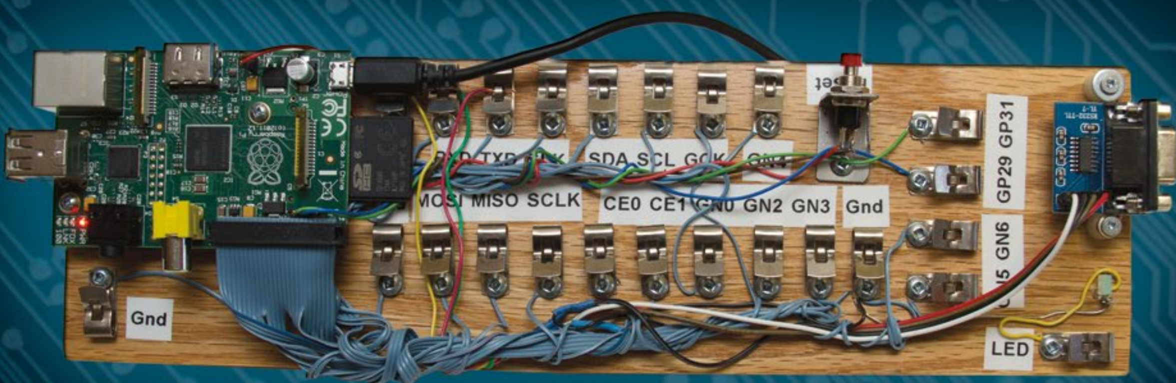
TECHNOLOGY IN ACTION™

Mastering the Raspberry Pi

A COMPLETE REFERENCE GUIDE AND PROJECT IDEA GENERATOR FOR THE RASPBERRY PI



Warren Gay

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

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Contents at a Glance

CHAPTER 1

Why This Book?

This book developed out of a need for an in-depth work about the Raspberry Pi that just didn't seem to exist. If I had found one, I would have gladly purchased it. A quick survey revealed a large number of "how to get started" books. But I pined for something with the kind of meat that appeals to engineering types. Give me numbers, formulas, and design procedures.

Almost all of that information is available out there on the Internet *somewhere*. But I discovered that some questions take considerable time to research. If you know exactly where to look, the answer is right there. But if you're just starting out with the Raspberry Pi, you have several online Easter-egg hunts ahead of you. How much is your time worth?

Here's a short sample of some of the questions answered in this book:

- How much current can a general purpose input/output (GPIO) port source or sink?
- What is the resistance of the GPIO internal pull-up/pull-down resistor?
- Which GPIO does the 1-Wire interface use?
- What is the GPIO voltage range for a 0 bit or 1 bit?
- How do you budget the GPIO power?

Some of these questions have simple answers, while others require an "it depends" explanation. You might be wondering why you need to know the internal GPIO pull-up resistance. Chapter 27 discusses this in connection with motor driver interfaces and what happens at boot time. A number of questions arise when you start designing interfaces to the outside world. While you may not aspire to be an electronics engineer, it helps to think like one.

Who Needs This Book?

This is an important question and the answer, of course, depends on what you are looking for. So let's cut to the chase. This book is

- Not an easy "how to get started" book (These are plentiful.)
- Not a book about Scratch, Python, or Ruby programming
- Not a "download package X, configure it, and install it thusly" book
- Not a media server or retro games console handbook
- Not a book on how to use or administer Linux

This book is targeted to those who have the following:

- A college/university level or hobbyist interest
- Some exposure to Linux (Raspbian Linux)
- Some exposure to the C programming language
- Some exposure to digital electronics

This Book Is Primarily About

In very broad terms, this book can be described primarily as follows:

- A Raspberry Pi hardware reference, with software exploration
- An electronics interfacing projects book, exploring the hardware and software to drive it

In a nutshell, it is a *reference* and *projects* book for the Raspberry Pi. The reference coverage is *extensive* compared to other offerings. A considerable section of the book is also dedicated to projects. I believe that this combination makes it one of the best choices for a book investment.

An ever-increasing number of interface boards can be purchased for the Pi, and the choices increase with each passing month. However, this book takes a "bare metal" approach and does not use any additional extender/adapter board solutions. You can, of course, use them, but they are not required.

This text also uses a "poor student" approach, using cheap solutions that can be purchased as Buy It Now sales on eBay. These then are directly interfaced to the GPIO pins, and I discuss the challenges and safety precautions as required. This approach should also meet the needs of the hobbyist on a limited budget.

You should have a beginning understanding of the C programming language to get the most out of the software presented. Since the projects involve electronic interfacing, a beginning understanding of digital electronics is also assumed. The book isn't designed to teach electronics, but some formulas and design procedures are presented.

Even those with no interest in programming or electronics will find the wealth of reference material in this book worth owning. The back of the book contains a bibliography for those who want to research topics further.

Learning Approach

Many times a construction article in a magazine or a book will focus on providing the reader with a *virtual kit*. By this, I mean that every tool, nut and bolt, component, and raw material is laid out, which if properly assembled, will achieve the project's end purpose. This is fine for those who have no subject area knowledge but want to achieve that end result.

However, this book does *not* use that approach. The goal of this book is to help you learn *how to design* solutions for your Rasbperry Pi. You cannot learn design if you're not allowed to think for yourself! For this reason, I encourage the substitution of parts and design changes. Considerable effort is expended in design procedure. This book avoids a "here is exactly how you do it" approach that many online projects use.

I explain the challenges that must be reviewed, and how they are evaluated and overcome. One simple example is the 2N2222A transistor driver (see Chapter 12), where the design procedure is provided. If you choose to use a different junk box transistor, you can calculate the base resistor needed, knowing its H_{FE} (or measured on a digital multimeter). I provide a recipe of sorts, but you are not required to use the exact same ingredients.

In some cases, a project is presented using a purchased assembled PCB driver. One example (in Chapter 27) is the ULN2003A stepper motor driver PCB that can be purchased from eBay for less than $5 (free shipping). The use of the PCB is entirely optional, since this single-chip solution can be breadboarded. The PCB, however, offers a cheap, ready-made solution with LED indicators that can be helpful in developing the solution. In many cases, the assembled PCB can be purchased for about the same price as the components themselves. Yet these PCB solutions don't rob you of the interface design challenge that remains. They simply save you time.

It is intended that you, the reader, *not* use the presented projects as exact recipes to be followed. Use them as *guidelines*. Explore them as presented first if you like, but do not be afraid to substitute or alter them in some way. By the time you read this book, some PCBs used here may no longer be available. Clever eBay searches for chip numbers may turn up other manufactured PCB solutions. The text identifies the kind of things to watch out for, like unwanted pull-up resistors and how to locate them.

By all means, change the presented software! It costs nothing to customize software. Experiment with it. The programs are purposely provided in a "raw" form. They are *not* meant to be deployed as finished solutions. They are boiled down as much as possible to be easily read and understood. In some cases, error checking was removed to make the code more readable. All software provided in this book is placed in the public domain with no restrictions. Mold it to your needs.

If you follow the projects presented—or better, try them all—you'll be in a good position to develop new interface projects of your own design. You'll know what questions to ask and how to research solutions. You'll know how to interface 3-volt logic to 5-volt logic systems. You'll know how to plan for the state of the GPIO outputs as the Raspberry Pi boots up, when driving external circuits. Experience is the best teacher.

Organization of This Book

This book is organized into four major parts. The first part is an introduction, which does *not* present "how to get started" material but does cover topics like static IP addressing, SSH, and VNC access. I'll otherwise assume that you already have all the "getting started" material that you need.

Part 2 is a large reference section dedicated to the Raspberry Pi hardware. It begins with power supply topics, header strips (GPIO pins), LEDs, and how to wire a reset button. Additional chapters cover SDRAM, CPU, USB, Ethernet (wired and wireless), SD cards, and UART (including RS-232 adapters). A large focus chapter on GPIO is presented. Additional chapters cover Linux driver access to 1-Wire devices, the I2C bus, and the SPI bus. Each chapter examines the hardware and then the software API for it.

In Part 3, important software aspects of the Raspberry Pi are examined. This part starts with a full exploration of the boot process, initialization (from boot to command prompt), and `vcgencmd` and its options. The Linux console and the serial console are documented. Finally, software development chapters on cross- compiling the kernel are covered in detail.

Part 4 is the fun part of the book, where you apply what you learned to various projects. All of the projects are inexpensive and easy to build. They include interfacing 1-Wire sensors, an I2C GPIO extender, a nunchuk as a mouse, an infrared reader, unipolar and bipolar stepper motor drivers, switch debouncing, PWM, and a remote sensor/console. There is also a real-time clock project for the Model A owner (which can be tried on the Model B). These cover the majority of the interfacing use cases that you will encounter.

The meanings of acronyms used in this advanced level book will be taken for granted. As the reader, you are likely familiar with the terms used. If however, you find yourself in need of clarification, Appendix A contains an extensive glossary of terms.

Software in This Book

I generally dislike the "download this guy's package X from here and install it thusly" approach. The problem is that the magic remains buried inside package X, which may not always deliver in the ways that you need. Unless you study their source code, you become what ham radio people call an *appliance operator*. You learn how to install and configure things but you don't learn how they work.

For this reason, a bare metal approach is used. The code presented is unobstructed by hidden software layers. It is also independent of the changes that might occur to magic package X over time. Consequently, it is hoped that the programs that compile today will continue to compile successfully in the years to come.

Python programmers need not despair. Knowing how things are done at the bare metal level can help your understanding. Learning exactly what happens at the system level is an improvement over a vague idea of what a Python package is doing for you. Those who write packages for Python can be inspired by this book.

The software listings have been kept as short as possible. Books filled with pages of code listings tend to be "fluffy." To keep the listing content reduced, the unusual technique of `#include`-ing shared code is often used. Normally, program units are compiled separately and linked together at the end. But that approach requires header files, which would just fill more pages with listings.

The source code used in this book is available for download from this website:

```
git://github.com/ve3wwg/raspberry_pi.git
```

There you can also obtain the associated make files. The `git clone` command can be used on your Raspberry Pi as follows:

```
$ git clone git://github.com/ve3wwg/raspberry_pi.git
```

To build a given project, simply change to the project subdirectory and type the following:

```
$ cd ./raspberry_pi
$ make
```

If you are making program changes and want to force a rebuild from scratch, simply use this:

```
$ make clobber all
```

Final Words

If you are still reading, you are considering purchasing or have purchased this book. That makes me truly excited for you, because chapters of great Raspberry Pi fun are in your hands! Think of this book as a Raspberry Pi owners manual with fun reference projects included. Some may view it as a cookbook, containing basic idea recipes that can be tailored to personal needs. If you own a Raspberry Pi, you need this book!

A lot of effort went into including photos, figures, and tables. These make the book instantly more useful as a reference and enjoyable to read. Additional effort went into making the cross-references to other areas of the book instantly available.

Finally, this is the type of book that you can lie down on the couch with, read through once, while absorbing things along the way. Afterward, you can review the chapters and projects that interest you most. Hopefully, you will be inspired to try all of the projects presented!

CHAPTER 2

The Raspberry Pi

Before considering the details about each resource within the Raspberry Pi, it is useful to take a high-level inventory. In this chapter, let's just list what you get when you purchase a Pi.

In later chapters, you'll be looking at each resource from two perspectives:

- The hardware itself—what it is and how it works
- The driving software and API behind it

In some cases, the hardware will have one or more kernel modules behind it, forming the device driver layer. They expose a software API that interfaces between the application and the hardware device. For example, applications communicate with the driver by using `ioctl(2)` calls, while the driver communicates with the I2C devices on the bus. The `/sys/class` file system is another way that device drivers expose themselves to applications. You'll see this when you examine GPIO in Chapter 12.

There are some cases where drivers don't currently exist in Raspbian Linux. An example is the Pi's PWM peripheral that you'll look at in Chapter 30. Here we must map the device's registers into the application memory space and drive the peripheral directly from the application. Both direct access and driver access have their advantages and disadvantages.

So while our summary inventory here simply lists the hardware devices, you'll be examining each from a hardware and software point of view in the chapters ahead.

Models

A hardware inventory is directly affected by the model of the unit being examined. The Raspberry Pi comes in two models:

- Model A (introduced later as a hardware-reduced model)
- Model B (introduced first and is the full hardware model)

Figure 2-1 shows the Model B and its interfaces. Table 2-1 indicates the differences between the two models.

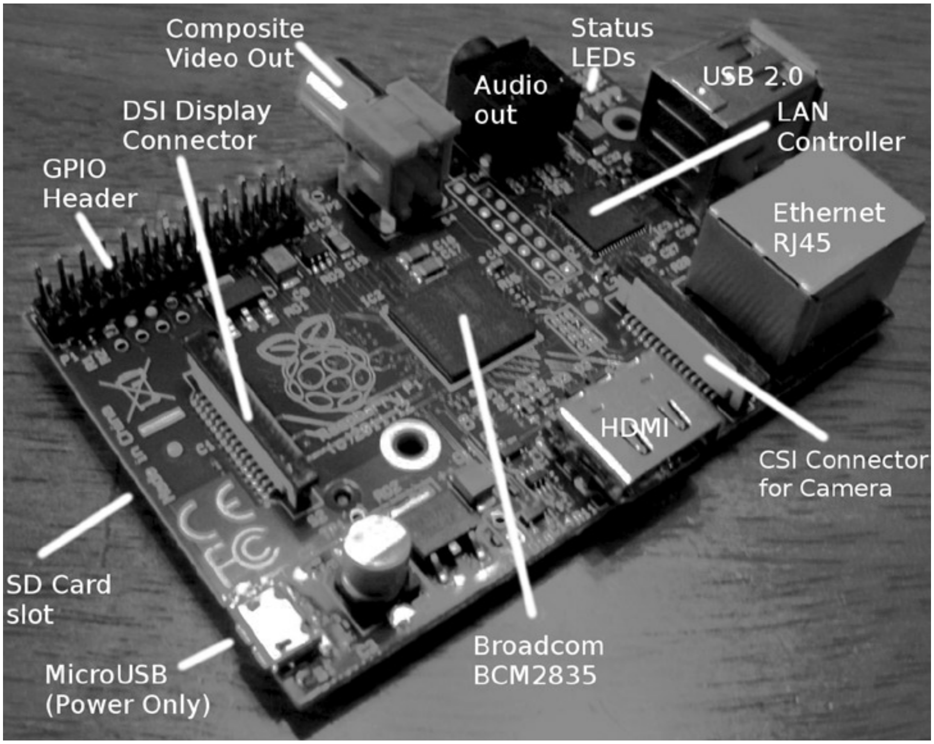

Figure 2-1. *Model B interfaces*

Table 2-1. *Model Differences*

Resource	Model A	Model B
RAM	256 MB	512 MB
USB ports	1	2
Ethernet port	None	10/100 Ethernet (RJ45)
Power consumption[10]	300 mA (1.5 W)	700 mA (3.5 W)
Target price[9]	$25.00	$35.00

As you can see, one of the first differences to note is the amount of RAM available. The revision 2.0 (Rev 2.0) Model B has 512 MB of RAM instead of 256 MB. The GPU also shares use of the RAM. So keep that in mind when budgeting RAM.

In addition, the Model A does not include an Ethernet port but can support networking through a USB network adapter. Keep in mind that only one USB port exists on the Model A, requiring a hub if other USB devices are needed.

Finally, the power consumption differs considerably between the two models. The Model A is listed as requiring 300 mA vs. 700 mA for the Model B. Both of these figures should be considered low because consumption rises considerably when the GPU is active (when using the desktop through the HDMI display port).

The maximum current flow that is permitted through the 5 V micro-USB connection is about 1.1 A because of the fuse. However, when purchasing a power supply/adapter, it is recommended that you seek supplies that are rated higher than 1.2 A because they often don’t live up to their specifications. Chapter 4 provides more details about power supplies.

Hardware in Common

The two Raspberry Pi models share some common features, which are summarized in Table 2-2.[9] The Hardware column lists the broad categories; the Features column provides additional specifics.

Table 2-2. *Common Hardware Features*

Hardware	Features	Comments
System on a chip	Broadcom BCM2835	CPU, GPU, DSP, SDRAM, and USB port
CPU model	ARM1176JZF-S core	With floating point
Clock rate	700 MHz	Overclockable to 800 MHz
GPU	Broadcom VideoCore IV	
	OpenGL ES 2.0	3D
	OpenVG	3D
	MPEG-2	
	VC-1	Microsoft, licensed
	1080p30 H.264	Blu-ray Disc capable, 40 Mbit/s
	MPEG-4	AVC high-profile decoder and encoder
	1 Gpixel/s, 1.5 Gtexels/s	24 GFLOPS with DMA
Video output	Composite RCA	PAL and NTSC
	HDMI	Rev 1.3 and 1.4
	Raw LCD panels	Via DSI
Audio output	3.5 mm jack	
	HDMI	
Storage	SD/MMC/SDIO	Card slot
Peripherals	8 × GPIO	
	UART	
	I2C bus	100 kHz
	SPI bus	Two chip selects, +3.3 V, +5 V, ground
Power source	5 V via micro-USB	

Which Model?

One of the questions that naturally follows a model feature comparison is why the Model A? Why wouldn't everyone just buy Model B?

Power consumption is one deciding factor. If your application is battery powered, perhaps a data-gathering node in a remote location, then power consumption becomes a critical factor. If the unit is supplemented by solar power, the Model A's power requirements are more easily satisfied.

Cost is another advantage. When an Arduino/AVR class of application is being considered, the added capability of the Pi running Linux, complete with a file system on SD, makes it irresistible. Especially at the model A price of $25.

Unit cost may be critical to students in developing countries. Networking can be sacrificed, if it still permits the student to learn on the cheaper Model A. If network capability is needed later, even temporarily, a USB network adapter can be attached or borrowed.

The main advantage of the Model B is its networking capability. Networking today is so often taken for granted. Yet it remains a powerful way to integrate a larger system of components. The project outlined in Chapter 29 demonstrates how powerful ØMQ (ZeroMQ) can be in bringing separate nodes together.

CHAPTER 3

Preparation

While it is assumed that you've already started with the Raspberry Pi, there may be a few things that you want to do before working through the rest of this book. For example, if you normally use a laptop or desktop computer, you may prefer to access your Pi from there. Consequently, some of the preparation in this chapter pertains to network access.

If you plan to do most or all of the projects in this book, I highly recommend using something like the Adafruit Pi Cobbler (covered later in this chapter). This hardware breaks out the GPIO lines in a way that you can access them on a breadboard. If you're industrious, you could build a prototyping station out of a block of wood. I took this approach but would buy the Adafruit Pi Cobbler if I were to do it again (this was tedious work).

Static IP Address

The standard Raspbian SD card image provides a capable Linux system, which when plugged into a network, uses DHCP to automatically assign an IP address to it. If you'd like to connect to it remotely from a desktop or laptop, then the dynamic IP address that DHCP assigns is problematic.

There are downloadable Windows programs for scanning the network. If you are using a Linux or Mac host, you can use Nmap to scan for it. The following is an example session from a MacBook Pro, using the MacPorts collection `nmap` command. Here a range of IP addresses are scanned from 1–254:

```
$ sudo nmap -sP 192.168.0.1-254
Starting Nmap 6.25 (http://nmap.org) at 2013-04-14 19:12 EDT
. . .
Nmap scan report for mac (192.168.0.129)
Host is up.
Nmap scan report for rasp (192.168.0.132)
Host is up (0.00071s latency).
MAC Address : B8:27:EB:2B:69:E8 (Raspberry Pi Foundation)
Nmap done : 254 IP addresses (6 hosts up) scanned in 6.01 seconds
$
```

In this example, the Raspberry Pi is clearly identified on 192.168.0.132, complete with its MAC address. While this discovery approach works, it takes time and is inconvenient.

If you'd prefer to change your Raspberry Pi to use a static IP address, see the "Wired Ethernet" section in Chapter 9 for instructions.

Using SSH

If you know the IP address of your Raspberry Pi or have the name registered in your hosts file, you can log into it by using SSH. In this example, we log in as user pi on a host named rasp (in this example, from a Mac):

```
$ ssh pi@rasp
pi@rasp's password:
Linux raspberrypi 3.2.27+ #250 PREEMPT ... armv6l
...
Last login : Fri Jan 18 22:19:50 2013 from 192.168.0.179
$
```

Files can also be copied to and from the Raspberry Pi, using the scp command. Do a man scp on the Raspberry Pi to find out more.

It is possible to display X Window System (X-Window) graphics on your laptop/desktop, if there is an X-Window server running on it. (Windows users can use Cygwin for this, available from www.cygwin.com.) Using Apple's OS X as an example, first configure the security of your X-Window server to allow requests. Here I'll take the lazy approach of allowing all hosts (performed on the Mac) by using the xhost command:

```
$ xhost +
access control disabled, clients can connect from any host
$
```

From the Raspberry Pi, connected through the SSH session, we can launch Xpdf, so that it opens a window on the Mac:

```
$ export DISPLAY=192.168.0.179:0
$ xpdf &
```

Here, I've specified the Mac's IP address (alternatively, an /etc/hosts name could be used) and pointed the Raspberry Pi to use the Mac's display number :0. Then we run the xpdf command in the background, so that we can continue to issue commands in the current SSH session. In the meantime, the Xpdf window will open on the Mac, while the Xpdf program runs on the Raspberry Pi.

This doesn't give you graphical access to the Pi's desktop, but for developers, SSH is often adequate. If you want remote graphical access to the Raspberry's desktop, see the next section, where VNC is introduced.

VNC

If you're already using a laptop or your favorite desktop computer, you can conveniently access your Raspberry Pi's graphical desktop over the network. Once the Raspberry Pi's VNC server is installed, all you need is a VNC client on your accessing computer. Once this is available, you no longer need a keyboard, mouse, or HDMI display device connected to the Raspberry Pi. Simply power up the Pi on your workbench, with a network cable plugged into it.

You can easily install the VNC server software on the Pi at the cost of about 10.4 MB in the root file system. The command to initiate the download and installation is as follows:

```
$ sudo apt-get install tightvncserver
```

After the software is installed, the only remaining step is to configure your access to the desktop. The vncserver command starts up a server, after which you can connect remotely to it.

Using SSH to log in on the Raspberry Pi, type the following command:

```
$ vncserver :1 -geometry 1024x740 -depth 16 -pixelformat rgb565
```

You will require a password to access your desktop.

```
Password:
Verify:
Would you like to enter a view-only password (y/n ) ? n
New 'X' desktop is rasp:1

Creating default startup script/home/pi/.vnc/xstartup Starting applications specified ➥
in/home/pi/.vnc/xstartup
Log file is/home/pi/.vnc/rasp:1.log
$
```

The password prompts are presented only the first time that you start the VNC server.

Display Number

In the `vncserver` command just shown, the first argument identifies the display number. Your normal Raspberry Pi X-Window desktop is on display `:0`. So when you start up a VNC server, choose a new unique display number like `:1`. It doesn't have to be the number 1. To a limited degree, you can run multiple VNC servers if you find that useful. For example, you might choose to start another VNC server on `:2` with a different display resolution.

Geometry

The `-geometry 1024x740` argument configures the VNC server's resolution in pixels. This example's resolution is unusual in that normally 1024×768 would be used for a display resolution, a common geometry choice for monitors. But this need not be tied to a *physical* monitor resolution. I chose the unusual height of ×740 to prevent the VNC client program from using scrollbars (on a Mac). Some experimentation may be required to find the best geometry to use.

Depth

The `-depth 16` argument is the pixel-depth specification. Higher depths are possible, but the resulting additional network trafficc might curb your enthusiasm.

Pixel Format

The last command-line argument given is `-pixelformat rgb565`. This particular example specifies that each pixel is 5 bits, 6 bits, 5 bits—for red, green and blue, respectively.

Password Setup

To keep unauthorized people from accessing your VNC server, a password is accepted from you when you start the server for the first time. The password chosen can be changed later with the `vncpasswd` command.

Server Startup

If you often use VNC, you may want to define a personal script or alias to start it on demand. Alternatively, have it started automatically by the Raspberry Pi as part of the Linux initialization. See Chapter 17 for more information about initialization scripts.

VNC Viewers

To access your VNC server on the Raspberry Pi, you need a corresponding VNC viewer on the client side. On the Mac, you can use the MacPorts collection to install a viewer:

```
$ sudo port install vnc
```

Once the viewer is installed, you can access your VNC server on the Raspberry Pi at 192.168.0.170, display `:1`, with this:

```
$ vncviewer 192.168.0.170:1
```

If you have your Raspberry Pi in the hosts file under `rasp`, you can use the name instead:

```
$ vncviewer rasp:1
```

When the VNC viewer connects to the server, you will be prompted for a password. This obviously keeps others out of your VNC server.

For Ubuntu Linux, you can install the xvnc4viewer package. For Windows, several choices are available, such as RealVNC and TightVNC.

If you find that the screen resolution doesn't work well with your client computer, experiment with different VNC server resolutions (`-geometry`). I prefer to use a resolution that doesn't result in scrollbars in the viewer. Scrolling around your Raspberry Pi desktop is a nuisance. You can eliminate the need for scrolling by reducing the geometry dimensions.

Stopping VNC Server

Normally, you don't need to stop the VNC server if you are just going to reboot or shut down your Raspberry Pi. But if you want to stop the VNC server without rebooting, this can be accomplished. Supply the display number that you used in the VNC server startup (`:1` in this example) using the `-kill` option:

```
$ vncserver -kill :1
```

This can be useful as a security measure, or to save CPU resources when the server isn't being used. This can also be useful if you suspect a VNC software problem and need to restart it.

Prototype Station

The danger of working with the tiny Raspberry Pi's PCB is that it moves all over the surface as wires tug at it. Given its low mass, it moves easily and can fall on the floor and short wires out in the process (especially around curious cats).

For this reason, I mounted my Raspberry Pi on a nice block of wood. A small plank can be purchased from the lumberyard for a modest amount. I chose to use teak since it looks nice and doesn't crack or warp. Even if you choose to use something like the Adafruit Pi Cobbler, you may find it useful to anchor the Raspberry Pi PCB. Mount the PCB on the wood with spacers. Figure 3-1 shows my prototype station.

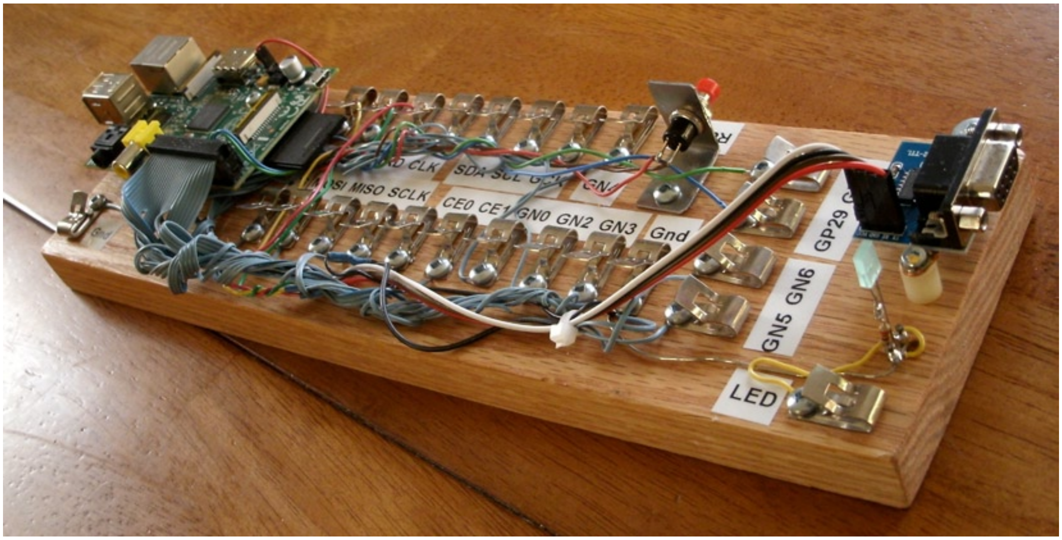

Figure 3-1. *A simple prototype station*

Retro Fahnestock clips were installed and carefully wired to a connector on header strip P1 (the wiring was the most labor-intensive part of this project).

■ **Tip** Fahnestock clips can be economically purchased at places like `www.tubesandmore.com` (part # S-H11-4043-6).

A small PCB for the RS-232 interface was acquired from eBay ($2.32 total) and mounted at the end of the station. Wires from the RS-232 PCB were routed back to RX/TX and +3.3 V clips and simply clipped into place (this allows you to disconnect them, if you wish to use those GPIO pins for some other purpose). The RS-232 PCB is permanently grounded for convenience.

The RS-232 PCB is necessary only for those who wish to use a serial console or to interface with some other serial device. The PCB acquired was advertised on eBay as "MAX232CSE Transfer Chip RS-232 To TTL Converter Module COM Serial Board." The converter (based on the MAX232CSE chip) will work with TTL or 3.3 V interfaces. Connecting the RS-232 converter's VCC connection to the Raspberry Pi +3.3 V supply makes it compatible with the Pi.

■ **Caution** Do not connect the RS-232 converter to +5 V, or you will damage the Pi. For additional information about this, see Chapter 11.

In Figure 3-1 you can see a simple bracket holding a small push button (top right). This has been wired up to P6 for a reset button. This is not strictly required if your power supply is working correctly (power-on reset works rather well). Unlike an AVR setup, *you are not likely to use reset very often*. Chapter 5 has more details about this.

The LED was added to the station last. It was soldered to a pair of half-inch finishing nails, nailed into the wood. The LED's cathode has a 220 Ω resister soldered in series with it to limit the current and wired to ground. The anode is connected to the Fahnestock clip labeled LED. The LED can be tested by connecting an alligator lead from the LED clip to the +3.3 V supply clip (this LED also tolerates +5 V). Be sure to choose a low- to medium-current LED that requires about 10 mA or less (16 mA is the maximum source current from a GPIO pin).

To test your prototyping station, you may want to use the script listed in the "GPIO Tester" section in Chapter 12. That script can be used to blink a given GPIO pin on and off in 1-second intervals.

Adafruit Pi Cobbler

A much easier approach to prototype connections for GPIO is to simply purchase the Adafruit Pi Cobbler kit, which is available from the following site:

`learn.adafruit.com/adafruit-pi-cobbler-kit/overview`

This kit provides you with these features:

- Header connector for the Pi's P1
- Ribbon cable
- Small breakout PCB
- Breakout header pins

After assembly, you plug the ribbon cable onto the header P1. At the other end of the ribbon cable is a small PCB that provides 26 pins that plug into your prototype breadboard. A small amount of assembly is required.

Gertboard

Students might consider using a Gertboard, which is available from this site:

`uk.farnell.com`

The main reason behind this recommendation is that the Raspberry Pi's connections to the outside world are sensitive, 3.3 V, and vulnerable to static electricity. Students will want to connect all manner of buttons, switches, motors, and relays. Many of these interfaces require additional buffers and drivers, which is what the Gertboard is there for.

In addition to providing the usual access to the Pi's GPIO pins, the Gertboard also provides these features:

- Twelve *buffered* I/O pins
- Three push buttons
- Six open collector drivers (up to 50 V, 500 mA)
- A motor controller (18 V, 2 A)
- A two-channel 8/10/12 bit digital-to-analog converter
- A two-channel 10-bit analog-to-digital converter
- A 28-pin DIP ATmega microcontroller

This provides a ready-made learning environment for the student, who is anxious to wire up something and just "make it work." Many of the 3-volt logic and buffering concerns are eliminated, allowing the student to focus on projects.

Bare Metal

Despite the availability of nice adapters like the Gertboard, the focus of this text is on interfacing directly to the Pi's 3 V GPIO pins. Here are some of the reasons:

- No specific adapter has to be purchased for the projects in this book.
- Any specified adapter can go out of production.
- You'll not likely use an expensive adapter on each *deployed* Pi.
- Bare metal interfacing will exercise your design skills.

If we were to do projects with only wiring involved, there wouldn't be much learning involved. Facing the design issues that arise from working with weak 3 V GPIOs driving the outside world will be much more educational.

The third bullet speaks to finished projects. If you're building a robot, for example, you're not going to buy Gertboards everywhere you need to control a motor or read sensor data. You're going to want to economize and build that yourself. This book is designed to help you *face* those kinds of challenges.

CHAPTER 4

Power

One of the most frequently neglected parts of a system tends to be the power supply—at least when everything is working. Only when things get weird does the power supply begin to get some scrutiny.

The Raspberry Pi owner needs to give the power supply extra respect. Unlike many AVR class boards, where the raw input voltage is followed by an onboard 5 V regulator, the Pi expects its power to be regulated at the input. The Pi does include onboard regulators, but these regulate to lower voltages (3.3 V and lower).

Figure 4-1 illustrates the rather fragile Micro-USB power input connector. There is a large round capacitor directly behind the connector that people often grab for leverage. It is a mistake to grab it, however, as many have reported “popping it off” by accident.

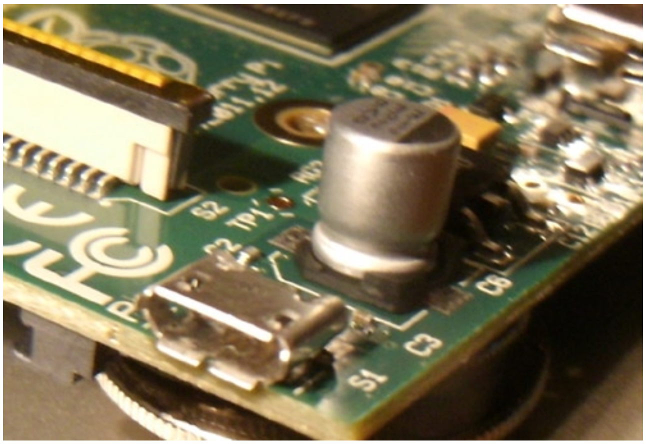

Figure 4-1. *Micro-USB power input*

Calculating Power

Sometimes power supplies are specified in terms of voltage, and power handling capability in watts. The Pi's input voltage of 5 V must support a *minimum* of 700 mA (Model B). Let's compute a power supply figure in watts (this does not include any added peripherals):

$$\begin{aligned} P &= V \times I \\ &= 5 \times 0.7 \\ &= 3.5\,W \end{aligned}$$

The 3.5 W represents a minimum requirement, so we should overprovision this by an additional 50%:

$$\begin{aligned} P &= 3.5 \times 1.50 \\ &= 5.25\,W \end{aligned}$$

The additional 50% yields a power requirement of 5.25 W.

■ **Tip** Allow 50% extra capacity for your power supply. A power supply gone bad may cause damage or many other problems. One common power-related problem for the Pi is loss of data on the SD card.

Current Requirement

Since the power supply being sought produces one output voltage (5 V), you'll likely see adapters with advertised *current* ratings instead of power. In this case, you can simply factor a 50% additional current instead:

$$\begin{aligned} I_{supply} &= I_{Pi} \times 1.50 \\ &= 0.700 \times 1.50 \\ &= 1.05\,A \end{aligned}$$

To double-check our work, let's see whether this agrees with the power rating we computed earlier:

$$\begin{aligned} P &= V \times I \\ &= 5 \times 1.05 \\ &= 5.25\,W \end{aligned}$$

The result does agree. You can conclude this section knowing that you *minimally* need a 5 V supply that produces one of the following:

- 5.25 W or more
- 1.05 A or more (ignoring peripherals)

Supplies that can meet either requirement, should be sufficient. However, you should be aware that not all advertised ratings are what they seem. Cheap supplies often fail to meet their own claims, so an additional margin must always be factored in.

Peripheral Power

Each additional circuit that draws power, especially USB peripherals, must be considered in a power budget. Depending on its type, a given USB peripheral plugged into a USB 2 port can expect up to 500 mA of current, assuming it can obtain it. (Pre Rev 2.0 USB ports were limited to 140 mA by polyfuses.)

Wireless adapters are known to be power hungry. Don't forget about the keyboard and mouse when used, since they also add to the power consumption. If you've attached an RS-232 level shifter circuit (perhaps using MAX232CPE), you should budget for that small amount also in the 3 V supply budget. This will indirectly add to your +5 V budget, since the 3 V regulator is powered from it. (The USB ports use the +5 V supply.) Anything that draws power from your Raspberry Pi should be tallied.

Model B Input Power

The Raspberry Pi's input voltage is fixed at exactly 5 V (±0.25 V). Looking at the schematic in Figure 4-2, you can see how the power enters the micro-USB port on the pin marked VBUS. Notice that the power flows through fuse F3, which is rated at 6 V, 1.1 A. If after an accidental short, you find that you can't get the unit to power up, check that fuse with an ohmmeter.

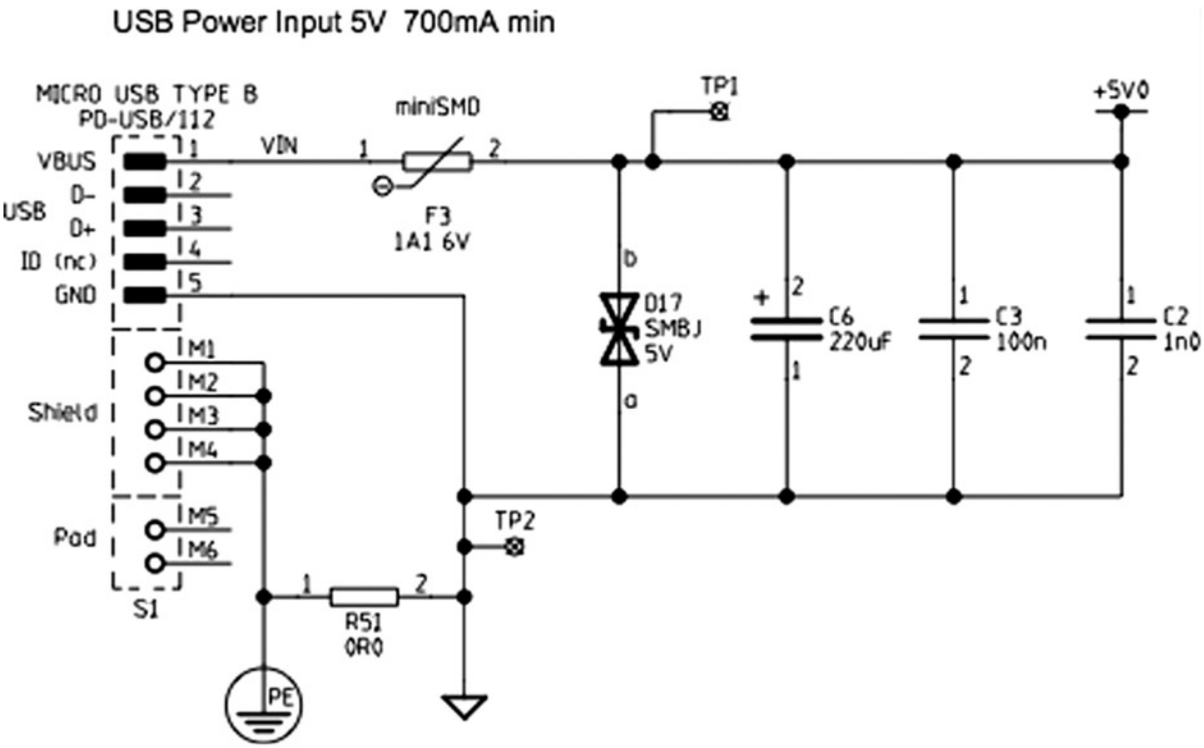

Figure 4-2. *Model B Rev 2.0 input power*

If you bring the input +5 V power into the Pi through header P1, P5, or TP1, for example, you will lose the safety of the fuse F3. So if you bypass the micro-USB port to bring in power, you may want to include a safety fuse in the supplying circuit.

Figure 4-3 shows the 3.3 V regulator for the Pi. Everything at the 3.3 V level is supplied by this regulator, and the current is limited by it.

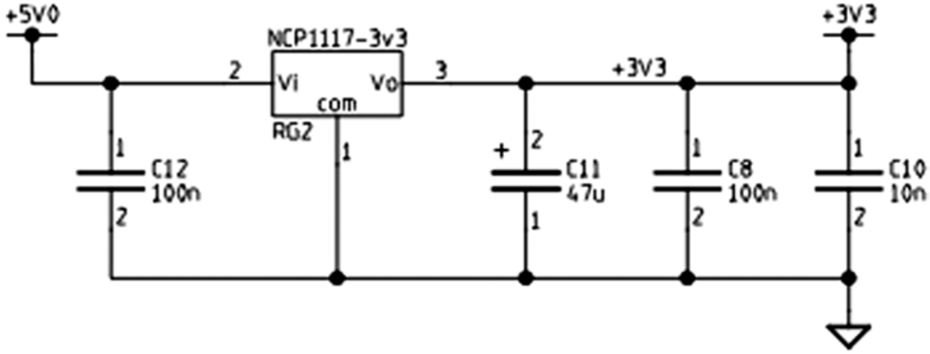

Figure 4-3. *3.3 V power*

Model A Input Power

Like the Model B, the Model A receives its power from the micro-USB port. The Model A power requirement is 300 mA, which is easily supported by a powered USB hub or desktop USB 2 port. A USB 2 port is typically able to supply a maximum of 500 mA unless the power is divided among neighboring ports. You may find in practice, however, that not all USB ports will deliver 500 mA.

As with the Model B, factor the power required by your USB peripherals. If your total nears or exceeds 500 mA, you may need to power your Model A from a separate power source. Don't try to run a wireless USB adapter from the Model A's USB port if the Pi is powered by a USB port itself. The total current needed by the Pi and wireless adapter will likely exceed 500 mA. Supply the wireless adapter power from a USB hub, or power the Pi from a 1.2 A or better power source. Also be aware that not all USB hubs function correctly under Linux, so check compatibility if you're buying one for that purpose.

3.3 Volt Power

Since the 3.3 V supply appears at P1-01, P1-17, and P5-02, it is useful to examine Figure 4-3 (shown previously) to note its source. This supply is indirectly derived from the input 5 V supply, passing through regulator RG2. The maximum excess current that can be drawn from it is 50 mA; the Raspberry Pi uses up the remaining capacity of this regulator.

When planning a design, you need to budget this 3 V supply carefully. Each GPIO output pin draws from this power source an additional 3 to 16 mA, depending on how it is used. For more information about this, see Chapter 12.

Powered USB Hubs

If your power budget is stretched by USB peripherals, you may want to consider the use of a *powered* USB hub. In this way, the *hub* rather than your Raspberry Pi provides the necessary power to the downstream peripherals. The hub is especially attractive for the Model A because it provides additional ports.

Again, take into account that not all USB hubs work with (Raspbian) Linux. The kernel needs to cooperate with connected USB hubs, so software support is critical. The following web page lists known working USB hubs:

http://elinux.org/RPi_Powered_USB_Hubs

Power Adapters

This section pertains mostly to the Model B because the Model A is easily supported by a USB 2 port. We'll first look at an unsuitable source of power and consider the factors for finding suitable units.

An Unsuitable Supply

The example shown in Figure 4-4 was purchased on eBay for $1.18 with free shipping (see the upcoming warning about fakes). For this reason, it was tempting to use it.

Figure 4-4. *Model A1265 Apple adapter*

This is an adapter/charger with the following ratings:

- *Model*: A1265
- *Input*: 100–240 VAC
- *Output*: 5 V, 1 A

When plugged in, the Raspberry Pi's power LED immediately lights up, which is a good sign for an adapter (vs. a charger). A fast rise time on the power leads to successful power-on resets. When the voltage was measured, the reading was +4.88 V on the +5 V supply. While not ideal, it is within the range of acceptable voltages. (The voltage must be between 4.75 and 5.25 V.)

The Apple unit seemed to work fairly well when HDMI graphics were *not* being utilized (using serial console, SSH, or VNC). However, I found that when HDMI was used and the GPU had work to do (move a window across the desktop, for example), the system would tend to seize up. This clearly indicates that the adapter does not fully deliver or regulate well enough.

■ **Caution** Be very careful of counterfeit Apple chargers/adapters. The Raspberry Pi Foundation has seen returned units damaged by these. For a video and further information, see `www.raspberrypi.org/archives/2151`.

E-book Adapters

Some people have reported good success using e-book power adapters. I have also successfully used a 2 A Kobo charger.

Best Power Source

While it is possible to buy USB power adapters at low prices, it is wiser to spend more on a high-quality unit. It is not worth trashing your Raspberry Pi or experiencing random failures for the sake of saving a few dollars.

If you lack an oscilloscope, you won't be able to check how clean or dirty your supply current is. A better power adapter is cheaper than an oscilloscope. A shaky/noisy power supply can lead to all kinds of obscure and intermittent problems.

A good place to start is to simply Google "recommended power supply Raspberry Pi." Do your research and include your USB peripherals in the power budget. Remember that wireless USB adapters consume a lot of current—up to 500 mA.

■ **Note** A random Internet survey reveals a range of 330 mA to 480 mA for wireless USB adapter current consumption.

Voltage Test

If you have a DMM or other suitable voltmeter, it is worthwhile to perform a test after powering up the Pi. This is probably the very first thing you should do, if you are experiencing problems.

Follow these steps to perform a voltage test:

1. Plug the Raspberry Pi's micro-USB port into the power adapter's USB port.
2. Plug in the power adapter.
3. Measure the voltage between P1-02 (+5 V) and P1-25 (Ground): expect +4.75 to +5.25 V.
4. Measure the voltage between P1-01 (+3.3 V) and P1-25 (Ground): expect +3.135 to +3.465 V.

■ **Caution** Be very careful with your multimeter probes around the pins of P1. *Be especially careful not to short the +5 V to the +3.3 V pin*, even for a fraction of a second. Doing so will zap your Pi! If you feel nervous or shaky about this, leave it alone. You may end up doing more harm than good. As a precaution, put a piece of wire insulation (or spaghetti) over the +3.3 V pin.

The left side of Figure 4-5 shows the DMM probes testing for +5 V on header strip P1. Again, be very careful not to touch more than one pin at a time when performing these measurements. *Be particularly careful not to short between 5 V and 3.3 V*. To avoid a short-circuit, use a piece of wire insulation, heat shrink tubing, or even a spaghetti noodle over the other pin.

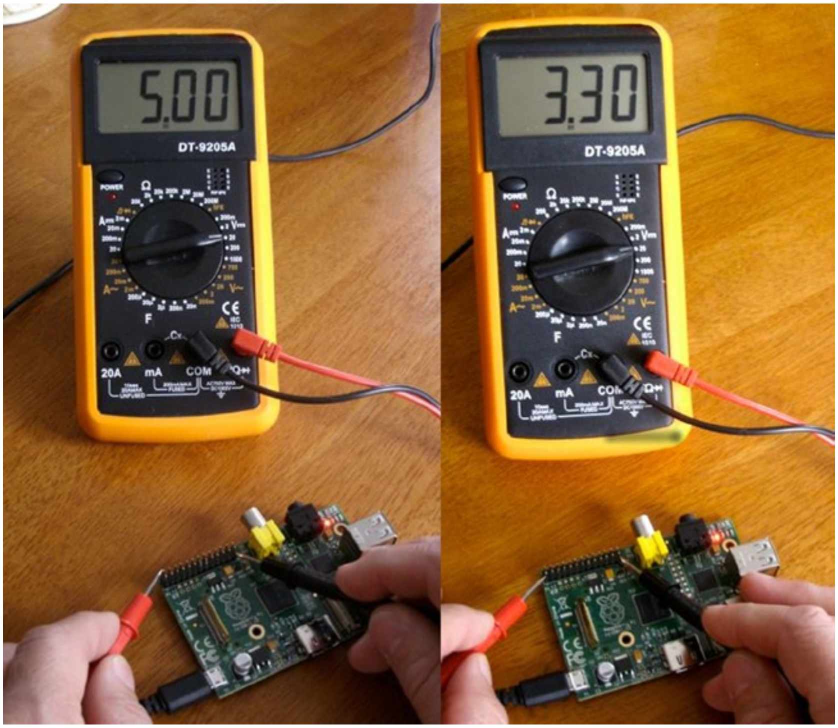

Figure 4-5. *Measuring voltages*

The right side of Figure 4-5 shows the positive DMM probe moved to P1-01 to measure the +3.3 V pin. Appendix B lists the ATX power supply standard voltage levels, which include +5 ± 0.25 V and +3.3 ± 0.165 V.

Battery Power

Because of the small size of the Raspberry Pi, it may be desirable to run it from battery power. Doing so requires a regulator and some careful planning. To meet the Raspberry Pi requirements, you must form a power budget. Once you know your maximum current, you can flesh out the rest. The following example assumes that 1 A is required.

Requirements

For clarity, let's list our battery power requirements:

- Voltage 5 V, within ± 0.25 V
- Current 1 A

Headroom

The simplest approach is to use the linear LM7805 as the 5 V regulator. But there are some disadvantages:

- There must be some headroom above the input voltage (about 2 V).
- Allowing too much headroom increases the power dissipation in the regulator, resulting in wasted battery power.
- A lower maximum output current can also result.

Your batteries should provide a minimum input of 5+2 V (7 V). Any lower input voltage to the regulator will result in the regulator "dropping out" and dipping below 5 V. Clearly, a 6 V battery input will not do.

LM7805 Regulation

Figure 4-6 shows a very simple battery circuit using the LM7805 linear regulator. Resistor R_L represents the load (the Raspberry Pi).

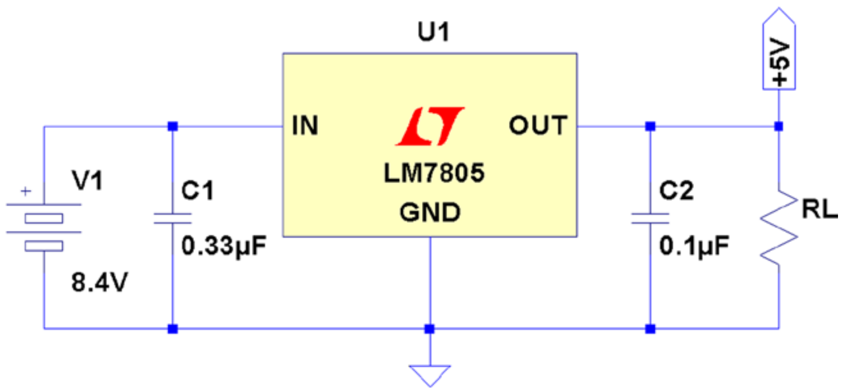

Figure 4-6. *Regulated battery supply*

The 8.4 V battery is formed from seven NiCad cells in series, each producing 1.2 V. The 8.4 V input allows the battery to drop to a low of 7 V before the minimum headroom of 2 V is violated.

Depending on the exact 7805 regulator part chosen, a typical heat-sinked parameter set might be as follows:

- *Input voltage*: 7–25 V
- *Output voltage*: 1.5 A (heat-sinked)
- *Operating temperature*: 125°C

Be sure to use a heat sink on the regulator so that it can dissipate heat energy to the surrounding air. Without one, the regulator can enter a thermal shutdown state, reducing current flow to prevent its own destruction. When this happens, the output voltage will drop below +5 V.

Keep in mind that the amount of power dissipated by the battery is more than that received by the load. If we assume that the Raspberry Pi is consuming 700 mA, a minimum of 700 mA is also drawn from the battery through the regulator (and it could be slightly higher). Realize that the regulator is dissipating additional energy because of its higher input voltage. The total power dissipated by the regulator and the load is as follows:

$$\begin{aligned} P_d &= P_L \times P_R \\ &= 5V \times 0.7\,A + (8.4\,V - 5\,V) \times 0.7\,A \\ &= 3.5\,W + 2.38\,W \\ &= 5.88\,W \end{aligned}$$

The regulator must dissipate the difference between the input and the output voltages (2.38 W). This additional energy heats up the regulator with the energy being given away at the heat sink. Because of this, designers avoid using a high input voltage on linear regulator circuits.

If the regulator is rated at a maximum of 1.5 A at 7 V (input), the power maximum for the regulator is about 10.5 W. If we apply an input voltage of 8.4 V instead of 7, we can derive what our 5 V maximum current will be:

$$\begin{aligned} I_{\max} &= \frac{P_{\max}}{V_{in}} \\ &= \frac{10.5\,W}{8.4\,V} \\ &= 1.25\,A \end{aligned}$$

From this, we find that the 8.4 V battery regulator circuit can provide a maximum of 1.25 A at the output, without exceeding the regulator's power rating. Multiply 8.4 V by 1.25 A to convince yourself that this equals 10.5 W.

DC-DC Buck Converter

If the application is designed for data acquisition, for example, it is desirable to have it run as long as possible on a given set of batteries or charge cycle. A switching regulator may be more suitable than the linear regulator.

Figure 4-7 shows a very small PCB that is about 1.5 SD cards in length. This unit was purchased from eBay for $1.40, with free shipping. At these prices, why would you build one?

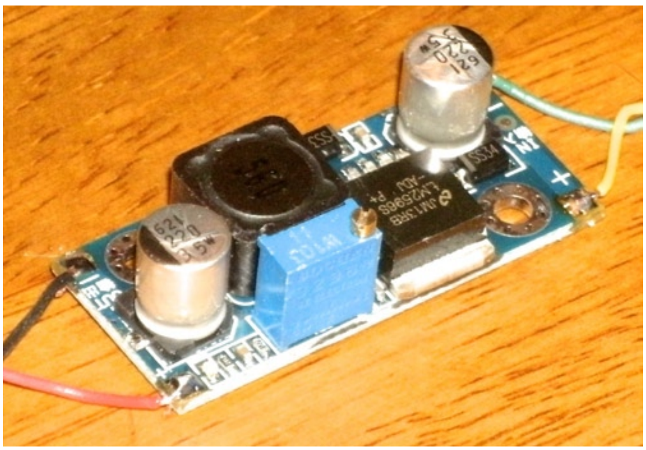

Figure 4-7. *DC-DC buck converter*

They are also simple to use. You have + and – input connections and + and – output connections. Feed power in at one voltage and get power out at another voltage. This is so simple that you'll forgive me if I omit the diagram for it.

But don't immediately wire it up to your Raspberry Pi, until you have calibrated the output voltage. While it *might* come precalibrated for 5 V, it is best not to count on it. If the unit produces a higher voltage, you might fry the Pi.

The regulated output voltage is easily adjusted by a multiturn trim pot on the PCB. Adjust the pot while you read your DMM.

The specifications for the unit I purchased are provided in Table 4-1 for your general amusement. Notice the wide range of input voltages and the fact that it operates at a temperature as low as –40ºC. The wide range of input voltages and current up to 3 A clearly makes this a great device to attach to solar panels that might vary widely in voltage.

Table 4-1. *DC-DC buck converter specifications*

Parameter	Min	Max	Units	Parameter	Min	Max	Units
Input voltage	4.00	35.0	Volts	Output ripple		30.9	mA
Input current		3.0	Amps	Load regulation	±0.5	%	
Output voltage	1.23	30.0	Volts	Voltage regulation	±2.5	%	
Conversion efficiency		92	%	Working temperature	–40	+85	°C
Switching frequency		150	kHz	PCB size		45×20×12	mm
				Net weight		10	g

The specification claims up to a 92% conversion efficiency. Using 15 V on the input, I performed my own little experiment with measurements. With the unit adjusted to produce 5.1 V at the output, the readings shown in Table 4-2 were taken.

Table 4-2. *Readings taken from experiment*

Parameter	Input	Output	Units
Voltage	15.13	5.10	Volts
Current	0.190	0.410	Amps
Power	2.87	2.09	Watts

From the table we expected to see more power used on the input side (2.87 W). The power used on the output side was 2.09 W. The efficiency then becomes a matter of division:

$$\frac{2.09}{2.87} = 0.728$$

From this we can conclude that the measured conversion efficiency was about 72.8%.

How well could we have done if we used the LM7805 regulator? The following is a best case estimate, since I don't have an actual current reading for that scenario. But we do know that at least as much current that flows out of the regulator must flow into it (likely more). So what is the absolute best that the LM7805 regulator could theoretically do? Let's apply the same current draw of 410 mA for the Raspberry Pi at 5.10 V, as shown in Table 4-3. (This was operating without HDMI output in use.)

Table 4-3. *Hypothetical LM7805 power use*

Parameter	Input	Output	Units
Voltage	7.1	5.10	Volts
Current	0.410	0.410	Amps
Power	2.91	2.09	Watts

The power efficiency for this best case scenario amounts to this:

$$\frac{2.09}{2.91} = 0.718$$

The absolute best case efficiency for the LM7805 regulator is 71.8%. But this is achieved at its *optimal* input voltage. Increasing the input voltage to 12 V causes the power dissipation to rise considerably, resulting in a 42.5% efficiency (this calculation is left to the reader as an exercise). Attempting to operate the LM7805 regulator at 15.13 V, as we did with the buck converter, would cause the efficiency to drop to less than 33.7%. Clearly, the buck converter is much more efficient at converting power from a higher voltage source.

Signs of Insufficient Power

In the forums, it has been reported that ping sometimes doesn't work from the desktop (with HDMI), yet works OK in console mode.[42] Additionally, I have seen that desktop windows can freeze if you move them (HDMI). As you start to move the terminal window, for example, the motion would freeze part way through, as if the mouse stopped working.

These are signs of the Raspberry Pi being power starved. The GPU consumes more power when it is active, performing accelerated graphics. Either the desktop freezes (GPU starvation) or the network interface fails (ping). There may be other symptoms related to HDMI activity.

Another problem that has been reported is resetting of the Raspberry Pi shortly after starting to boot. The board starts to consume more power as the kernel boots up, which can result in the Pi being starved.[43]

If you lose your Ethernet connection when you plug in a USB device, this too may be a sign of insufficient power.[44]

While it may seem that a 1 A power supply should be enough to supply a 700 mA Raspberry Pi, you will be better off using a 2 A supply instead. Many power supplies simply don't deliver their full advertised ratings.

The micro-USB cable is something else to suspect. Some are manufactured with thin conductors that can result in a significant voltage drop. Measuring the voltage as shown previously in the "Voltage Test" section may help diagnose that. Try a higher-quality cable to see whether there is an improvement.

No Power

If your Pi appears dead, even though power is present at the input, the input polyfuse could have blown. If this was a recent event, allow the unit to cool down. The polymer in the fuse recrystallizes, but this can take several hours. If you think the F3 poly fuse is permanently destroyed, see the Linux wiki page[45] for how to test it.