</td>
<td></td>
<td>Binary (switch) state changes</td>
</tr>
<tr>
<td>EV_LED</td>
<td></td>
<td>LED on/off changes</td>
</tr>
<tr>
<td>EV_SND</td>
<td></td>
<td>Output to sound devices</td>
</tr>
<tr>
<td>EV_REP</td>
<td></td>
<td>For use with autorepeating devices</td>
</tr>
<tr>
<td>EV_FF</td>
<td></td>
<td>Force feedback commands to input device</td>
</tr>
<tr>
<td>EV_PWR</td>
<td></td>
<td>Power button/switch event</td>
</tr>
<tr>
<td>EV_FF_STATUS</td>
<td></td>
<td>Receive force feedback device status</td>
</tr>
</tbody>
</table>

**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:

```c
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.
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>
<thead>
<tr>
<th>Macro</th>
<th>Synonym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTN_LEFT</td>
<td>BTN_MOUSE</td>
<td>Left mouse button</td>
</tr>
<tr>
<td>BTN_RIGHT</td>
<td></td>
<td>Right mouse button</td>
</tr>
<tr>
<td>BTN_MIDDLE</td>
<td></td>
<td>Middle mouse button</td>
</tr>
<tr>
<td>BTN_SIDE</td>
<td></td>
<td>Side mouse button</td>
</tr>
</tbody>
</table>

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

```c
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:

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

<table>
<thead>
<tr>
<th>Macro</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS_X</td>
<td>Move X to this absolute X coordinate</td>
</tr>
<tr>
<td>ABS_Y</td>
<td>Move Y to this absolute Y coordinate</td>
</tr>
</tbody>
</table>

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

```c
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:

```c
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:

```c
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 absmmin[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.

```c
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:

```c
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-r--T 1 root input 13, 64 Dec 31 1969 event0
crw-rw-r--T 1 root input 13, 65 Dec 31 1969 event1
crw-rw-r--T 1 root input 13, 66 Dec 31 1969 event2
crw-rw-r--T 1 root input 13, 67 Feb 23 13:40 event3
crw-rw-r--T 1 root input 13, 63 Dec 31 1969 mice
crw-rw-r--T 1 root input 13, 32 Dec 31 1969 mouse0
crw-rw-r--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:

```c
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:

```c
... 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`:

```c
static void
uinput_movement(int fd,int x,int y) {
    struct input_event ev;
    int rc;
... memset(&ev,0,sizeof(ev));
... ev.type = EV_KEY;
... ev.code = REL_X;        /* Mouse movement */
... ev.value = 1;
... rc = write(fd,&ev,sizeof(ev));
    assert(rc == sizeof(ev));
... ev.value = 0;
... rc = write(fd,&ev,sizeof(ev));
    assert(rc == sizeof(ev));
```
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:

```c
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`:

```ini
# 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.
CHAPTER 3  ■  NUNCHUK-MOUSE

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/xorg.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:

```bash
#!/bin/bash
# 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 us the
# /dev/input/event%d pathname, for the Nunchuk.

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

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-dev[0-9]*)"
      echo $event
      exit 0  # Found it
    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:

```bash
$ 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.

```c
#include <stdio.h>
#include <math.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 <linux/i2c-dev.h>
#include <linux/input.h>
#include <linux/uinput.h>
#include "timed_wait.c"

static int is_signaled = 0;      /* Exit program if signaled */
static int i2c_fd = -1;          /* Open /dev/i2c-1 device */
static int f_debug = 0;          /* True to print debug messages */

typedef struct {
    unsigned char stick_x;   /* Joystick X */
    unsigned char stick_y;   /* Joystick Y */
    unsigned accel_x;        /* Accel X */
    unsigned accel_y;        /* Accel Y */
    unsigned accel_z;        /* Accel Z */
    unsigned z_button:1;     /* Z button */
    unsigned c_button:1;     /* C button */
    unsigned char raw[6];    /* Raw received data */
} nunchuk_t;

/*
 * Open I2C bus and check capabilities:
 */
static void
i2c_init(const char *node) {
```
unsigned long i2c_funcs = 0;    /* Support flags */
int rc;

i2c_fd = open(node,0_RDWR);    /* Open driver/dev/i2s-1 */
if (i2c_fd < 0 ) {
    perror("Opening/dev/i2s-1");
    puts("Check that the i2c-dev & i2c-bcm2708 kernel modules" 
         "are loaded.");
    abort();
}
/*
 * Make sure the driver supports plain I2C I/O:
 */
rc = ioctl(i2c_fd,I2C_FUNCS,&i2c_funcs);
assert(rc >= 0);
assert(i2c_funcs & I2C_FUNC_I2C);

/*
 * Configure the nunchuk for no encryption:
 */
static void
nunchuk_init(void) {
    static char init_msg1[] = {0xF0, 0x55};
    static char init_msg2[] = {0xFB, 0x00};
    struct i2c_rdwr_ioctl_data msgset;
    struct i2c_msg iomsgs[1];
    int rc;

    iomsgs[0].addr = 0x52;     /* Address of Nunchuk */
    iomsgs[0].flags = 0;       /* Write */
    iomsgs[0].buf = init_msg1; /* Nunchuk 2 byte sequence */
    iomsgs[0].len = 2;         /* 2 bytes */

    msgset.msks = iomsgs;
    msgset.nmsgs = 1;

    rc = ioctl(i2c_fd,I2C_RDWR,&msgset);
    assert(rc == 1);
    timed_wait(0,200,0);        /* Nunchuk needs time */
    iomsgs[0].addr = 0x52;     /* Address of Nunchuk */
    iomsgs[0].flags = 0;       /* Write */
    iomsgs[0].buf = init_msg2; /* Nunchuk 2 byte sequence */
    iomsgs[0].len = 2;         /* 2 bytes */
Chapter 3  Nunchuk-Mouse

```c
89         msgset.msgs = iomgs;
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 iomgs[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         iomgs[0].addr = 0x52;  /* Nunchuk address */
113         iomgs[0].flags = 0;  /* Write */
114         iomgs[0].buf = zero;  /* Sending buf */
115         iomgs[0].len = 1;  /* 1 byte */
116
117         msgset.msgs = iomgs;
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         iomgs[0].addr = 0x52;  /* Nunchuk address */
130         iomgs[0].flags = I2C_M_RD;  /* Read */
131         iomgs[0].buf = (char *)data->raw;  /* Receive raw bytes here */
132         iomgs[0].len = 6;  /* 6 bytes */
133
134         msgset.msgs = iomgs;
135         msgset.nmsgs = 1;
136
68
```
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
dump_data(nunchuk_t *data) {
163     int x;
164
165     printf("Raw nunchuk data : ");
166     for (x = 0; x < 6; ++x )
167         printf("[\02X],", data->raw[x]);
168     putchar(\n");
169
170     printf(".stick_x = \04X (%4u)\n", data->stick_x, data->stick_x);
171     printf(".stick_y = \04X (%4u)\n", data->stick_y, data->stick_y);
172     printf(".accel_x = \04X (%4u)\n", data->accel_x, data->accel_x);
173     printf(".accel_y = \04X (%4u)\n", data->accel_y, data->accel_y);
174     printf(".accel_z = \04X (%4u)\n", data->accel_z, data->accel_z);
175     printf(".z_button= %d\n", data->z_button);
176     printf(".c_button= %d\n", data->c_button);
177 }
178
179 /*
180 * Close the I2C driver : 
181 */
static void
i2c_close(void) {
    close(i2c_fd);
    i2c_fd = -1;
}

∗
∗ Open a uinput node :
∗ /
static int
uinput_open(void) {
    int fd;
    struct uinput_user_dev uinp;
    int rc;

    fd = open("/dev/uinput",O_WRONLY|O_NONBLOCK);
    if ( fd < 0 ) {
        perror("Opening/dev/uinput");
        exit(1);
    }

    rc = ioctl(fd,UI_SET_EVBIT,EV_KEY);
    assert(!rc);
    rc = ioctl(fd,UI_SET_EVBIT,EV_REL);
    assert(!rc);

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

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

    ioctl(fd,UI_SET_KEYBIT,BTN_MOUSE);
    ioctl(fd,UI_SET_KEYBIT,BTN_TOUCH);
    ioctl(fd,UI_SET_KEYBIT,BTN_MOUSE);
    ioctl(fd,UI_SET_KEYBIT,BTN_LEFT);
    ioctl(fd,UI_SET_KEYBIT,BTN_MIDDLE);
    ioctl(fd,UI_SET_KEYBIT,BTN_RIGHT);

    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;
rc = write(fd,&uinp,sizeof(uinp));
assert(rc == sizeof(uinp));
rc = ioctl(fd,UI_DEV_CREATE);
assert(!rc);
return fd;
}

/*
 * Post keystroke down and keystroke up events:
 * (unused here but available for your own experiments)
 */

static void
uinput_postkey(int fd,unsigned key) {
        struct input_event ev;
        int rc;

        memset(&ev,0,sizeof(ev));
        ev.type = EV_KEY;
        ev.code = key;
        ev.value = 1;            /* Key down */
        rc = write(fd,&ev,sizeof(ev));
        assert(rc == sizeof(ev));

        ev.value = 0;            /* Key up */
        rc = write(fd,&ev,sizeof(ev));
        assert(rc == sizeof(ev));
}

/*
 * Post a synchronization point:
 */

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));
}

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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     /* Button down or up events:
291      */
292     for ( x=0; x < 3; ++x )  {
293         ev.type = EV_KEY;
294         ev.value = up_down;  /* Button Up or down */
295         if ( buttons & (1 << x) ) { /* Button 0, 1 or 2 */
296             ev.code = codes[x];
297             write(fd,&ev,sizeof(ev));
298         }
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  * Synthesize a button click :
327  *  up_down  1=up,  0=down
328  * buttons  1=Left, 2=Middle, 4=Right
329 */
330 static void
331 uinput_click(int fd,int up_down,int buttons) {
332     static unsigned codes[] = {BTN_LEFT, BTN_MIDDLE, BTN_RIGHT};
333     struct input_event ev;
334     int x;
335
336     memset(&ev,0,sizeof(ev));
337
338     /* Button down or up events:
339      */
340     for ( x=0; x < 3; ++x )  {
341         ev.type = EV_KEY;
342         ev.value = up_down;  /* Button Up or down */
343         if ( buttons & (1 << x) ) { /* Button 0, 1 or 2 */
344             ev.code = codes[x];
345             write(fd,&ev,sizeof(ev));
346         }
347     }
348 }
349 }
350
351 /*
352  * Synthesize relative mouse movement:
353 */
354 static void
355 uinput_movement(int fd,int x,int y) {
356     struct input_event ev;
357     int rc;
358
359     memset(&ev,0,sizeof(ev));
360     ev.type = EV_REL;
361     ev.code = REL_X;
362     ev.value = x;
363
364     rc = write(fd,&ev,sizeof(ev));
365     assert(rc == sizeof(ev));
366
367     ev.code = REL_Y;
368     ev.value = y;
369     rc = write(fd,&ev,sizeof(ev));
370     assert(rc == sizeof(ev));
371 }
372
72
/*
 * Close uinput device:
 */
static void
uinput_close(int fd) {
    int rc;

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

/* Signal handler to quit the program: */
static void
sigint_handler(int signo) {
    is_signaled = 1; /* Signal to exit program */
}

/* Curve the adjustment:
 */
static int
curve(int relxy) {
    int ax = abs(relxy); /* abs (relxy) */
    int sgn = relxy < 0 ? -1 : 1; /* sign (relxy) */
    int mv = 1; /* Smallest step */

    if ( ax > 100 )
        mv = 10; /* Take large steps */
    else if ( ax > 65 )
        mv = 7;
    else if ( ax > 35 )
        mv = 5;
    else if ( ax > 15 )
        mv = 2; /* 2nd smallest step */
    return mv * sgn;
}

/* Main program:

```c
int main(int argc, char **argv) {
    int fd, need_sync, init = 3;
    int rel_x = 0, rel_y = 0;
    nunchuk_t data0, data, last;

    if ( argc > 1 && !strcmp(argv[1], "-d") )
        f_debug = 1;     /* Enable debug messages */

    (void)uinput_postkey;   /* Suppress compiler warning about unused */

    i2c_init("/dev/i2c-1");     /* Open I2C controller */
    nunchuk_init();         /* Turn off encryption */
    signal(SIGINT, sigint_handler); /* Trap on SIGINT */
    fd = uinput_open();     /* Open /dev/uinput */

    while ( !is_signaled ) {
        if ( nunchuk_read(&data) < 0 )
            continue;

        if ( f_debug )
            dump_data(&data); /* Dump nunchuk data */

        if ( init > 0 && !data0.stick_x && !data0.stick_y ) {
            data0 = data; /* Save initial values */
            last = data;
            --init;
            continue;
        }

        need_sync = 0;
        if ( abs(data.stick_x - data0.stick_x) > 2
             || abs(data.stick_y - data0.stick_y) > 2 ) {
            rel_x = curve(data.stick_x - data0.stick_x);
            rel_y = curve(data.stick_y - data0.stick_y);
            if ( rel_x || rel_y ) {
                uinput_movement(fd, rel_x, -rel_y);
                need_sync = 1;
            }
        }

        if ( last.z_button != data.z_button ) {
            uinput_click(fd, data.z_button, 1);
            need_sync = 1;
        }
    }
}
```

if ( last.c_button != data.c_button ) {
    uinput_click(fd, data.c_button, 4);
    need_sync = 1;
}

if ( need_sync )
    uinput_syn(fd);
last = data;

putchar(\n');

uinput_close(fd);
i2c_close();
return 0;
}

/* 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.

![DS1307 Pinout](image)

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](image)

**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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logic 0 Output ($I_{OL} = 5 \text{ mA}$)</td>
<td>$V_{OL}$</td>
<td>0.4</td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>( V_{CC} )</td>
<td>4.5</td>
<td>5.0</td>
<td>5.5</td>
<td>Volts</td>
</tr>
<tr>
<td>Battery voltage</td>
<td>( V_{BAT} )</td>
<td>2.0</td>
<td>3.5</td>
<td></td>
<td>Volts</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-fail voltage</td>
<td>( V_{PF} )</td>
<td>( 1.26 \times V_{BAT} )</td>
<td>( 1.25 \times V_{BAT} )</td>
<td>( 1.284 \times V_{BAT} )</td>
<td>Volts</td>
</tr>
</tbody>
</table>

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?

<table>
<thead>
<tr>
<th>Signal</th>
<th>Raspberry Pi</th>
<th>DS1307</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{IL}$</td>
<td>$\leq 0.8 \text{ volts}$</td>
<td>$\leq 0.8 \text{ volts}$</td>
</tr>
<tr>
<td>$V_{IH}$</td>
<td>$\geq 1.3 \text{ volts}$</td>
<td>$\geq 2.2 \text{ volts}$</td>
</tr>
</tbody>
</table>

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 kΩ. Reversing the DMM leads should read the same (proving only resistance). Performing the same test with the SCL input, I also read 3.3 kΩ.

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 kΩ 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.
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 kΩ 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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCL clock frequency</td>
<td>$f_{SCL}$</td>
<td>0</td>
<td>100</td>
<td>kHz</td>
<td></td>
</tr>
</tbody>
</table>

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.
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

<table>
<thead>
<tr>
<th>Bit</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>0 Clock running</td>
</tr>
<tr>
<td></td>
<td>1 Clock (osc) halt</td>
</tr>
<tr>
<td>24hr</td>
<td>0 24-hour format</td>
</tr>
<tr>
<td>12hr</td>
<td>1 12-hour format</td>
</tr>
<tr>
<td>OUT</td>
<td>0 SQW/OUT = Low</td>
</tr>
<tr>
<td></td>
<td>1 SQW/OUT = High</td>
</tr>
<tr>
<td>SQWE</td>
<td>0 SQW/OUT is OUT</td>
</tr>
<tr>
<td></td>
<td>1 SQW/OUT is SQW</td>
</tr>
<tr>
<td>RS1</td>
<td>0</td>
</tr>
<tr>
<td>RS0</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RS1</th>
<th>RS0</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1 Hz</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>4.096 kHz</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>8.192 kHz</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>32.768 kHz</td>
</tr>
</tbody>
</table>

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.

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.
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 multmessage 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:

<table>
<thead>
<tr>
<th>GPIO</th>
<th>Line</th>
<th>GPIO</th>
<th>Line</th>
<th>P1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SDA0</td>
<td>2</td>
<td>SDA1</td>
<td>P1-03</td>
</tr>
<tr>
<td>1</td>
<td>SCL0</td>
<td>3</td>
<td>SCL1</td>
<td>P1-05</td>
</tr>
</tbody>
</table>

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[CCYY][.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.

---

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.

```c
typedef struct {
    /* Register Address 0x00 : Seconds */
    unsigned char secs_1s : 4; /* Ones digit : seconds */
    unsigned char secs_10s : 3; /* Tens digit : seconds */
    unsigned char ch : 1; /* CH bit */
    /* Register Address 0x01 : Minutes */
    unsigned char mins_1s : 4; /* Ones digit : minutes */
    unsigned char mins_10s : 3; /* Tens digit : minutes */
    unsigned char mbz_1 : 1; /* Zero bit */
    /* Register Address 0x02 : Hours */
    unsigned char hour_1s : 4; /* Ones digit : hours */
    unsigned char hour_10s : 2; /* Tens digit : hours (24 hr mode) */
    unsigned char mode_1224 : 1; /* Mode bit : 12/24 hour format */
    /* Register Address 0x03 : Day of Month */
    unsigned char wkday : 3; /* Day of week (1-7) */
    unsigned char mbz_2 : 5; /* Zero bits */
    /* Register Address 0x04 : Day of Month */
    unsigned char day_1s : 4; /* Ones digit : day of month (1-31) */
```

89
unsigned char day_10s : 2; /* Tens digit : day of month */
unsigned char mbz_3 : 2; /* Zero bits */
/* Register Address 0x05 : Month */
unsigned char month_1s : 4; /* Ones digit : month (1-12) */
unsigned char month_10s : 1; /* Tens digit : month */
/* Register Address 0x06 : Year */
unsigned char year_1s : 4; /* Ones digit : year (00-99) */
unsigned char year_10s : 4; /* Tens digit : year */
/* Register Address 0x07 : Control */
unsigned char rs0 : 1; /* RS0 */
unsigned char rs1 : 1; /* RS1 */
unsigned char mbz_5 : 2; /* Zeros */
unsigned char sqwe : 1; /* SQWE */
unsigned char mbz_6 : 2;
unsigned char outbit : 1; /* OUT */
} ds1307_rtc_regs;

1 /* End ds1307.h */

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

/* Open I2C bus and check cap abilities:
*/
static void
i2c_init(const char *node) {
    int rc;
    i2c_fd = open(node,O_RDWR); /* Open driver /dev/i2s-1 */
    if ( i2c_fd < 0 ) {
        perror("Opening /dev/i2s-1");
        puts("Check that the i2c-dev & i2c-bcm2708 kernelmodules "
             "are loaded.");
        abort();
    }
    /* Make sure the driver support 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 / ioct1 . h>
15 #include <1 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 */
```c
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     msgsetmsgs = &iomsgs[0];
41     msgsetmsgs = 1;
42
43     return ioctl(i2c_fd,I2C_RDWR,&msgset);
44 }  

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 buffer */
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
```
/* Make sure every character is a digit in argument 1. */
for ( cx=0; cx<slen; ++cx )
    if ( !isdigit(argv[1][cx]) )
        goto usage; /* Not a numeric digit */

/* Initialize I2C and clear rtc and t1 structures: */
i2c_init(node);           /* Initialize for I2C */
memset(&rtc,0,sizeof rtc);
memset(&t1,0,sizeof t1);

/* Extract YYYYMMDDhhmm[ss] from argument 1: */
strncpy(buf,argv[1],4)[4] = 0;       /* buf[] = "YYYY" */
if ( sscanf(buf,"%d",&v) != 1 || v < 2000 || v > 2099 )
    goto usage;
t1.tm_year = v - 1900;

strncpy(buf,argv[1]+4,2)[2] = 0;     /* buf[] = "MM" */
if ( sscanf(buf,"%d",&v) != 1 || v <= 0 || v > 12 )
    goto usage;
t1.tm_mon = v-1;                   /* 0 − 11 */

strncpy(buf,argv[1]+6,2)[2] = 0;     /* buf[] = "DD" */
if ( sscanf(buf,"%d",&v) != 1 || v <= 0 || v > 31 )
    goto usage ;
t1.tm_mday = v;                    /* 1 − 31 */

strncpy(buf,argv[1]+8,2)[2] = 0;     /* buf[] = "hh" */
if ( sscanf(buf,"%d",&v) != 1 || v < 0 || v > 23 )
    goto usage;
t1.tm_hour = v;

if ( slen > 12 ) {
    /* Optional ss was provided: */
    strncpy(buf,argv[1]+10,2)[2] = 0;  /* buf[] = "ss" */
    if ( sscanf(buf,"%d",&v) != 1 || v < 0 || v > 59 )
        goto usage;
t1.tm_min = v;
}
 t1.tm_sec = v;
 }

 /*
 * Check the validity of the date :
 */
 t1.tm_isdst = -1;        /* Determine if daylight savings */
 t0 = t1;               /* Save initial values */
 if ( mktime(&t1) == 1L ) {    /* t1 is modified */
       bad_date : printf("Argument \"%s\" is not a valid calendar date.\n",argv[1]) ;
          exit(2);
 }

 /*
 * If struct t1 was adjusted , then the original date/time
 * values were invalid :
 */
 if ( t0.tm_year != t1.tm_year || t0.tm_mon != t1.tm_mon
 | | t0.tm_mday != t1.tm_mday || t0.tm_hour != t1.tm_hour
 | | t0.tm_min != t1.tm_min || t0.tm_sec != t1.tm_sec )
       goto bad_date;

 /*
 * Populate DS1307 registers :
 */
 rtc.secs_10s = t1.tm_sec / 10;
 rtc.secs_1s = t1.tm_sec % 10;
 rtc.mins_10s = t1.tm_min / 10;
 rtc.mins_1s = t1.tm_min % 10;
 rtc.hour_10s = t1.tm_hour / 10;
 rtc.hour_1s = t1.tm_hour % 10;
 rtc.month_10s = (t1.tm_mon + 1) / 10;
 rtc.month_1s = (t1.tm_mon + 1) % 10;
 rtc.day_10s = t1.tm_mday / 10;
 rtc.day_1s = t1.tm_mday % 10;
 rtc.year_10s = (t1.tm_year + 1900 - 2000) / 10;
 rtc.year_1s = (t1.tm_year + 1900 - 2000) % 10;

   rtc.wkday = t1.tm_wday + 1;        /* Weekday 1-7 */
   rtc.mode_1224 = 0;               /* Use 24 hour format */

 #if 0       /* Change to a 1 for debugging */
 printf("%d%d-%d%d-%d%d %d%d:%d%d:%d%d (wkday %d )\n",
    rtc.year_10s,rtc.year_1s,
    rtc.month_10s,rtc.month_1s,
    rtc.day_10s,rtc.day_1s,
Chapter 4  ■  REAL-TIME CLOCK

    rtc.hour_10s, rtc.hour_1s,
    rtc.mins_10s, rtc.mins_1s,
    rtc.secs_10s, rtc.secs_1s,
    rtc.wkday);

    #end if

    /*
    * Display RTC values submitted :
    * /

    strftime(dtbuf, sizeof dtbuf, date_format, &t1);

    if (rc < 0)
        perror("Writing to DS1307 RTC");
    else if (rc != 1)
        printf("Incomplete write : %d msgs of 2written \n", rc);

    i2c_close();
    return rc == 1? 0 : 4;

/***************************************************************************/
/* ds1307get.c : Read real-time DS1307 clock on I2C bus
******************************************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <ctype.h>
#include <time.h>
#include <fcntl.h>
#include <unistd.h>
#include <string.h>
#include <errno.h>
#include <assert.h>
#include <linux/i2c-dev.h>
#include "i2c_common.c"    /* I2C routines */
#include "ds1307.h"   /* DS1307 types */

/* Change to i2c-0 if using early Raspberry Pi */
static const char *node = "/dev/i2c-1";
```c
/*
 * Read: [ S ] 0xB1 <regaddr> <rtcbuf[0]> . . . <rtcbuf[n−1]> [P]
 */

static int i2c_rd_rtc(ds1307_rtc_regs *rtc) {
    struct i2c_rdwr_ioctl_data msgset;
    struct i2c_msg iomsgs[2];
    char zero = 0x00;          /* Register 0x00 */

    iomsgs[0].addr = 0x68;    /* DS1307 */
    iomsgs[0].flags = 0;      /* Write */
    iomsgs[0].buf = &zero;    /* Register 0x00 */
    iomsgs[0].len = 1;

    iomsgs[1].addr = 0x68;    /* DS1307 */
    iomsgs[1].flags = I2C_M_RD; /* Read */
    iomsgs[1].buf = (char *)rtc;
    iomsgs[1].len = size of *rtc;

    msgset.msgs=iomsgs;
    msgset.nmsgs=2;

    return ioctl(i2c_fd,I2C_RDWR,&msgset);
}

/* Main program:
 */

int main(int argc,char **argv) {
    ds1307_rtc_regs rtc;     /* DS1307 Register Values */
    struct tm t0, t1;        /* Unix date / time values */
    char *date_format = getenv("DS1307_FORMAT");
    char dtbuf[256];         /* Formatted date/time */
    int rc;                  /* Return code */

    /*
     * If no environment variable named DS1307_FORMAT, then
     * set a default date/time format.
     */
    if ( !date_format )
        date_format = "%Y-%m-%d%H:%M:%S(%A)";

    /*
     * Initialize I2C and clear rtc and t1 structures:
     */
    i2c_init(node);          /* Initialize for I2C */
```
Chapter 4 — Real-Time Clock

```c
    memset(&rtc,0,sizeof rtc);
    memset(&t1,0,sizeof t1);

    rc = i2c_rd_rtc(&rtc);
    if ( rc < 0 ) {
        perror("Reading DS1307 RTC clock.");
        exit(1);
    } else if ( rc != 2 ) {
        fprintf(stderr,"Read error: got %d of 2 msgs.\n",rc);
        exit(1);
    } else
        rc = 0;

    /*
    * Check the date returned by the RTC:
    */
    memset(&t1,0,sizeof t1);
    t1.tm_year = (rtc.year_10s * 10 + rtc.year_1s) + 2000 − 1900;
    t1.tm_mon = rtc.month_10s * 10 + rtc.month_1s − 1;
    t1.tm_mday = rtc.day_10s * 10 + rtc.day_1s;
    t1.tm_hour = rtc.hour_10s * 10 + rtc.hour_1s;
    t1.tm_min = rtc.mins_10s * 10 + rtc.mins_1s;
    t1.tm_sec = rtc.secs_10s * 10 + rtc.secs_1s;
    t1.tm_isdst = −1; /* Determine if daylight savings */
    t0 = t1;
    if ( mktime(&t1) == 1L /* t1 is modified */
        || t1.tm_year != t0.tm_year || t1.tm_mon != t0.tm_mon
        || t1.tm_mday != t0.tm_mday || t1.tm_hour != t0.tm_hour
        || t1.tm_min != t0.tm_min || t1.tm_sec != t0.tm_sec ) {
        strftime(dtbuf,sizeof dtbuf,date_format,&t0);
        fprintf(stderr,"Read RTC date is not valid: %s\n",dtbuf);
        exit(2);
    }

    if ( t1.tm_wday != rtc.wkday−1 ) {
        fprintf(stderr,
            "Warning:RTC weekday is incorrect %d but should be %d\n",
            rtc.wkday,t1.tm_wday);
    }

#if 0 /* Change to a 1 for debugging */

    printf("%d%d-%d%d-%d%d%d%d:%d%d:%d%d(wkday %d)\n",
        rtc.year_10s,rtc.year_1s ,
        rtc.month_10s,rtc.month_1s ,
        rtc.day_10s, rtc.day_1s ,
        rtc.hour_10s,rtc.hour_1s ,
```
rtc.mins_10s, rtc.mins_1s,
rtc.secs_10s, rtc.secs_1s,
rtc.wkday);
#endif

strftime (dtbuf, size of dtbuf, date_format, &t1);
puts(dtbuf);
i2c_close();
return rc == 8 ? 0 : 4;
}

/* End ds1397get.c */
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](image)

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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>$V_{CC}$</td>
<td>2.7</td>
<td></td>
<td>5.5</td>
<td>Volts</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply current</td>
<td>$I_{cc}$</td>
<td>$V_{cc} = 5.0$ volts</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>mA</td>
</tr>
<tr>
<td>Receiving distance</td>
<td>$L$</td>
<td></td>
<td>11</td>
<td>13</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Acceptance angle</td>
<td>$\theta \frac{1}{2}$</td>
<td></td>
<td>±35</td>
<td></td>
<td></td>
<td>Deg</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>$f_0$</td>
<td></td>
<td>37.9</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>$f_{BW}$</td>
<td></td>
<td>8</td>
<td></td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Voltage out low</td>
<td>$V_{OL}$</td>
<td>$R_{pullup} = 2.4 , k\Omega$</td>
<td></td>
<td>0.25</td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>Voltage out high</td>
<td>$V_{OH}$</td>
<td>$V_{cc} - 0.3$</td>
<td></td>
<td></td>
<td>$V_{cc}$</td>
<td>Volts</td>
</tr>
<tr>
<td>Operating temp.</td>
<td>$T_{opr}$</td>
<td></td>
<td>−30</td>
<td></td>
<td>+85</td>
<td>°C</td>
</tr>
</tbody>
</table>

**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.
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 kΩ.

**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. $R_1$ 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 kΩ 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.

<table>
<thead>
<tr>
<th>Out</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>No 38 kHz carrier seen</td>
</tr>
<tr>
<td>Low</td>
<td>38 kHz carrier is detected</td>
</tr>
</tbody>
</table>

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. 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.
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 5-1. IR Remote Waveform Times**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Brand</th>
<th>Component</th>
<th>High</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>NEC</td>
<td>Start bit</td>
<td>9</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 bit</td>
<td>0.56</td>
<td>0.56</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 bit</td>
<td>0.56</td>
<td>1.69</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stop bit</td>
<td>0.56</td>
<td>0.56</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>SIRCS</td>
<td>Start bit</td>
<td>2.4</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 bit</td>
<td>0.6</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 bit</td>
<td>1.2</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>RC5</td>
<td>Start bit</td>
<td>-</td>
<td>0.889</td>
<td>0.889</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 bit</td>
<td>-</td>
<td>0.889</td>
<td>0.889</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 bit</td>
<td>0.889</td>
<td>0.889</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Japan</td>
<td>Start bit</td>
<td>3.38</td>
<td>1.69</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 bit</td>
<td>0.42</td>
<td>0.42</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 bit</td>
<td>0.42</td>
<td>1.69</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Samsung</td>
<td>Start bit</td>
<td>4.5</td>
<td>4.5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 bit</td>
<td>0.56</td>
<td>0.56</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 bit</td>
<td>0.56</td>
<td>1.69</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stop bit</td>
<td>0.56</td>
<td>0.56</td>
<td>-</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Level</th>
<th>GPIO</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (1)</td>
<td>Low</td>
<td>Carrier present</td>
</tr>
<tr>
<td>Low (0)</td>
<td>High</td>
<td>Carrier absent</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start bit</td>
<td>Marks the start of a key-code</td>
</tr>
<tr>
<td>0 bit</td>
<td>0 bit for the code</td>
</tr>
<tr>
<td>1 bit</td>
<td>1 bit for the code</td>
</tr>
<tr>
<td>Stop bit</td>
<td>Stop bit (end of code)</td>
</tr>
</tbody>
</table>

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 for 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 E0E0609F
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 for 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 for 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
```

106
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.
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:

```
/*irdecode.c : Read IR remote control on GPIO 17 (GEN0)*/
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <unistd.h>
#include <string.h>
#include <errno.h>
#include <signal.h>
#include <setjmp.h>
#include <unistd.h>
#include <signal.h>
```

**Figure 5-3.** gnuplot waveform of an IR signal
#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" },
};
{ IR_8, "8" },
{ IR_9, "9" },
{ IR_EXIT, "\n<EXIT>\n" },
{ IR_RETURN, "\n<RETURN>\n" },
{ IR_MUTE, "\n<MUTE>\n" },
{ 0, 0 } /* End marker */
};

/* Compute the time difference in milliseconds: */
static double
msdiff(struct timeval *t1, struct timeval *t0) {
    unsigned long ut;
    double ms;
    ms = (t1->tv_sec - t0->tv_sec) * 1000.0;
    if (t1->tv_usec > t0->tv_usec)
        ms += (t1->tv_usec - t0->tv_usec) / 1000.0;
    else {
        ut = t1->tv_usec + 1000000UL;
        ut -= t0->tv_usec;
        ms += ut / 1000.0;
    }
    return ms;
}

/* 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, 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);

    /* Edge: /sys/class/gpio%d/edge */
    gpio_setpath(pin, gp_edge, buf, sizeof buf);
    f = fopen(buf, "w");
    assert(f);
    fprintf(f, "%s\n", edge);
    fclose(f);

    /* Value: /sys/class/gpio%d/value */
    gpio_setpath(pin, gp_value, buf, sizeof buf);
    fd = open(buf, O_RDWR);
    return fd;
}

/* Close (unexport) GPIO pin: */
static void gpio_close(int pin) {
    char buf[128];
    FILE *f;

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

/*
 * This routine will block until the open GPIO pin has changed
 * value.
 */

static int
gpio_poll(int fd,double *ms) {
    static char needs_init = 1;
    static struct timeval t0;
    static struct timeval t1;
    struct pollfd polls;
    char buf[32];
    int rc, n;

    if ( needs_init ) {
        rc = gettimeofday(&t0,0);
        assert(!rc);
        needs_init = 0;
    }

    polls.fd = fd; /* /sys/class/gpio17/value */
    polls.events = POLLPRI; /* Exceptions */

    do {
        rc = poll(&polls,1,-1); /* Block */
        if ( is_signaled )
            longjmp(jmp_exit,1);
    } while ( rc < 0 && errno == EINTR );

    assert(rc > 0);
    rc = gettimeofday(&t1,0);
    assert(!rc);

    *ms = msdiff(&t1,&t0);
    lseek(fd,0,SEEK_SET);
    n = read(fd,buf,sizeof buf); /* Read value */
    assert(n>0);
    buf[n] = 0;
    rc = sscanf(buf,"%d",&n);
    assert(rc==1);
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
Start: word = 0;
count = 0;

/*
 * Wait for a space of 46 ms :
*/
do {
    v = wait_change(&ms);
} while ( ms < 46.5 );

/*
 * Wait for start : 4.5ms high, then 4.5ms low :
*/
for ( v=1;; ) {
    if ( v )
        v = wait_level(0);
    v = wait_level(1);
    v = wait_change(&ms); /* High to Low */
    if ( !v && ms >= 4.0 && ms <= 5.0 ) {
        v = wait_change(&ms);
        if ( v && ms >= 4.0 && ms <= 5.0 )
            break ;
    }
}

/*
 * Get 32 bi t code :
*/
do {
    /* Wait for line to go low */
    v = wait_change(&ms);
    if ( v || ms < 0.350 || ms > 0.8500 )
        goto Start;

    /* Wait for line to go high */
    v = wait_change(&ms);
    if ( !v || ms < 0.350 || ms > 2.0 )
        goto Start;

    b = ms < 1.000 ? 0 : 1;
    word = (word << 1) | b;
} while ( ++count < 32 );

/*
 * Eliminate key stutter :
*/
```c
gettimeofday(&t1,0);
if ( word == last && t0.tv_sec && msdiff(&t1,&t0) < 1100.0 )
    goto Start; /* Too soon */

t0 = t1;
fprintf(stderr,"CODE %08lx\n",word);
return word;
}

/*
* Get text form of remote key :
*/
static const char *
getircode(void) {
    unsigned long code;
    int kx;
    for (;;) {
        code = getword();
        for ( kx=0; ir_codes[kx].text; ++kx )
            if ( ir_codes[kx].ir_code == code )
                return ir_codes[kx].text;
    }
}

/*
* Main program :
*/
int main(int argc,char **argv) {
    const char *key;
    int optch;
    int f_dump = 0, f_gnuplot = 0, f_noinvert = 0;
    while ( (optch = getopt(argc,argv,"dgnsp:h")) != EOF )
        switch ( optch ) {
            case 'd':
                f_dump = 1;
                break;
            case 'g':
                f_gnuplot = 1;
                break;
            case 'n':
                f_noinvert = 1;
                break;
            case 'p':
                gpio_inpin = atoi(optarg);
```
break;

340                  case 'h' :
341                          /* Fall thru */
342                  default :             fprintf (stderr,
343 usage :
344                          "Usage: %s [-d ] [-g ] [-n ] [-p
345                          
gpio]\n",argv[0]);
346                          fputs("where: 
" -d\t\tdumps events\n"
347                          " -g\t\tgplot waveforms\n"
348                          " -n\t\tdon't invert GPIO input \n"
349                          " -p \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                   */

int v;
double ms, t = 0.0;

wait_change(&ms); /* Wait for first change */

for (;;) {
    v = wait_change(&ms) ^ f_noinvert;
    if (!f_gnuplot)
        printf("%12.3f\t%d\n", ms, v);
    else {
        printf("%12.3f\t%d\n", t, v^1);
        t += ms;
        printf("%12.3f\t%d\n", t, v^1);
        printf("%12.3f %12.3f\n", t, v, ms);
    }
}

exit: fputs("\nExit.\n", stdout);
close(gpio_fd); /* Close gpio%d/value */
gpio_close(gpio_inpin); /* Unexport gpio */
return 0;

} /* End irdecode.c */
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](image-url)
This particular stepper motor has these markings on it:

<table>
<thead>
<tr>
<th>12 V</th>
<th>0.16</th>
<th>A/Ø</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 Ω</td>
<td>100</td>
<td>S/R</td>
</tr>
</tbody>
</table>

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:

\[
I = \frac{V}{R} = \frac{12}{75} = 160mA
\]

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](image-url)
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:

<table>
<thead>
<tr>
<th>Wire 1</th>
<th>Wire 2</th>
<th>Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Red</td>
<td>84 Ω</td>
</tr>
<tr>
<td>Red</td>
<td>White</td>
<td>168 Ω</td>
</tr>
<tr>
<td>White</td>
<td>Brown</td>
<td>168 Ω</td>
</tr>
<tr>
<td>Brown</td>
<td>Black</td>
<td>84 Ω</td>
</tr>
<tr>
<td>etc.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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:

\[ I_{\text{Winding}} = \frac{V}{R_{\text{winding}}} \]

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?

\[ I_{\text{Winding}} = \frac{6}{40} = 150mA \]
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.

![ULN2003A PCB schematic](image)

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 kΩ 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 and the maximum of 12 V is applied, each LED conducts about this:

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

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 INx 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.
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 6-4.** ULN2003A driving a winding

**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:

\[
V_{IL} = 2 \times V_{BE} = 2 \times 0.6 = 1.2V
\]
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:

<table>
<thead>
<tr>
<th>Signal</th>
<th>Raspberry Pi</th>
<th>ULN2003A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{OL}$</td>
<td>$\leq 0.8 \text{ V}$</td>
<td>$I_c$</td>
</tr>
<tr>
<td></td>
<td>1.2 V</td>
<td>500 mA</td>
</tr>
<tr>
<td></td>
<td>2.4 V</td>
<td>100 mA</td>
</tr>
<tr>
<td>$V_{OH}$</td>
<td>$\geq 1.3 \text{ V}$</td>
<td>2.7 V</td>
</tr>
<tr>
<td></td>
<td>3.0 V</td>
<td>300 mA</td>
</tr>
</tbody>
</table>

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

\[ I_\text{pull\_up} = \frac{V_{\text{CC}}}{R_{\text{pull\_up}}} = \frac{3.3\text{V}}{50\text{ kΩ}} = 66\text{ µA} \]

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 \( R_y, R_1, \) and \( R_2 \) are connected in series between the input and ground. This effectively provides a pull-down resistance of approximately 13.6 kΩ. 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.

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

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

(*†*) No pull-up resistor
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

![Wave Drive (Mode 0)](image)

**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

![Full-Step Drive (Mode 1)](image)

**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.

![Waveform Diagram](image)

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

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>
<thead>
<tr>
<th>GPIO</th>
<th>GENX</th>
<th>P1</th>
<th>Mode</th>
<th>Stepper Wire</th>
<th>ULN2003A</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>GEN0</td>
<td>P1-11</td>
<td>Output</td>
<td>Red</td>
<td>1B</td>
<td>Field A</td>
</tr>
<tr>
<td>24</td>
<td>GEN5</td>
<td>P1-18</td>
<td></td>
<td>White</td>
<td>2B</td>
<td>Field B</td>
</tr>
<tr>
<td>22</td>
<td>GEN3</td>
<td>P1-15</td>
<td></td>
<td>Brown</td>
<td>3B</td>
<td>Field C</td>
</tr>
<tr>
<td>23</td>
<td>GEN4</td>
<td>P1-16</td>
<td></td>
<td>Green</td>
<td>4B</td>
<td>Field D</td>
</tr>
</tbody>
</table>
Figure 6-9 shows how a pointer knob can be used for a pointer. Otherwise, this is your opportunity to get creative.

![Stepper motor with knob used as a pointer](image)

**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.
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.

### Table 6-3. Single-Character Commands

<table>
<thead>
<tr>
<th>Char</th>
<th>Command</th>
<th>Char</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Quit</td>
<td>0</td>
<td>12 o’clock (noon)</td>
</tr>
<tr>
<td>&lt;</td>
<td>Slower steps</td>
<td>1</td>
<td>1 o’clock</td>
</tr>
<tr>
<td>&gt;</td>
<td>Faster steps</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>?</td>
<td>Help</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>9</td>
<td>9</td>
<td>9 o’clock</td>
</tr>
<tr>
<td>J</td>
<td>Stepper mode 0</td>
<td>A</td>
<td>10 o’clock</td>
</tr>
<tr>
<td>K</td>
<td>Stepper mode 1</td>
<td>B</td>
<td>11 o’clock</td>
</tr>
<tr>
<td>L</td>
<td>Stepper mode 2</td>
<td>+=</td>
<td>Step clockwise</td>
</tr>
<tr>
<td>P</td>
<td>Show current position</td>
<td>-</td>
<td>Step counterclockwise</td>
</tr>
<tr>
<td>O</td>
<td>Toggle drive on/off</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

```c
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <unistd.h>
#include <errno.h>
#include <math.h>
#include <ctype.h>
#include <termio.h>
#include <sys/mman.h>
#include <signal.h>
#include <assert.h>

#include "gpio_io.c" /* GPIO routines */
#include "timed_wait.c" /* timed_wait () */

static const int steps_per_360 = 100; /* Full steps per rotation */

static const int gpios[] = { 17, 24, 22, 23 };

static float step_time = 0.1; /* Seconds */
static int drive_mode = 0; /* Drive mode 0, 1, or 2 */
static int step_no = 0; /* Step number */
static int steps_per_r = 100; /* Steps per rotation */
```
static int position = 0; /* Stepper position */
static int on_off = 0; /* Motor drive on/off */
static int quit = 0; /* Exit program if set */

>Status so many fractional seconds

static void
await(float seconds) {
    long sec, usec;
    sec = floor(seconds); /* Seconds to wait */
    usec = floor((seconds_sec)*1000000); /* Microseconds */
    timed_wait(sec,usec,0); /* Wait */
}

* Set motor drive mode

static void
set_mode(int mode) {
    int micro_steps = mode < 2 ? 1 : 2;
    step_no = 0;
    drive_mode = mode;
    steps_per_r = steps_per_360 * micro_steps;
    printf("Drive mode %d\n",drive_mode);
}

* Drive all fields according to bit pattern in pins

static void
drive(int pins) {
    short x;
    for ( x=0; x<4; ++x )
        gpio_write(gpios [x],pins & (8>>x) ? 1 : 0);
}

* Advance motor:
*   dir = -1 Step counter_clockwise
*   dir = 0 Turn on existing fields
*   dir = +1 Step clockwise

www.it-ebooks.info
static void advance(int dir) {
    static int m0drv[] = {8, 4, 2, 1};
    static int m1drv[] = {9, 12, 6, 3};
    static int m2drv[] = {9, 8, 12, 4, 6, 2, 3, 1};

    switch (drive_mode) {
    case 0: /* Simple mode 0 */
        step_no = (step_no + dir) & 3;
        drive(m0drv[step_no]);
        await(step_time/4.0);
        break;
    case 1: /* Mode 1 drive */
        step_no = (step_no + dir) & 3;
        drive(m1drv[step_no]);
        await(step_time/6.0);
        break;
    case 2: /* Mode 2 drive */
        step_no = (step_no + dir) & 7;
        drive(m2drv[step_no]);
        await(step_time/12.0);
    }

    on_off = 1; /* Mark as drive enabled */
}

/* Move +/- n steps, keeping track of position */
static void move(int steps) {
    int movement = steps;
    int dir = steps >= 0 ? 1 : -1;
    int inc = steps >= 0 ? -1 : 1;

    for (; steps != 0; steps += inc)
        advance(dir);

    position = (position + movement + steps_per_r) % steps_per_r;
}

/* Move to an hour position */
static void move_oclock(int hour) {
    int new_pos = floor((float)hour * steps_per_r/12.0);
    int diff;

    printf("Moving to %d o'clock.\n",hour);

    if ( new_pos >= position ) {
        diff = new_pos - position;
        if ( diff <= steps_per_r/2 )
            move(diff);
        else move(-(position + steps_per_r - new_pos));
    } else {
        diff = position - new_pos;
        if ( diff <= steps_per_r/2 )
            move(-diff);
        else move (new_pos + steps_per_r - position);
    }
}

static void help(void) {
    puts("Enter 0-9,A,B for 0_9,10,11 o'clock.\n"
          " '<' to slow motor speed, \n"
          " '>' to increase motor speed, \n"
          " 'J ', 'K' or 'L' for modes 0-2,\n"
          " '+'/' '-' to step 1 step,\n"
          " 'O' to toggle drive on/off, \n"
          " 'P' to show position, \n"
          " 'Q' to quit.\n");
}

int main(int argc,char **argv) {
    int tty = 0;                 /* Use stdin */
    struct termios sv_ios, ios;
    int x, rc;
    char ch;

    if ( argc >= 2 )
        drive_mode = atoi(argv[1]); /* Drive mode 0_2 */

ready = tcgetattr(tty,&sv_ios);       /* Save current settings */
assert(!rc);
ios = sv_ios;
cfmakeraw(&ios);                     /* Make into a raw config */
ios.c_oflag = OPOST | ONLCR;      /* Keep output editing */
rc = tcsetattr(tty,TCSAFLUSH,& ios);    /* Put terminal into
                                      raw mode */
assert(!rc);
gpio_init();                        /* Initialize GPIO access */
drive(0);                            /* Turn off output */
for ( x=0; x<4; ++x )
gpio_config(gpios[x],Output);        /* Set GPIO pin as Output */
help();
set_mode(drive_mode);
printf("Step time: %6.3f seconds\n",step_time);
while ( !quit ) {
    write(1," : ",2);
    rc = read(tty,&ch,1);       /* Read char */
    if ( rc != 1 )
        break;
    if ( islower(ch) )
        ch = toupper(ch);
    write(1,&ch,1);
    write(1,\"\n",1);
    switch ( ch ) {
        case 'Q':           /* Quit */
            quit = 1;
            break;
        case '<' :          /* Go slower */
            step_time *= 2.0;
            printf ("Step time: %6.3 f seconds \n",
                    step_time);
            break;
        case '>':           /* Go faster */
            step_time /= 2.0;
            printf ("Step time: %6.3 f seconds \n",
                    step_time);
            break;
        case '?':           /* Provide help */
            case 'H':
                help ();
                break;
    }
}
break;
    case 'J':    /* Mode 0 */
    case 'K':    /* Mode 1 */
    case 'L':    /* Mode 2 */
        move_oclock(0);
        set_mode((int) ch - (int) 'J');
        break;
    case 'A':    /* 10 o'clock */
    case 'B':    /* 11 o'clock */
        move_oclock ((int) ch - (int) 'A'+10);
        break;
    case 'O':    /* Toggle on/ off drive */
        on_off ^= 1;
        if ( !on_off )
            drive(0); /* Turn off motor drive */
        else advance(0); /* Re_assert motor drive */
        break;
    case '+':    /* Advance +1 */
    case '=':    /* Tread '=' as '+' for convenience */
    case '-':    /* Counter clock wise 1 */
        move(ch == '-' ? -1 : 1);
        /* Fall thru */
    case 'P':    /* Display Position */
        printf("Position: %d of %d\n",position,
steps_per_r);
        break;
    default:     /* 0 to 9'o clock */
        if ( ch >= '0' && ch <= '9' )
            move_oclock((int) ch - (int) '0');
        else write (1,"??\n",4);
    }
}

puts("\nExit.");

drive(0);
for ( x=0; x<4; +++ )
    gpio_config(gpios[x],Input); /* Set GPIO pin as Input */
tcsetattr(tty,TCSAFLUSH,&sv_ios); /* Restore terminal mode */
return 0;

/* End unipolar.c */
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](image)
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 $Q_4$ 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:

<table>
<thead>
<tr>
<th>In1</th>
<th>In2</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Motor Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>No current flow</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>Right to left</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>Left to right</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>On</td>
<td>On</td>
<td>No current flow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 ($t_{rr} \leq 200 \text{ ns}$). A slow-reacting diode can allow the voltage to spike into the surrounding circuit.

![Figure 7-2. L298 with protective diodes](image)

**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.
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 ($V_J$) 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:

<table>
<thead>
<tr>
<th>+5V</th>
<th>+5V</th>
</tr>
</thead>
<tbody>
<tr>
<td>EnA</td>
<td>In1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$</td>
<td>Supply voltage (pin 4)</td>
<td>$V_{IH} + 2.5$</td>
<td></td>
<td>46</td>
<td>Volts</td>
</tr>
<tr>
<td>$V_{ss}$</td>
<td>Logic supply voltage (pin 9)</td>
<td>4.5</td>
<td>5</td>
<td>7</td>
<td>Volts</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>GPIO</th>
<th>L298</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>Volts</td>
</tr>
<tr>
<td>$V_{OL}$</td>
<td>$\leq 0.8 \text{ V}$</td>
</tr>
<tr>
<td>$V_{OH}$</td>
<td>$\geq 1.3 \text{ V}$</td>
</tr>
</tbody>
</table>
If you look carefully at the chart, there is a dodgy area where the GPIO output can be as low as $V_{OH} \approx 1.3\,\text{V}$ and still be in spec as far as the Raspberry Pi is concerned. We see that the L298 considers signals $V_{IL} \leq 1.5\,\text{V}$ as a low. Worse, only voltages $\geq 2.3\,\text{V}$ are considered high by the L298. The good news is that the L298 input current is very low:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test Conditions</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{HI}$</td>
<td>High-voltage input current</td>
<td>$V_i = H \leq V_{SS} - 0.6,\text{V}$</td>
<td>30</td>
<td>100</td>
<td>mA</td>
</tr>
</tbody>
</table>

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 $3.135 - 0.3 = 2.835\,\text{V}$. This is only 0.535 V above the minimum $V_{OH} = 2.3\,\text{V}$ 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](image)

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.
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).
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 \textit{motor-safe} GPIO pins for the driver inputs.
- Drive the enable inputs from a \textit{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 \textit{four} input controls need to be taken from the \textit{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 \textit{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.

![L298 schematic](image)

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:

<table>
<thead>
<tr>
<th>Character</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wave mode, one phase</td>
</tr>
<tr>
<td>2</td>
<td>Wave mode, two phase</td>
</tr>
<tr>
<td>3</td>
<td>Half-step mode</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Character</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Single step clockwise</td>
</tr>
<tr>
<td>-</td>
<td>Single step counterclockwise</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Character</th>
<th>Command</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Forward (free running)</td>
</tr>
<tr>
<td>R</td>
<td>Reverse (free running)</td>
</tr>
<tr>
<td>S</td>
<td>Stop</td>
</tr>
<tr>
<td>&gt;</td>
<td>Go faster (halve the step time)</td>
</tr>
<tr>
<td>&lt;</td>
<td>Go slower (double the step time)</td>
</tr>
<tr>
<td>Q</td>
<td>Quit</td>
</tr>
</tbody>
</table>
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.
#include <math.h>
#include <ctype.h>
#include <termio.h>
#include <sys/mman.h>
#include <pthread.h>
#include <assert.h>

#include "gpio_io.c"                  /* GPIO routines */
#include "timed_wait.c"               /* timed_wait() */

/*
 * GPIO definitions :
 */
static const int g_enable    = 17;  /* L298 EnA and EnB */
static const int g_in1   = 27;      /* L298 In1 */
static const int g_in2   = 22;      /* L298 In2 */
static const int g_in3   = 23;      /* L298 In3 */
static const int g_in4   = 24;      /* L298 In4 */

static volatile int stepper_mode = 0;      /* Stepper mode − 1 */
static volatile float step_time = 0.1;     /* Step time in seconds */

static pthread_mutex_t mutex;       /* For inter−thread locks */
static pthread_cond_t cond;         /* For inter−thread signaling */

/*
 * Await so many fractional seconds
 */
static void
await(float seconds) {
    long sec, usec;
    sec = floor(seconds);                /* Seconds to wait */
    usec = floor( (seconds−sec)*1000000); /* Microseconds */
    timed_wait(sec,usec,0);              /* Wait */
}

/*
 * Enable/Disable drive to the motor
 */
static inline void
enable(int enable) {
    gpio_write(g_enable, enable);
}

/*
 * Drive the appropriate GPIO outputs :
 */
static void
drive(int L1L2) {
    gpio_write(g_in1, L1L2&0x08);
    gpio_write(g_in2, L1L2&0x04);
    gpio_write(g_in3, L1L2&0x02);
    gpio_write(g_in4, L1L2&0x01);
}

/*
 * Take one step in a direction :
 */
static void
step(int direction) {
    static const int modes[3][8] = {
        { 0b1000, 0b0010, 0b0100, 0b0001 },      /* Mode 1 */
        { 0b1010, 0b0110, 0b0101, 0b1001 },      /* Mode 2 */
        { 0b1000, 0b1010, 0b0010, 0b0110, 0b0100, 0b0101, 0b0001, 0b1001 }
    } ;
    static int stepno = 0;            /* Last step no.*/
    int m = stepper_mode < 2 ? 4 : 8; /* Max steps for mode */
    if ( direction < 0 )
        direction = m - 1;
    enable(0);                      /* Disable motor */
    drive(modes[stepper_mode][stepno]); /* Change fields */
    enable(1);                      /* Drive motor */
    stepno = (stepno+direction) % m; /* Next step */
}

/*
 * Set the stepper mode of operation :
 */
static inline void
set_mode(int mode) {
    enable(0);
    stepper_mode = mode;
}

/*
 * Take a command off the input queue
 */
static char
get_cmd(void) {
    char c;

    pthread_mutex_lock(&mutex);

    while ( !cmd )
        pthread_cond_wait(&cond,&mutex);

    c = cmd;
    cmd = stop = 0;
    pthread_mutex_unlock(&mutex);
    pthread_cond_signal (&cond); /* Signal that cmd is taken */

    return c;
}

/*
 * Stepper controller thread :
 */
static void *
controller(void * ignored) {
    int command;
    int direction;

    for ( stopped = 1; ; ) {
        command = get_cmd();
        direction = command == 'F' ? 1 : -1;

        for ( stopped = 0; !stop; ) {
            step(direction);
            await(step_time);
        }

        stopped = 1;

    } return 0;
}
Queue up a command for the controller thread:

```c
static void queue_cmd(char new_cmd) {
    pthread_mutex_lock(&mutex); /* Gain exclusive access */
    /* Wait until controller grabs and zeros cmd */
    while (cmd)
        pthread_cond_wait(&cond, &mutex);
    cmd = new_cmd; /* Deposit new command */
    pthread_mutex_unlock(&mutex); /* Unlock */
    pthread_cond_signal(&cond); /* Signal that cmd is there */
}
```

Stop the current operation:

```c
static void stop_cmd(void) {
    for (stop = 1; !stopped; stop = 1)
        await(0.100);
}
```

Provide usage info:

```c
static void help(void) {
    puts("Enter:
          1 - One phase mode
          2 - Two phase mode
          3 - Half step mode
          R - Toggle Reverse (counter-clockwise)
          F - Toggle Forward (clockwise)
          S - Stop motor
          + - Step forward
          - - Step backwards
          > - Faster step times
          < - Slower step times
          ? - Help
          Q - Quit" );
}
```
Main program

```c
int main(int argc, char **argv) {
    pthread_t tid; /* Thread id */
    int tty = 0; /* Use stdin */
    struct termios sv_ios, ios;
    int rc, quit;
    char ch, lcmd = 0;

    rc = tcgetattr(tty,&sv_ios); /* Save current settings */
    assert(!rc);
    ios = sv_ios;
    cfmakeraw(&ios); /* Make into a raw config */
    ios.c_oflag = OPOST | ONLCR; /* Keep output editing */
    rc = tcsetattr(tty,TCSAFLUSH,&ios); /* Put into raw mode */
    assert(!rc);

    /* Initialize and configure GPIO pins : */
    gpio_init();
    gpio_config(g_enable,Output);
    gpio_config(g_in1,Output);
    gpio_config(g_in2,Output);
    gpio_config(g_in3,Output);
    gpio_config(g_in4, Output);
    enable(0); /* Turn off output */
    set_mode(0); /* Default is one phase mode */
    help();

    pthread_mutex_init(&mutex,0); /* Mutex for inter-thread locking */
    pthread_cond_init(&cond,0); /* For inter-thread signaling */
    pthread_create(&tid,0,controller,0); /* The thread itself */

    /* Process single-character commands : */
    for ( quit=0; !quit; ) {
        /*
        * Prompt and read input char :
        */
        write(1,"": ",2);
    }
```
rc = read(tty,&ch,1);
if ( rc != 1 )
    break;
if ( islower(ch) )
    ch = toupper(ch);

write(1,&ch,1);
write(1,\n",1);

/*
 * Process command char :
 */

switch ( ch ) {
case '1':    /* One phase mode */
    stop_cmd();
    set_mode(0);
    break;
case '2':    /* Two phase mode */
    stop_cmd();
    set_mode(1);
    break;
case '3':    /* Half step mode */
    stop_cmd();
    set_mode(2);
    break;
case '<':    /* Make steps slower */
    step_time *= 2.0;
    printf("Step time is now %.3f ms\n",step_time*1000.0);
    break;
case '>':    /* Make steps faster */
    step_time /= 2.0;
    printf("Step time is now %.3f ms\n",step_time*1000.0);
    break;
case 'F':    /* Forward : run motor */
    if ( !stopped && lcmd != 'R' ) {
        stop_cmd(); /* Stop due to toggle */
        lcmd = 0;
    } else {
        op_cmd(); /* Stop prior to change direction */
        queue_cmd(lcmd='F');
    }
    break;
case 'R':    /* Reverse : run motor */
if ( !stopped && lcmd != 'F' ) {
    stop_cmd();
    lcmd = 0;
} else {
    stop_cmd();
    queue_cmd(lcmd='R');
}
break;
case 'S' : /* Just stop */
    stop_cmd();
    break;
case '+' : /* Step clockwise */
case '=' : /* So we don’t have to shift for + */
    stop_cmd();
    step(1);
    break;
case '-' : /* Step counterclockwise */
    stop_cmd();
    step(-1);
    break;
case 'Q' : /* Quit */
    quit = 1;
    break;
default : /* Unsupported */
    stop_cmd();
    help();
}
stop_cmd();
enable(0);
puts("\nExit.\n");
tcsetattr(tty,TCSAFLUSH,&sv_ios); /* Restore terminal mode */
return 0;
/* End bipolar.c */
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.
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.
The datasheet for this part from various manufacturers shows the $V_{IL}$ and $V_{IH}$ levels when $V_{DD} = +5 \, \text{V}$ (and higher). The values shown for $V_{OH}$ for each $V_{DD}$ are all listed at a value of $V_{DD} - 0.5 \, \text{V}$. Extrapolating from that, I have assumed $V_{OH} = 3.3 - 0.5 = 2.8 \, \text{V}$ 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Raspberry Pi, GPIO</th>
<th>CD4013, $V_{DD} = +3.3 , \text{V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{IL}$</td>
<td>$\leq 0.8 , \text{V}$</td>
<td>$\leq 0.05 , \text{V}$ $V_{OL}$</td>
</tr>
<tr>
<td>$V_{IH}$</td>
<td>$\geq 1.3 , \text{V}$</td>
<td>$\geq 2.8 , \text{V}$† $V_{OH}$</td>
</tr>
</tbody>
</table>

†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 $V_{IL}$ 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:

<table>
<thead>
<tr>
<th>Pin</th>
<th>Function</th>
<th>Wired to</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Clock 1</td>
<td>Ground</td>
<td>Not used</td>
</tr>
<tr>
<td>5</td>
<td>Data 1</td>
<td>Ground</td>
<td>Not used</td>
</tr>
<tr>
<td>8</td>
<td>Set 2</td>
<td>Ground</td>
<td>If FF2 not used</td>
</tr>
<tr>
<td>9</td>
<td>Data 2</td>
<td>Ground</td>
<td>Not used</td>
</tr>
<tr>
<td>10</td>
<td>Reset 2</td>
<td>Ground</td>
<td>If FF2 not used</td>
</tr>
<tr>
<td>11</td>
<td>Clock 2</td>
<td>Ground</td>
<td>Not used</td>
</tr>
</tbody>
</table>
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):

```bash
$ ./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 $R_1$. 
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 `SW1` and `LED`. This is necessary because a console may be offline when the last switch or LED change occurs.

Whenever `SW1` 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`.

```
Receiving sensor at: tcp://localhost:9999

SW1: ???
LED: ???

Commands: ⬜️ Online?

0 - Turn remote LED off.
1 - Turn remote LED on.
X - Shutdown sensor node.
Q - Quit the console.
```

**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 SW1. 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.
static void *context = 0; /* ZMQ context */
static void *publisher = 0; /* Publishing socket */
static void *console = 0; /* Pull socket */

static int SW1 = 0; /* Switch status */
static int LED = 0; /* LED status */
static int stop = 0; /* Nonzero when shutting down */

static int gp_SW1 = 22; /* GPIO 22 (input) */
static int gp_LED = 27; /* GPIO 22 (output) */
static int fd_SW1 = -1; /* Open fd for SW1 */

#include "mutex.c"

/*
 * Publish the LED setting to the console(s)
 */
static void
publish_LED(void) {
    char buf [256];
    size_t n;
    int rc;

    n = sprintf(buf,"led:%d",LED);
    mutex_lock();
    rc = zmq_send(publisher,buf,n,0);
    assert(rc!=-1);
    mutex_unlock();
}

/*
 * Publish the switch setting to the console(s)
 */
static void
publish_SW1(void) {
    char buf[256];
    size_t n;
    int rc;

    n = sprintf(buf,"sw1:%d",SW1);
    mutex_lock();
    rc = zmq_send(publisher,buf,n,0);
    assert(rc!=-1);
    mutex_unlock();
}
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;

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

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);
/* Edge : /sys/class/gpio%d/edge */
gpio_setpath(pin, gp_edge,buf,sizeof buf);
f = fopen(buf,"w");
assert(f);
fprintf(f,"%s\n",edge);
fclose(f);

/* Value : /sys/class/gpio%d/value */
gpio_setpath(pin,gp_value,buf,sizeof buf);
fd = open(buf,0_RDWR);
return fd;

* Open/sys/class/gpio%d/value for output :
static int
gpio_open_output(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);

    /* Direction : /sys/class/gpio%d/direction */
gpio_setpath(pin,gp_direction,buf,sizeof buf);
f = fopen(buf,"w");
assert(f);
fprintf(f,"out\n");
fclose(f);

    /* Value : /sys/class/gpio%d/value */
gpio_setpath(pin,gp_value,buf,sizeof buf);
fd = open(buf,0_WRONLY);
return fd;

}
static void gpio_close(int pin) {
    char buf[128];
    FILE *f;

    /* Unexport : /sys/class/gpio/unexport */
    gpio_setpath(pin, gp_unexport, buf, sizeof(buf);
    f = fopen(buf, "w");
    assert(f);
    fprintf(f, "%d\n", pin);
    fclose(f);
}

/*
 * This routine will block until the open GPIO pin has changed
 * value.
 */
static int gpio_poll(int fd) {
    struct poll fd_polls;
    char buf[32];
    int rc, n;

    polls.fd = fd; /* /sys/class/gpio/value */
    polls.events = POLLPRI; /* Exceptions */

    do {
        rc = poll (&polls, 1, -1); /* Block */
    } while (rc < 0 && errno == EINTR);
    assert(rc > 0);

    lseek(fd, 0, SEEK_SET);
    n = read(fd, buf, sizeof(buf)); /* Read value */
    assert(n > 0);
    buf[n] = 0;
    rc = sscanf(buf, "%d", &n);
    assert(rc == 1);
    return; /* Return value */
}

/*
 * Write to the GPIO pin
 */
static void gpio_write(int fd, int dbit) {
    write(fd, dbit ? "1\n" : "0\n", 2);
}

/*
Monitor switch changes on GPIO
*/
static void *
SW1_monitor_thread(void *arg) {
    int rc;

    while ( !stop ) {
        rc = gpio_poll(fd_SW1);       /* Watch for SW1 changes */
        if ( rc < 0 )
            break;
        SW1 = rc;
        publish_SW1();
    }
    return 0;
}

/*
Periodic broadcast to consoles thread
*/
static void *
console_thread(void *arg) {
    while ( !stop ) {
        sleep(3);
        publish_SW1();
        publish_LED();
    }
    return 0;
}

/******************************
Main thread : read switch changes and publish to console (s)
******************************/
int main(int argc, char **argv) {
    pthread_t tid;
    int rc = 0;
    char buf[256];
    int fd_LED = -1;          /* GPIO 27 */
mutex_init();

/* Open GPIO for LED */
fd_LED = gpio_open_output(gp_LED);
if ( fd_LED < 0 ) {
    printf("%s : Opening GPIO %d for output.\n", strerror (errno),gp_LED);
    return 1;
}

/* Open GPIO for SW1 */
fd_SW1 = gpio_open_edge(22,"both"); /* GPIO input */
if ( fd_SW1 < 0 ) {
    printf("%s: Opening GPIO %d for input.\n", strerror(errno),gp_SW1);
    return 1;
}

context = zmq_ctx_new();
assert(context);

/* Create a ZMQ publishing socket */
publisher = zmq_socket(context,ZMQ_PUB);
assert(publisher);
rc = zmq_bind(publisher,service_sensor_pub);
assert(!rc);

/* Create a console PULL socket */
console = zmq_socket(context, ZMQ_PULL);
assert(console);
rc = zmq_bind(console,service_sensor_pull);
assert(rc != -1);

SW1 = 0;
publish_SW1();
publish_LED();
rc = pthread_create(&tid,0,SW1_monitor_thread,0);
assert(!rc);
rc = pthread_create(&tid,0,console_thread,0);
assert(!rc);

/* In this thread, we "pull" console commands : */
remote-Control panel

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     mutex_lock();
316     zmq_close(console);
317     console = 0;
318     rc = zmq_send(publisher,"off: " 4,0);
319     assert(rc !=−1);
320     sleep(3);
321     zmq_close(publisher);
322     publisher = 0;
323     gpio_close(gp_SW1);
324     gpio_close(gp_LED);
325     mutex_unlock();
326     return 0;
327 } /* 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).

www.it-ebooks.info
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.

```c
/* ************************************************************************** */
/* console.c - Raspberry Pi Sensor Console
 * **************************************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <assert.h>
#include <pthread.h>
#include <curses.h>

#include <zmq.h>

#include "mutex.c"

static char *host_name = "local host"; /* Default host name */
static char service_sensor_pub[128]; /* Service name for sensor */
static char service_sensor_pull[128]; /* Service name for sensor’s cmds */

static void *context = 0; /* ZMQ context object */
static void *subscriber = 0; /* Subscriber socket */
static void *console = 0; /* Push socket */

static int SW1 = -1; /* Known status of SW1 */
static int LED = -1; /* Known status of LED */

/* Post the status of SW1 to the console screen */
*/
```
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 }

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 {

attrset(A_NORMAL);
addstr("Off"); /* LED is now off */
}
}
attrset(A_NORMAL);
if ( SW1 >= 0 || LED >= 0 )
mvprintw(7,15,"ONLINE ");
move(7, 12);
refresh();
mutex_unlock(); /* Release hold on curses */
}
/
/ * Post online status to screen */
static void
post_offline(void) {
    SW1 = −1;
    LED = −1;
    mutex_lock(); /* Lock for shared curses access */
    attrset(A_REVERSE|A_BLINK);
    mvprintw(7,15,"OFFLINE");
    refresh();
    mutex_unlock(); /* Done with curses */
    post_LED();
    post_SW1();
}
/
/* Main console thread for command center */
static void *
command_center(void *ignored) {
    int rc;
    post_LED(); /* Post unknown LED status */
    post_SW1(); /* Post unknown SW1 status */
    for (;;) {
        mutex_lock(); /* Lock curses */
        move (7,12); /* Move cursor to command point */
        refresh();
        mutex_unlock(); /* Release curses*/

rc = getch();    /* Wait for keystroke */
mutex_lock();    /* Lock curses */
mvaddch(7,12,rc); /* Echo character that was typed */
refresh();
mutex_unlock();  /* Release curses */

switch (rc) {
    case '0':
        /* Tell sensor to turn off LED */
        rc = zmq_send(console,"led : 0",5,0);
        assert(rc !=-1);
        break;
    case '1':
        /* Tell sensor to turn on LED */
        rc = zmq_send(console,"led: 1",5,0);
        assert(rc!=-1);
        break;
    case 'x':
    case 'X':
        rc = zmq_send(console,"stop :",5,0);
        assert(rc!=-1);
        break;
    case 'q':
    case 'Q':
        /* Quit the command console */
        sleep(1);
        clear();
        refresh();
        endwin();
        exit(0);
        break;
    default :
        ;
}

/* Main thread : init/receive published SW1/LED status updates */
/* Specify the IP number or hostname of the sensor on the command line as argument one : $ ./console myrasp */
int
main(int argc, char **argv) {
    char buf[1024];
    int rc;
    pthread_t tid;

    if ( argc > 1 )
        host_name = argv[1];
    sprintf(service_sensor_pub,"tcp://%s:9999",host_name);
    sprintf(service_sensor_pull,"tcp://%s:9998",host_name);

    mutex_init();
    context = zmq_ctx_new();
    assert(context);

    subscriber = zmq_socket(context,ZMQ_SUB);
    assert(subscriber);

    rc = zmq_connect(subscriber,service_sensor_pub);
    if (rc == -1) perror("zmq_connect\n");
    assert(rc!=-1);

    rc = zmq_setsockopt(subscriber,ZMQ_SUBSCRIBE,"sw1:", 4);
    assert(rc!=-1);
    rc = zmq_setsockopt(subscriber,ZMQ_SUBSCRIBE,"led:", 4);
    assert(rc!=-1);
    rc = zmq_setsockopt(subscriber,ZMQ_SUBSCRIBE, "off:",4);
    assert(rc!=-1);

    console = zmq_socket(context,ZMQ_PUSH);
    assert(console);

    rc = zmq_connect(console, service_sensor_pull);
    assert(!rc);

    initscr();
cbreak();
noecho();
nonl();
clear();
box(stdscr,0,0);
move(1,2);
printw("Receiving sensor at: %s",service_sensor_pub);
attrset(A_UNDERLINE);
mvaddstr(7,2,"Commands:");
attrset(A_NORMAL);
mvaddstr(9,2,"0 − Turn remote LED off.");
mvaddstr(10,2,"1 − Turn remote LED on.");
mvaddstr(11,2,"X − Shutdown sensor node.");
mvaddstr(12,2,"Q − Quit the console.");
mprintw(7,15,"Online ?");

rc = pthread_create(&tid,0,command_center,0);
assert(!rc);

for(;;) {
    rc = zmq_recv(subscriber,buf,sizeof buf − 1,0);
    assert(rc >= 0 && rc < sizeof buf −1);
    buf[rc] = 0;
    if ( !strncmp(buf,"off:",4) )
        post_offline();
    if ( !strncmp(buf,"sw1:",4) ) {
        sscanf(buf,"sw1:%d",&SW1);
        post_SW1();
    }
    if ( !strncmp(buf,"led:",4) ) {
        sscanf(buf,"led:%d",&LED);
        post_LED();
    }
    return 0;
}

/∗ console.c */

/* Mutex . c */

static pthread_mutex_t mutex;

static void
mutex_init(void) {
    int rc = pthread_mutex_init(&mutex, 0);
    assert(!rc);
}
static void mutex_lock(void) {
    int rc = pthread_mutex_lock(&mutex);
    assert(!rc);
}

static void mutex_unlock(void) {
    int rc = pthread_mutex_unlock(&mutex);
    assert(!rc);
}

/* End mutex.c */
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:

\[ V_{\text{avg}} = 3.3 \times 0.75 \]
\[ = 2.475V \]

If the GPIO output signal was high only 10% of the time, the averaged result is \( V_{\text{avg}} = 0.33 \) 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](image)

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:

\[ R_1 = \frac{3.3}{0.0001} = 33 \text{kΩ} \]

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:

  $$I_{\text{div}} = \frac{19200000}{f}$$

  where:

  • $I_{\text{div}}$ is the computed integer divisor.
  • $f$ is the desired PWM frequency.

  The range of the resulting $I_{\text{div}}$ is checked against the peripheral’s limits. The value of $I_{\text{div}}$ 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.

  $idiv = (\text{long})( \text{clock_rate} / (\text{double}) \text{freq} );$
  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 $I_{\text{div}}$ is loaded:

  \[ \text{ugclk}[\text{PWMCLK\_DIV}] = 0x5A000000 | (idiv << 12) \]
Finally, the clock source is set to use the oscillator, and the clock is enabled:

\[ \text{ugclk[PWMCLK_CNTL]} = 0x5A000011; \]

After this, GPIO 18 is configured for ALT function 5, to gain access to the PWM peripheral:

\[ \text{INP_GPIO(18);} \quad /\!*\text{ Set ALT = 0 }*/\]
\[ \text{SET_GPIO_ALT(18,5);} \quad /\!*\text{ Or in '5' }*/\]

The way the \text{SET_GPIO_ALT()} macro is defined requires that the \text{INP_GPIO()} macro be used first. The \text{INP_GPIO()} macro clears the ALT function bits so that \text{SET_GPIO_ALT()} can \text{or} in the new bits (the value 5, in this case).

The remaining steps ready the PWM peripheral:

\[ \text{pwm_ctl->MODE1 = 0;} \quad /\!*\text{ PWM mode }*/\]
\[ \text{pwm_ctl->RPTL1 = 0;} \]
\[ \text{pwm_ctl->SBIT1 = 0;} \]
\[ \text{pwm_ctl->POLA1 = 0;} \]
\[ \text{pwm_ctl->USEF1 = 0;} \]
\[ \text{pwm_ctl->MSEN1 = 0;} \quad /\!*\text{ PWM mode }*/\]
\[ \text{pwm_ctl->CLRF1 = 1;} \]

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 \text{pwm_ratio()}:

\[
\text{static void}
\text{pwm_ratio(unsigned n, unsigned m) { }
\]
\[
\text{...}
\]

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.

\[ \text{pwm_ctl->PWEN1 = 0;} \quad /\!*\text{ Disable }*/\]
\[ *\text{pwm_rng1} = m; \]
\[ *\text{pwm_dat1} = n; \]

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:

```c
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:

```bash
$ ./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:

```bash
$ ./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.
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("%.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 <unistd.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 + 0x2000000)
22 #define PWM_BASE (BCM2708_PERI_BASE + 0x20C000)
23 #define CLK_BASE (BCM2708_PERI_BASE + 0x101000)
24
190
# define PWMCLK_CNTL 40
# define PWMCLK_DIV 41

static volatile unsigned *ugpio = 0;
static volatile unsigned *ugpwm = 0;
static volatile unsigned *ugclk = 0;

statics struct S_PWM_CTL {
    unsigned     PWEN1 : 1;
    unsigned     MODE1 : 1;
    unsigned     RPTL1 : 1;
    unsigned     SBIT1 : 1;
    unsigned     POLA1 : 1;
    unsigned     USEF1 : 1;
    unsigned     CLRF1 : 1;
    unsigned     MSEN1 : 1;
} volatile *pwm_ctl = 0;

static struct S_PWM_STA {
    unsigned     FULL1 : 1;
    unsigned     EMPT1 : 1;
    unsigned     WERR1 : 1;
    unsigned     RERR1 : 1;
    unsigned     GAP01 : 1;
    unsigned     GAP02 : 1;
    unsigned     GAP03 : 1;
    unsigned     GAP04 : 1;
    unsigned     BERR : 1;
    unsigned     STA1 : 1;
} volatile *pwm_sta = 0;

static volatile unsigned *pwm_rng1 = 0;
static volatile unsigned *pwm_dat1 = 0;

#define INP_GPIO(g) *( ugpio+((g )/10)) &= ~(7<<(((g)%10)*3))
#define SET_GPIO_ALT(g,a) \
    *(ugpio+(((g)/10))) |= (((a)<=3?(a)+4:((a)==4?3:2))<<(((g)%10)*3))

/*
 * Establish the PWM frequency :
 */
static int
pwm_frequency(float freq) {
    const double clock_rate = 19200000.0;
    long idiv;
    int rc = 0;
    }
/* Kill the clock:
ugclk[PWMCLK_CNTL] = 0x5A000020; // Kill clock */
pwm_ctl->PWEN1 = 0; // Disable PWM
usleep(10);

/* Compute and set the divisor:
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;
}
ugclk[PWMCLK_DIV] = 0x5A000000 | ( idiv << 12 );

/* Set source to oscillator and enable clock: */
ugclk[PWMCLK_CNTL] = 0x5A000011;

/* GPIO 18 is PWM, when set to Alt Func 5: */
INP_GPIO(18); // Set ALT = 0 */
SET_GPIO_ALT(18,5); // Or in '5 ', */
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;
return rc ;

/* Initialize GPIO/PWM/CLK Access */
static void pwm_init() {
    int fd;
    char *map;

    fd = open("/dev/mem",O_RDWR|O_SYNC); /* Needs root access */
    if ( fd < 0 ) {
        perror("Opening /dev/mem");
        exit(1);
    }

    map = (char *)mmap(
        NULL,                    /* Any address */
        BLOCK_SIZE,              /* # of bytes */
        PROT_READ|PROT_WRITE,
        MAP_SHARED,              /* Shared */
        fd,                      /* /dev/mem */
        PWM_BASE                 /* Offset to GPIO */
    );

    if ( (long)map == -1L ) {
        perror("mmap(/dev/mem)");  
        exit(1);
    }

    /* Access to PWM */
    upwm = (volatile unsigned *)map;
    pwm_ctl = (struct S_PWM_CTL *) &ugpwm[BCM2835_PWM_CONTROL];
    pwm_sta = (struct S_PWM_STA *) &ugpwm[BCM2835_PWM_STATUS];
    pwm_rng1 = &ugpwm[BCM2835_PWM0_RANGE];
    pwm_dat1 = &ugpwm[BCM2835_PWM0_DATA];

    map = (char *)mmap(
        NULL,                    /* Any address */
        BLOCK_SIZE,              /* # of bytes */
        PROT_READ|PROT_WRITE,
        MAP_SHARED,              /* Shared */
        fd,                      /* /dev/mem */
        CLK_BASE                 /* Offset to GPIO */
    );

    if ( (long)map == -1L ) {
        perror("mmap(/dev/mem)");  
        exit(1);
    }
/* Access to CLK */
ugclk = (volatile unsigned *)map;

map = (char *)mmap(
    NULL,   /* Any address */
    BLOCK_SIZE,  /* # of bytes */
    PROT_READ|PROT_WRITE,
    MAP_SHARED, /* Shared */
    fd,     /* /dev/mem */
    GPIO_BASE  /* Offset to GPIO */
    );

if ( (long)map == -1L ) {
    perror("mmap(/dev/mem)");
    exit(1);
}

/* Access to GPIO */
ugpio = (volatile unsigned *)map;
close(fd);

/* Set PWM to ratio N/M, and enable it : */
static void
pwm_ratio(unsigned n,unsigned m) {
    pwm_ctl->PWEN1 = 0; /* Disable */
    *pwm_rng1 = m;
    *pwm_dat1 = n;

    if ( !pwm_sta->STA1 ) {
        if ( pwm_sta->RERR1 )
            pwm_sta->RERR1 = 1;
        if ( pwm_sta->WERR1 )
            pwm_sta->WERR1 = 1;
        if ( pwm_sta->BERR )
            pwm_sta->BERR = 1;
    }
    usleep(10); /* Pause */
pwm_ctl->PWEN1 = 1; /* Enable */
}
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;
            } close(pipe);
            printf("%.1f\n",total);
            fflush(stdout);
            pwm_ratio(total,100);
            usleep(300000);
        }
    }
}
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:

```c
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:

```c
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.

```c
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():

```c
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 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.

```c
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.

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#include <string.h>
#include <math.h>
#include <pthread.h>

#include "gpio_io.c"

typedef struct {
  int     gpio;   /* GPIO out put 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;

/*
 * Timed wait from a float
 */
static void float_wait(double seconds) {
  fd_set mt;
  struct timeval timeout;
  int rc;
```
FD_ZERO(&mt);
timeout.tv_sec = floor(seconds);
timeout.tv_usec = floor((seconds - floor(seconds)) * 1000000);

do {
    rc = select(0,&mt,&mt,&mt,&timeout);
} while (rc < 0 && timeout.tv_sec && timeout.tv_usec);

void *
soft_pwm(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->chg0 = 0; !pwm->chg0 && !pwm->stopf; ) {
            gpio_write(pwm->gpio, 1);
            float_wait(ontime);
            gpio_write(pwm->gpio, 0);
            float_wait(fperiod ontime);
        }
    }

    return 0;
}

*/
* Open a soft PWM object:
*/
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->chg0 = 0;
    pwm->stopf = 0;
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]);
```c
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;
    }
}
gpio_init();
if ( argc > 1 ) {
    /* Run PWM mode */
    pwm = pwm_open(22,1000.0);   /* GPIO 22 (GEN3) */
    pwm_ratio(pwm,n,m);          /* n% , Start it */
    printf("PWM set for %d/%d, frequency %.1f "
        "(for 60 seconds)\n",n,m,f);
    sleep(60);
    printf("Closing PWM.\n");
    pwm_close(pwm);
} else {
    /* Run CPU Meter */
    puts("CPU Meter Mode: ");
    pwm = pwm_open(22,500.0);  /* GPIO 22 (GEN3) */
    pwm_ratio(pwm,1,100);      /* Start at 1%  */
    for (;;) {
        pipe = popen("ps -eo pcpu | sed 1d","r");
        for ( total = 0.0 ; fgets(buf,sizeof buf,pipe); ) {
            sscanf(buf,"%f ",&pct);
            total += pct;
        }
        printf("%.1f%% ",total);
        fflush (stdout) ;
        pclose(pipe);
        pwm_ratio(pwm,total,100);
        printf("\r%.1f%% ",total);
        fflush (stdout) ;
    }
```
170     usleep(300000);
171 }   
172 }   
173 
174  return 0;
175 }   
176 
177 /* End softpwm.c */
**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
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIFO</td>
<td>First in, first out</td>
</tr>
<tr>
<td>FSP</td>
<td>Flash storage processor</td>
</tr>
<tr>
<td>FTL</td>
<td>Flash translation layer</td>
</tr>
<tr>
<td>FUSE</td>
<td>Filesystem in Userspace (File system in USErspace)</td>
</tr>
<tr>
<td>GNU</td>
<td>GNU is not Unix</td>
</tr>
<tr>
<td>GPIO</td>
<td>General-purpose input/output</td>
</tr>
<tr>
<td>GPU</td>
<td>Graphics processing unit</td>
</tr>
<tr>
<td>GTF</td>
<td>Generalized Timing Formula</td>
</tr>
<tr>
<td>H.264</td>
<td>MPEG-4 Advanced Video Coding (AVC)</td>
</tr>
<tr>
<td>H-Bridge</td>
<td>An electronic circuit configuration that allows voltage to be reversed across the load</td>
</tr>
<tr>
<td>HDMI</td>
<td>High-Definition Multimedia Interface</td>
</tr>
<tr>
<td>HID</td>
<td>Human interface device</td>
</tr>
<tr>
<td>I2C</td>
<td>Two-wire interface invented by Philips</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated circuit</td>
</tr>
<tr>
<td>IDE</td>
<td>Integrated development environment</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ISP</td>
<td>Image Sensor Pipeline</td>
</tr>
<tr>
<td>JFFS2</td>
<td>Journalling Flash File System 2</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid-crystal display</td>
</tr>
</tbody>
</table>
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
APPENDIX A | GLOSSARY

**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
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.

<table>
<thead>
<tr>
<th>Supply (Volts)</th>
<th>Tolerance</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Ripple (Peak to Peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5 V</td>
<td>±5%</td>
<td>± 0.25 V</td>
<td>+4.75 V</td>
<td>+5.25 V</td>
</tr>
<tr>
<td>-5 V</td>
<td>±10%</td>
<td>±0.50 V</td>
<td>-4.50 V</td>
<td>-5.50 V</td>
</tr>
<tr>
<td>+12 V</td>
<td>±5%</td>
<td>±0.60 V</td>
<td>+11.40 V</td>
<td>+12.60 V</td>
</tr>
<tr>
<td>-12 V</td>
<td>±10%</td>
<td>±1.2 V</td>
<td>-10.8 V</td>
<td>-13.2 V</td>
</tr>
<tr>
<td>+3.3 V</td>
<td>±5%</td>
<td>±0.165 V</td>
<td>+3.135 V</td>
<td>+3.465 V</td>
</tr>
<tr>
<td>+5 V&lt;sub&gt;SB&lt;/sub&gt;</td>
<td>±5%</td>
<td>±0.25 V</td>
<td>+4.75 V</td>
<td>+5.25 V</td>
</tr>
</tbody>
</table>
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 hobbyist.

**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.

<table>
<thead>
<tr>
<th>V</th>
<th>I</th>
<th>R</th>
</tr>
</thead>
</table>

**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.

<table>
<thead>
<tr>
<th>Name</th>
<th>Prefix</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiples</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mega</td>
<td>M</td>
<td>$10^6$</td>
</tr>
<tr>
<td>kilo</td>
<td>k</td>
<td>$10^3$</td>
</tr>
<tr>
<td>milli</td>
<td>m</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>micro</td>
<td>µ</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Fraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nano</td>
<td>n</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>pico</td>
<td>p</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>
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.

- -mcu=arm1176jzf-s can be used in place of -march=armv6zk
  -mtune=arm1176jzf-s.
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.

![USB card reader and MacBook Pro SD slot](image)

**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:

```bash
$ 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:

```bash
$ mount
/dev/disk0s2 on / (hfs, NFS exported, local, journaled)
```

Insert the SD card:

```bash
$ 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:

```bash
$ 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:

```bash
$ 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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Experimenting with Raspberry Pi

Warren W. Gay
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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