

## CREATING FUNCTIONOIDS WITH LEGO MINDSTORMS ROBOTICS INVENTION SYSTEM

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**S**ay the word *LEGO* and most adults think of a million tiny plastic pieces strewn across a floor, waiting to be stepped on with bare feet. Anyone who has ever had one of those little angle pieces jab into a tender arch or break the skin on a heel knows how painful owning a LEGO set can be!

Still, apart from that occasional torture of walking over hard plastic, LEGO sets are wonderful amusements for both young and old. You can build most anything with LEGO parts. And with the help of your PC and the LEGO Mindstorms *Robotics Invention System* you can even create your own *functionoids*—functional (and sometimes useful!) computer programmed robots. In this chapter, we'll look at the popular LEGO Mindstorms Robotics Invention System, discuss what it has to offer, and give you detailed information on how the Mindstorms system works.

The LEGO Mindstorms Robotics Invention System comes with a detailed “Constructapedia” of practical robotic experiments. Moreover, other projects available on the LEGO Mindstorms Web page—and indeed hundreds of other independent Web pages—ensure that you'll have plenty to experiment with. Because of the wealth of printed project designs available, we won't get into the general use of the Mindstorms set in this chapter. Instead, we'll talk about the internals of the LEGO Mindstorms robot and how to “hack” it to extend its usefulness.

Be sure to also check out Chapter 14, “Programming the LEGO Mindstorms RCX: Advanced Methods,” for additional details on programming the Mindstorms robot using third-party tools and utilities.

# What Makes Up the Mindstorms System

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The LEGO Mindstorms Robotics Invention System (RIS) consists of three major parts:

The *RCX* (Robotic Command Explorer) controller. The RCX is otherwise known as a “brick” or “programmable brick.” The term comes from robotics researchers at the Massachusetts Institute of Technology, who were the original developers of the concept behind the RCX. You can attach a collection of motors and sensors to the RCX and create a mobile automaton. Because the RCX uses standard LEGO “bumps,” you can attach regular LEGO parts to it and build your own robot.

The Mindstorms *programming environment*, otherwise known as *RCX Code*, allows you to create, store, and download programs from your personal computer and into the RCX. While the Mindstorms programming environment is the standard method for writing programs for the RCX, it is not the only one. Chapter 14 addresses two popular alternative programming environments for the LEGO RCX.

A two-way *communications tower* for transmitting signals between your computer and the RCX. The tower uses modulated infrared (IR) light rather than radio signals, so two or more RCX units can be programmed in the same room (you can adjust the power output of the IR tower to avoid interference).

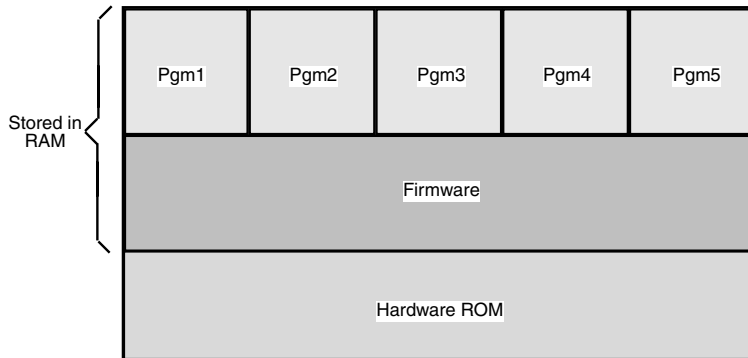
## A Look Inside the RCX

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The LEGO Mindstorms RCX contains an Hitachi H8/3292 *microcontroller*, running at 16 MHz. Hitachi calls its product a “single-chip microcomputer,” but many others in the chip industry refer to such devices as “microcontrollers.” Microcontrollers are like miniature computers but are designed for “embedded applications” for controlling hardware. The main advantage microcontrollers have over full computers is that they are fairly inexpensive—just a few dollars, as opposed to several hundred dollars.

The H8 supports several memory types, including both ROM (read-only memory) and RAM (random access memory). It also comes with its own built-in timers—three to be exact, though the RCX splits one of them to create a total of four. It also has eight 10-bit analog-to-digital converters. In all, it is a highly capable chip, which is one reason why the RCX can pack so many features in such a small package. (By the way, Chapters 31 through 33 of this book deal with several off-the-shelf microcontrollers, including the venerable Basic Stamp, that you can use with your robot creations. Be sure to check these chapters out if you are interested in creating your own version of the LEGO RCX.)

Figure 13.1 shows several different “layers” of the program instruction used in the RCX. At the bottom is a form of hardware *BIOS* (basic input/output system). This hardware level is a permanent part of the H8 processor and provides for very low-level functionality, including the downloading of programs. The hardware BIOS is stored in 16K bytes of ROM. It cannot be changed or erased.



**FIGURE 13.1** The Mindstorms RCX uses a hardware BIOS in ROM, along with firmware and data in RAM.

The *firmware* layer contains what could be considered the RCX’s operating system. This operating system can be periodically updated. In fact, when you first install the Mindstorms system on your computer, part of the setup process involves downloading the firmware from a file on your computer’s hard disk and into the RCX. Whenever LEGO releases updates for the RCX you need merely to return to the setup portion of the Mindstorms program and download the new version of the firmware.

Finally, the *data* layer contains the actual programs that you run on the RCX. Data programs are stored in random access memory. The batteries in the RCX continuously apply a small amount of power to the memory so your programs remain, even when the RCX is turned off.

Both the firmware and the data are stored in 32K bytes of RAM. Being RAM, the data cannot only be replaced; it can be erased (including accidentally). The RCX can store up to five separate programs. There is enough RAM capacity for the firmware and no more than 1.2K for each of the five programs. Program data is stored in a 6K-byte region; the rest of the RAM is allocated to the firmware. Compared to your desktop computer, that’s not very much storage space. However, the RCX needs relatively little RAM to run its programs. Since there are only five “slots” for programs, once you’ve downloaded a program into each slot you have to overwrite one of the old programs in order to download a new one.

Because data and firmware are held in RAM, all your programs will be wiped out if the batteries are removed or are allowed to become depleted. When the memory is swept clean you must also redownload the firmware. This involves running the basic setup section of the Mindstorms installation program.

## Brick Variations

The RCX that comes with the LEGO Mindstorms Robotic Invention System isn’t the only programmable brick that LEGO makes. The CyberMaster, for example, is a programmable robot designed primarily for use in schools.

Included in the LEGO Mindstorms Robot Discovery Set (RDS) is the Scout, another programmable brick that supports two motors and two sensors. You can also program the Scout via a computer (though the original RDS lacked this feature). The official Scout programming language from LEGO is PBrick Assembler, which is said to be a common language for LEGO's future products. You can find information on this programming language at the LEGO Mindstorms Web site at [www.legomindstorms.com](http://www.legomindstorms.com). Note that in this chapter we concentrate on the RCX, but that doesn't mean you should turn a blind eye toward the Scout. Feel free to explore the RCX, Scout, or preferably both!

LEGO sells a version of the LEGO Mindstorms Robotics Invention System that has different software than the retail version. The school version uses a programming platform known as *Robolab*, while the commercial or home version uses a fully graphical programming environment called RCX Code. The hardware is the same, but the software—the way to program the robot—is different.

## The Origins of the Mindstorms RCX

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Thanks to its unusual design and almost limitless potential, there has been much interest in the genesis of the Mindstorms RCX. The idea of integrating a small computer into a generic, programmable device goes back some years, and it has been the subject of very active research at the Massachusetts Institute of Technology. MIT first demonstrated so-called programmable bricks during the early 1990s, and these prototypes clearly influenced the design of the LEGO Mindstorms RCX. Researchers at MIT are quick to point out that the internals of the RCX were developed entirely by LEGO designers. Still, a quick look at <http://fredm.www.media.mit.edu/people/fredm/> and other Web pages hosted by MIT demonstrates the impact of this pioneering work.

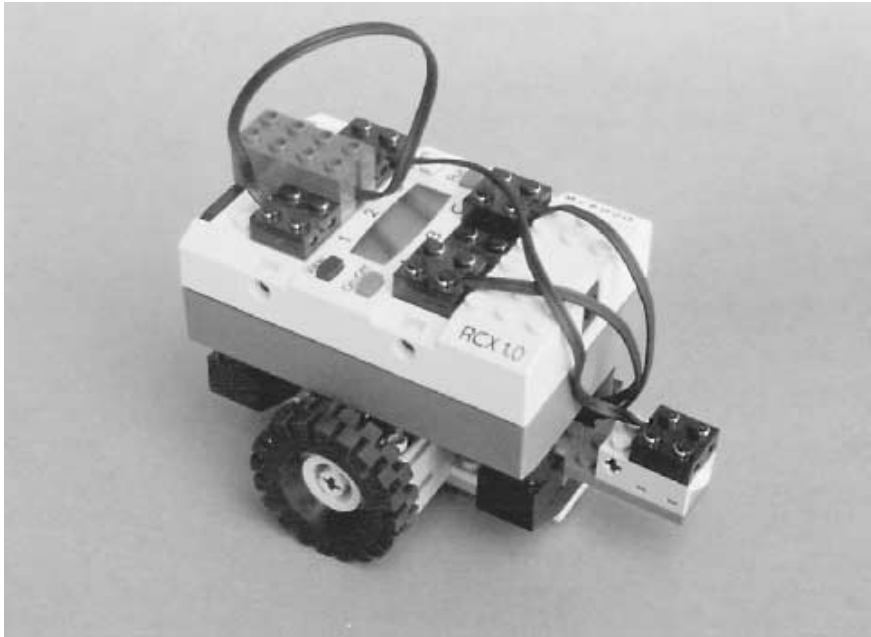
An important aspect of the “*brick*”-based *microcontroller* is that it extends the programmability and flexibility of the microcontroller to nontechnical users. As you'll discover in later chapters, wiring and programming microcontrollers is not a simple task for the newcomer. But the RCX, and its MIT ancestors, make working with microcontrollers much easier.

It is clear that the RCX is but the first of a new kind of universal, consumer-oriented microcontroller. Many others will follow. Because they are fully programmable, these microcontroller bricks will be useful in scores of projects, including home automation, home security, automotive applications, personal care and exercise equipment, toys, tools—you name it!

## Basic Robots

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As with most any LEGO assortment you buy, the LEGO Mindstorms RIS comes with a booklet of suggested project plans, but you're free to design most anything you want. And because you can use standard LEGO parts, you can cannibalize other kits to extend your Mindstorms creations. Figure 13.2 shows the PathFinder 1, the basic Mindstorms robot built with the RIS. Using two motors and two wheels, the robot vehicle is able to move



**FIGURE 13.2** The basic rover robot is equipped with two drive motors and a light sensor.

forward and back, and it can turn in place—that is, it has no turning radius like a car; it can just spin to turn.

While building the PathFinder is fun in itself, the real enjoyment—and challenge—comes in programming the thing. Pop the Mindstorms CD-ROM into your computer, and you can design your own programs to control the RCX. The Mindstorms CD-ROM comes with a programming tutorial, but the whole technique is so simple and straightforward that even nonprogrammers will easily master the basics. To program the RCX you merely click and drag predefined program blocks, connecting them on the screen like links of a chain. You can move the blocks around and add additional blocks in between.

And, of course, you are not limited to building just the standard two-wheel roving robot. With just the parts included in the Mindstorms RIS kit you can construct a simple robot arm, or even a walking robot. The RCX has three motor output ports; you can add a third motor (available separately) to create more complex robot creations.

## Robotic Sensors

One light and two touch sensors are included in the Mindstorms RIS box. These allow the RCX to interact with its environment (without the sensors, all you really have is an

expensive R/C toy). You get two touch sensors—they're really miniature spring-loaded momentary switches enclosed in a LEGO block and a light emitter/detector pair that can control the action of a motor when a change of light occurs. Additional sensor types are available, and we will discuss them in the following section.

## **SENSOR PROGRAMMING**

You control the sensors of the RCX using the graphical Mindstorms programming environment. The programming environment treats the input sensors as “events”: when a sensor event occurs, the RCX can be programmed to take some action. For example, suppose you've created the basic two-wheeled Pathfinder 1 roverbot. Your program starts by activating both motors so the robot travels in a forward direction. A touch sensor is attached to the front of the RCX. If the sensor is activated—when the RCX strikes an object—your program can reverse the motors so the robot travels in the opposite direction.

Similarly, a touch sensor mounted on the back of the RCX can be programmed to make the robot travel forward again. In a crowded room, the RCX would likely ping-pong back and forth between objects—fun for a while, but Mindstorms can do more. You can program your robot with time delays to create sophisticated movements. For instance, instead of just reversing both motors when a touch sensor is activated, you might activate just one motor for a brief moment. You can then command both the motors to turn on again in the forward direction. This would have the effect of turning the robot by an arbitrary amount, so that its travel around a room is less predictable.

## **USING THE LIGHT AND TOUCH SENSORS**

The light sensor can be used to enable your robot to detect the presence or absence of light. It is a fun gadget to use when constructing a flashlight-controlled robot. With such a robot, the RCX can be commanded to stop, turn, or reverse direction when a flashlight is directed at the sensor. The sensor includes its own light source, so you can also use it to construct a “line tracing” robot. The Mindstorms RIS kit comes with a large white pad with a black line that you can use as a “course” or track for the RCX to follow. You can draw your own line-following track on any light-colored surface.

## **OPTIONAL SENSORS**

Additional sensors are available from LEGO that you can connect directly to the RCX. These include the following:

*Temperature.* These sensors sense differences in temperature, such as operating indoors or outdoors or the direct touch of a human hand.

*Rotation.* Used with the drive motors, these sensors sense the actual number of rotations of the motor shaft, allowing you to position of the RCX robot more accurately.

In addition to LEGO-made sensors for the RCX, you can also construct your own. See the section “Making Your Own RCX Sensors” later in this chapter for more information.

## Downloading Programs

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One noteworthy feature of the Mindstorms is that the RCX is a nontethered controller. By not being connected to a PC, the RCX robot appears much more like an autonomous machine, even though you use your PC as a programming station. There is no control wire for the RCX to get tangled with. This is actually typical of most microcontrollers used in robotics; read more about microcontrollers in Part 5.

You download the programs you create on your PC to the RCX via a two-way infrared (IR) transceiver. The IR communications tower sends program code to the RCX, and the RCX responds to indicate a proper download. For optimum performance, you should place the IR tower no more than about a foot from the RCX, though I've successfully used the tower to download programs to an RCX that was four to five feet across the room.

When you think you have a working program, you place the RCX near the infrared transmitter and click the "Download" button in the Mindstorms programming screen. Most programs download in less than 10 seconds. When downloading is complete, you merely depress the "Run" button on the RCX unit and watch your robot creation come to life.

If your robot doesn't behave quite like you expected, you can reexamine your program, make changes, and download the revised code. Once you've built a program you like, you can save it for future reference. The RCX can store five programs internally at a time, but you can keep hundreds or even thousands of programs on your computer's hard disk drive. Just download them again into any of the RCX's five program slots when you want to run them.

## Remote Control

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An optional accessory for the RCX is a handheld infrared remote. This remote lets you operate the RCX from up to 20 feet away. You can individually control the forward or reverse direction of any of the three motor outputs (A, B, or C). You can also start and stop any of the five programs stored in the RCX's internal memory as well as send sequences of RCX code to override the internal programs.

## Hacking the Mindstorms

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Not long after LEGO introduced the first Mindstorms kit, folks found ways to hack into the RCX and programming software. Among the first hacks on the scene were various Microsoft ActiveX and programming components for coding the RCX using Microsoft Visual Basic. LEGO itself now offers (but does not actively support) an RCX software developer's kit (SDK) using Visual Basic. You can download the free documentation and software for it at the LEGO Mindstorms Web page ([www.legomindstorms.com](http://www.legomindstorms.com)).

The LEGO Visual Basic SDK works with both the RCX brick included with the RIS and the CyberMaster brick that accompanies the LEGO Technic CyberMaster, a product designed for classroom use. (Note: the Mindstorms Scout, used in the Robotics Discovery Set, has a separate SDK of its own.)

The SDK requires a special ActiveX (also called *OCX*) component, *spirit.ocx*, that serves as an interface between the Visual Basic programming platform and your PC's hardware. From there, you need only a copy of Visual Basic 5.0 or higher. In actuality, you can use most any programming platform that can interface to ActiveX modules with the SDK. However, the programming examples in the SDK are provided in Visual Basic, so if you use another language you'll need to do the language conversion yourself. Chapter 14, "Programming the LEGO Mindstorms RCX: Advanced Methods," discusses how to use Visual Basic with the Mindstorms robot.

Other RIS programming hacks are available as well. At <http://www.enteract.com/~dbaum/>, for instance, you can download NQC (Not Quite C), a development language that uses a C-like syntax for programming the LEGO RCX brick. Versions are available for use under Linux, Windows, and the Macintosh. The NQC language is provided using the "Mozilla Public License," a kind of open source license. NQC is discussed in detail in Chapter 14.

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## Making Your Own RCX Sensors

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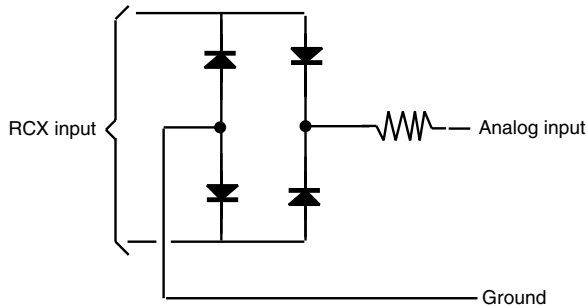
As we've mentioned, LEGO provides a number of sensors you can use with the Mindstorms RCX, including sensors for light, touch (simple switch), temperature, and wheel rotation. Several of these sensors—namely, the light sensor and the wheel rotation sensor—are powered; they require operating juice from the RCX to operate. At first glance, this may seem an impossibility: each input on the RCX has just two connections (there are four contact points on the connector brick, but each pair is wired together, so you can attach the connector with any orientation).

However, the RCX uses an interesting circuit connection to its sensor inputs so that a single pair of wires can serve both as outgoing power to run the circuit and as an input. The RCX's approach is to toggle the power to its sensors on and off very rapidly. During the on power times, the sensor receives current to operate. During the off times the sensor value is read. A capacitor in the sensor serves as a kind of voltage reservoir during the off times.

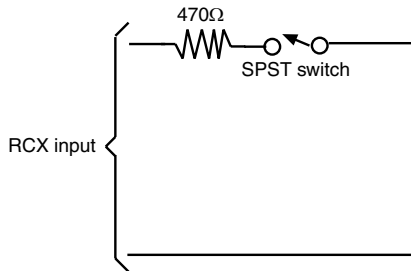
The RCX directs power and input to their particular portions of the sensor circuit by using a diode bridge, shown in Fig. 13.3. Connect your circuit as shown, being sure to add a 33 to 47  $\mu\text{F}$  capacitor across the V and ground rails; the capacitor is required to keep voltage applied to the circuit during the periods when the RCX is reading the value at the input.

You can, of course, also create your own unpowered contact-type sensors. These are easily connected to the inputs, as shown in Fig. 13.4. You simply wire a 470-ohm resistor in series with the switch. The resistor is used because the terminals of each RCX output are powered at 5 volts continuous. The resistor prevents a dead short across the terminals.





**FIGURE 13.3** The basic bridge diode network for RCX active sensors supplies power to the sensor electronics while providing the output signal back to the RCX.



**FIGURE 13.4** Nonactive sensors such as switches can be connected to the RCX via a 470-ohm resistor.

There are countless examples of homebrew RCX sensors on the Internet. Rather than repeat these excellent designs, I’ve provided a few quick samples here, and I refer you to several worthwhile pages on the Internet in Appendix C, “Robot Information on the Internet.”

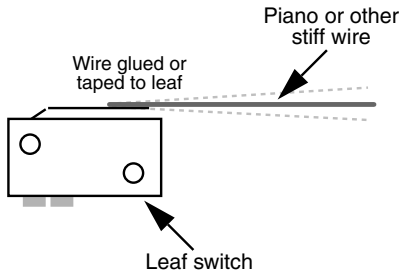
## REPLACEMENT TOUCH SENSOR

Figure 13.5 shows a replacement whisker-type touch sensor for the RCX that is made from a surplus leaf switch (often called a “Microswitch,” after the brand name that made this kind of switch popular). Use the schematic in Fig. 13.4 to connect the switch to the RCX input.

## SENSOR INPUT TECHNICAL DETAILS

Here are some useful technical details about the RCX inputs:

You must set the sensor type in the software before a sensor can be used. This is done with the RCX Code software that comes with the RCX unit or through a substitute programmer, such as Not Quite C.



**Figure 13.5** A leaf switch and small diameter wire (“piano wire” or “music wire”) makes for a good whisker-type bump sensor for the LEGO RCX.

When used with a nonpowered sensor (e.g., a touch switch), the sensor outputs 5 volts and can drive up to 10 milliamps (mA).

When used with a powered sensor (e.g., a light sensor), the sensor nominally outputs 7.5 to 9 volts (depending on battery capacity), with an “on/off” square wave. The square wave has a period of 2.8 milliseconds; the off period is 0.1 milliseconds in duration (meaning the RCX applies power for a much longer time than it detects the sensor reading). Note that the “off” voltage is 5 volts, not 0 volts.

## Using Alternative Motors and Output Devices

Caution! What follows should be considered for *experimental use only*. Connecting non-LEGO devices to your RCX can damage the RCX, and possibly the device you’ve attached to it. *Proceed at your own risk!*

Like many microcontroller-based electronics, the LEGO Mindstorms RCX uses motor driver circuitry to boost the current-handling capabilities required to drive motors. There are a number of ways to do this, including using bipolar transistors, power MOSFET transistors, and specially made H-bridge motor drivers (all of these technologies are fully explored in Part 3).

As of this writing (this kind of thing can change now and then), the RCX uses a trio of MLX10402 motor driver circuits, made by Melexis Microelectronic Integrated Systems, a company that specializes in automotive sensors and control. The MLX10402 includes overload protection against temperature and current extremes and has a maximum rating of about 500 mA, at 9 volts. The chip can handle motor voltages of 5 to 12 volts (with an absolute maximum of 16 volts), though it is designed to be controlled by 5 vdc, which is typical of computers and microcontrollers. Because the device is designed for use in automotive applications, it has excellent thermal ratings: a storage temperature of 0 to 125°C and a maximum die operating temperature of 150°C. The chip goes into protective fail-safe mode at temperatures exceeding this.

You control the motor attached to the MLX10402 by altering just two input lines (set Mode to HIGH), according to the following truth table, which gives you an idea of the capabilities of the RCX:

IN1	IN2	FUNCTION	DESCRIPTION
1	0	Forward	Turning
0	1	Backward	Turning opposite
1	1	Brake	Motor is shorted (fast stop)
0	0	Off	Motor is disabled (coast)

## HARDWARE HACKING WITH THE MLX10402 CHIP

While the RCX, or more specifically the MLX10402 chip, is primarily designed for operating a motor, it can also control a number of other devices, including relays and solenoids. And, of course, you can control other kinds of DC motors, not just the ones that come with the Mindstorms set. The factors to keep in mind are as follows:

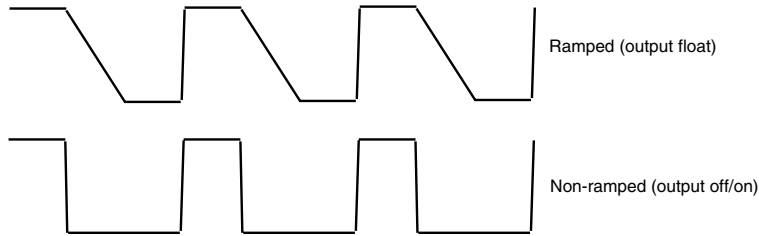
The RCX provides 9-vdc power to the three motor outputs, so the motors you use should be rated for 9-volt operation, “more or less.” Many 6- or 12-volt DC motors will run at 9 volts; 6 vdc motors will run fast, and 12 vdc motors will run slow. Damage *could* result to a 6-vdc motor that is operated at 9 vdc for long periods of time. If you are using relays or solenoids, look for 5–6 vdc units that will work acceptably. You can use diodes or resistors to drop the 9 volts from the RCX to the 5 or 6 volts expected by the relay coil.

The MLX10402 can provide up to 500 mA to each motor (this is the specification rating of the MLX10402; a more conservative rating you should go by is 400 mA). The standard 9 vdc motors that come with the LEGO Mindstorms consume no more than about 320 mA each, at 9 vdc. (This rating was determined by stalling the motor—clamping its output shaft so it will not move—and measuring the current draw when powered by 9 vdc.) Assuming the RX was designed to adequately handle up to three motors at a time (960 mA total), then the motors, relays, solenoids, and other devices you attach to the RCX should consume no more than about 960 mA total, worst case. If you are using motors, the “worst case” is the current rating of the motors when they are stalled (i.e., their shafts locked tight so they won’t turn).

When you are using a reduced power mode, the voltage to the outputs is “chopped” at a frequency of 8 milliseconds between pulses, as shown in Fig. 13.6. The ratio of on-time versus off-time determines the power delivered through the output. Note that the output has two modes: float and on/off, as shown in Fig 13.6. When in float mode, the output ramps from full voltage to 0 volts. In on/off mode, the output toggles from HIGH to LOW with no ramping.

## More and More LEGO

The LEGO Mindstorms community is a rather large one, and it’s growing. LEGO actively sponsors Mindstorms experimenters and hackers. The LEGO Mindstorms Web page, at



**FIGURE 13.6** The RCX uses pulse-width modulation to vary the power level of its three outputs. The pulses can be steep square waves, or they can be ramped.

[www.legomindstorms.com](http://www.legomindstorms.com), provides links for message boards, contests, tips and tricks, and a LEGO community called “First LEGO League,” for 9- through 14-year-olds interested in exploring robotics.

There are several Web forums devoted to LEGO that contain special sections for using and programming the Mindstorms RCX. Check out Lugnet at [www.lugnet.com](http://www.lugnet.com). This non-commercial Web forum is divided into several dozen discussion groups. Find the group that’s of interest to you and read through the postings by other visitors. Feel free to post your own message if you have a question or comment.

## From Here

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### *To learn more about...*

Constructing custom robots using standard LEGO parts  
Additional ways to program the LEGO RCX brick  
  
Using a microcontroller for the brains of a robot  
Using stepper motors  
  
Constructing sound sensors

### *Read*

Chapter 12, “Build Custom LEGO-based Robots”  
Chapter 14, “Programming the LEGO Mindstorms RCX: Advanced Methods”  
Chapters 31–33  
Chapter 19, “Working with Stepper Motors”  
Chapter 40, “Sound Output and Input”