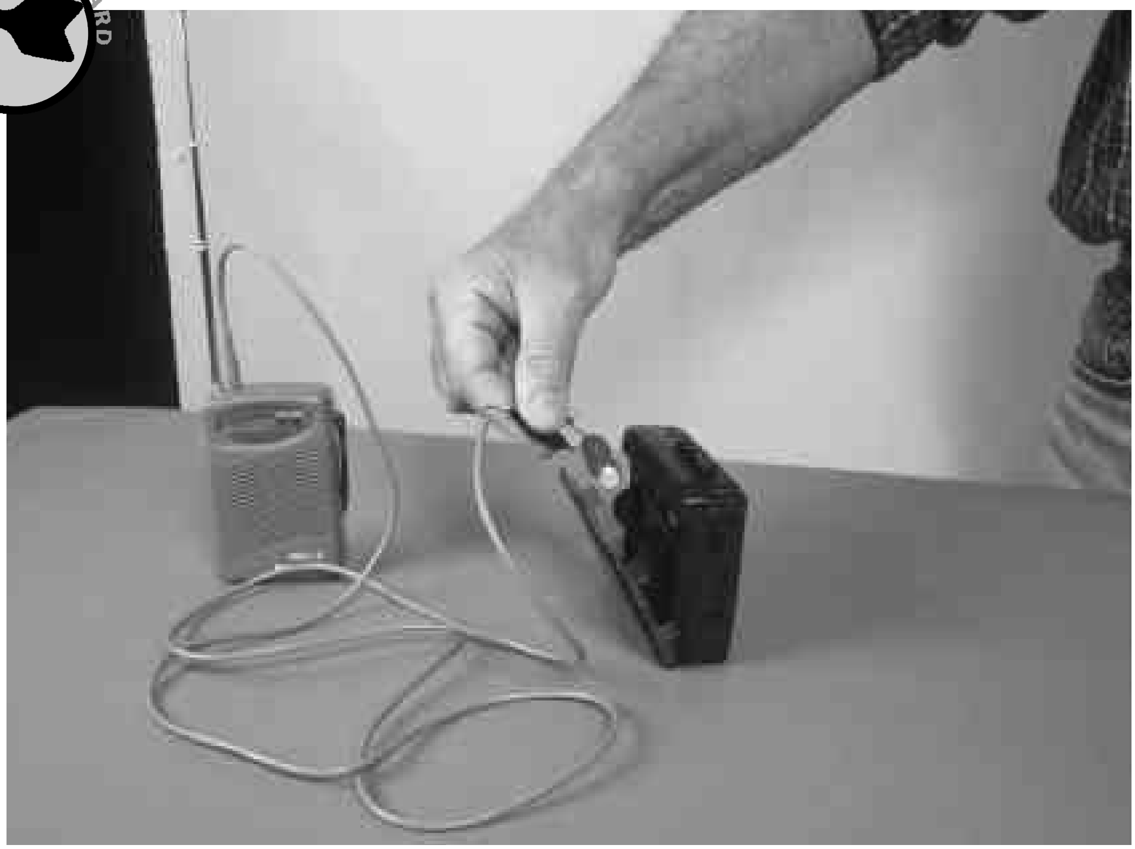
Modulated Coil

Hear the magnet!

Using a simple electromagnet, you can wirelessly transfer the sound from a radio to the speaker of a tape player.



Materials

- wire stripper or knife
- about 3 ft (1 m) of insulated wire (e.g., RadioShack #20 or #22 solid copper wire with plastic insulation)
- steel bolt, about $\frac{1}{4}$-in diameter and 2 in long (nut optional); exact size of bolt is not critical
- audio cable, 6 ft (2 m), $\frac{1}{8}$-in phone plug on one end and two alligator clips on the other (e.g., RadioShack #42-2421; a phone plug is sometimes called a mini plug)
- small radio with headphone jack (e.g., RadioShack #12-799)
- portable tape cassette player with speaker (if the player doesn't have its own speaker, you'll have to have the headphones on)

ASSEMBLY

1 Use a wire stripper or knife to remove about half an inch (1.2 cm) of the plastic insulation from each end of the wire. (If you happen to have enamel-insulated wire instead of plastic-insulated wire, use sandpaper to remove the enamel.)

2 If you have a nut for the bolt, screw it onto the end of the bolt. It may help keep the wire that you're about to wrap onto the bolt in place, but it isn't essential.

3 Start wrapping the wire around the bolt, leaving about an inch (2.5 cm) of wire free on the starting end of the wire. Begin as close as you can to one end of the bolt and proceed toward the other end. When you reach the other end, start another layer and proceed back toward the original end, but keep wrapping in the same direction (i.e., clock wise or counterclockwise, whichever direction you began with; see figure 1). If you reverse the direction of your wraps, you'll cancel the effect of the wire you wrapped initially. Keep wrapping the wire around the bolt, building up multiple layers if necessary, until you have at least 20 wraps. When you've finished wrapping, leave another inch (2.5 cm) of wire free.

Figure 1

Coil wrapped around bolt

4 Attach the two alligator clips on the audio cable to the ends of the wire on the bolt.

To Do and Notice

Turn on the radio and find a radio station with a strong, clear signal. Adjust the volume to medium-high. Plug the phone plug on the audio cable into the headphone jack on the radio. When you do this, you will no longer hear the radio, since the signal is being fed to the headphone circuit instead of to the speaker.

Be sure there is no tape in the tape player, and then press the play button. Adjust the volume control on the tape player to medium-high. Since there is no tape in the player, you should not hear any significant sound.

Bring the wire-wrapped bolt near the head of the tape player. You should hear the sound from the radio station playing through the speaker of the tape player. (Remember: If the tape player doesn't have its own speaker, you'll need to have the headphones on.)

What's Going On?

The radio sends an electric current through the audio cable and through the coils of wire wrapped around the bolt. The wire-wrapped bolt becomes an electromagnet, with the strength of its magnetic field determined in part by the size of the current flowing through the coils. Because the current carries an audio signal, it varies in strength, causing the magnetic field of the electromagnet to vary also.

The head of the tape player is essentially a device for detecting very small variations in a magnetic field. Normally it detects variations in the magnetic field on the audiotape as the tape travels by. In this case, however, it senses the fluctuating magnetic field in the coils of wire wrapped around the bolt.

So What?

The "T" mode of a hearing aid, which is designed to be used with a telephone, works on the principle of magnetic field coupling demonstrated by this snack. A telephone has a magnet whose field varies with the oscillations of the sound signal. A hearing aid, like the head of the tape recorder in the snack, detects small variations of the magnetic field. This fluctuating magnetic field induces current in the pickup coils of the hearing aid, and the current is converted to sound. This "T" mode eliminates the annoying high-pitched audio feedback to the hearing-aid microphone that is often present and can be made worse by covering the hearing aid with the telephone headset.

Going Further

Iron Versus Air

In principle you could use the coil of wire alone, without the bolt. You would then have an electromagnet with an air core rather than an iron core. The iron core, however, greatly intensifies the magnetic field. What would you have to do to achieve the same effect with an air core? Check your reasoning by building an air-core electromagnet.

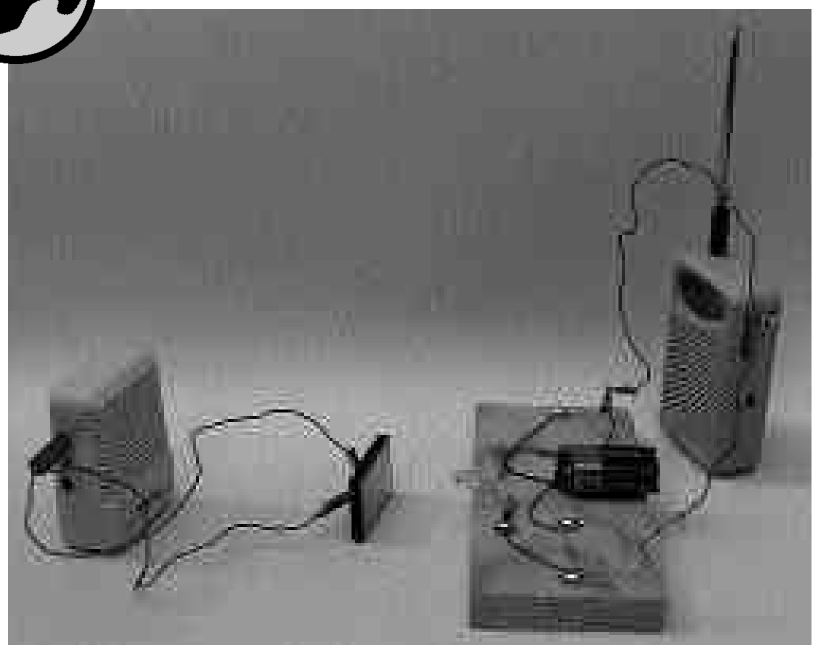
References

Rathjen, Don. "Trick of the Trade: Modulated Coil," *The Physics Teacher,* Vol. 36, No. 7, October 1998, p. 416.

Modulated LED

Listen to a beam of light.

Audio signals can be carried in radio waves through space and in electrical pulses through wires. Other forms of electromagnetic radiation, including visible light, can carry audio signals, too. You can build a simple device in which the signal from a radio is transmitted on a beam of light traveling between a light-emitting diode (LED) and a solar cell.



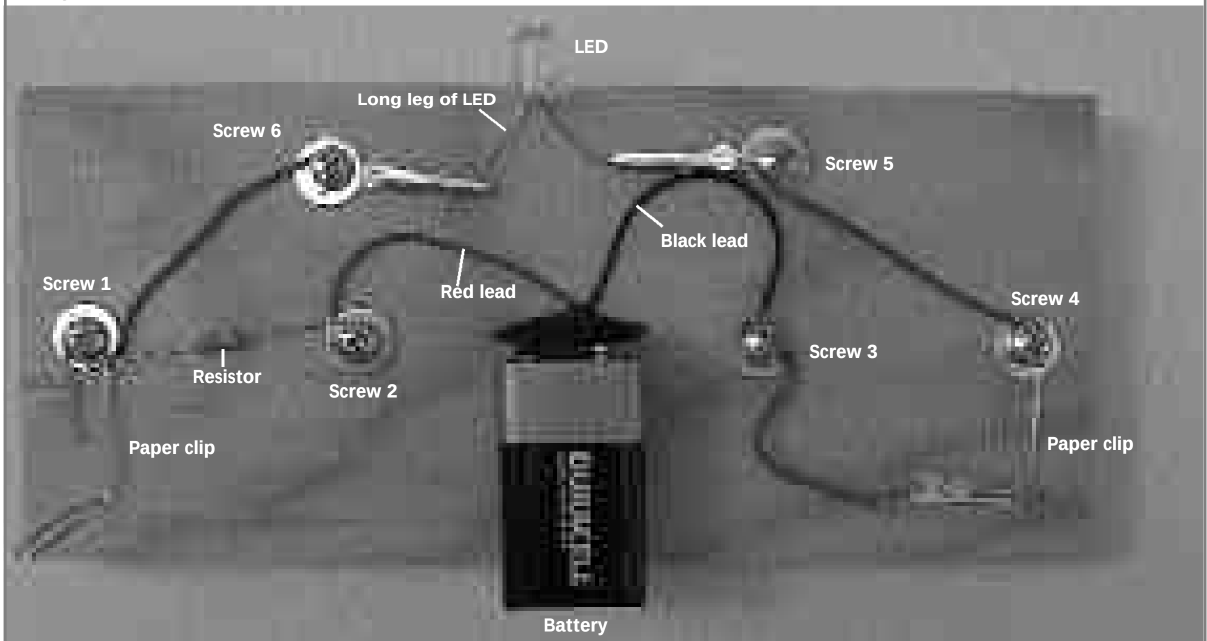
Materials

- 7 alligator clips (e.g., RadioShack #270-380 mini alligator clips)
- needle-nose pliers
- insulated copper wire, 22- or 20-gauge solid copper, 5 ft (1.5 m)
- wire stripper
- wooden board for base, approximately $3\frac{1}{2}$ in × 8 in (9 cm × 20 cm), can be made from $\frac{3}{4}$-in standard shelving or plywood
- 470-ohm resistor (RadioShack #271-1317)
- 2 paper clips
- 9-volt battery
- Velcro with adhesive back, approximately 1 in × 1 in (2.5 cm × 2.5 cm), to hold the battery to the board
- 9-volt battery snap connector (e.g., RadioShack #270-325 or #270-324)
- 6 sheet-metal screws, #8 × $\frac{5}{8}$ in
- 6 small flat steel washers (SAE #10)
- light-emitting diode (LED) (e.g., RadioShack #276-066 High Brightness Red LED)
- 2 phone plugs, $\frac{1}{8}$ in (e.g., RadioShack #274-286 or #274-287, sometimes called mini plugs; see Helpful Hint on page 52)
- amplified speaker (e.g., RadioShack #277-1008)
- solar cell (e.g., Edmund Scientific Co., 800-728-6999, www.edsci.com, #30398-09)
- small radio with headphone jack (e.g., RadioShack #12-799)

NOTE: Two premade 6-ft audio cables with a $\frac{1}{8}$-in phone plug on one end and two alligator clips on the other end (e.g., RadioShack #42-2421) can be substituted for the two phone plugs, about 3 ft (1 m) of the wire, and four of the alligator clips in the list of materials above. One of the cables will have to be altered slightly so that its alligator clips are far enough apart to be connected to the paper clips at screws 1 and 4 (see figure 1 on next page).

A S S E M B L Y

Figure 1



Components assembled on board

1 Flatten the ends of two of the alligator clips by bending the tabs outward with the needle-nose pliers (see figure 2).

Figure 2

A flattened alligator clip

2 Cut the wire into three 3-inch-long (8-cm) pieces and four 12-inch-long (30-cm) pieces. Strip about a half inch (1.2 cm) of insulation off all the ends.

3 Attach one of the short wires to an alligator clip.

4 Assemble components on the board as shown in figure 1. The ends of the short wires, the ends of the resistor, the paper clips, and the battery leads are all held in place between a screw head and its washer. The alligator clips with the flattened ends are held in place under their washers (at screws 5 and 6). Note the following:

a. The red lead from the battery should be attached to screw 2, and the black lead to screw 3.

b. The long leg of the LED should be attached to the jaws of the alligator clip at screw 6 and the shorter leg to the jaws of the alligator clip at screw 5. The LED will allow current to flow in only one direction, so it's important to connect the leads properly. The longer lead from the LED is the positive lead.

c. The alligator clip on the wire coming from screw 3 is used as a switch; when it's connected to the paper clip and the battery is in place the LED should be lit.

Helpful Hint

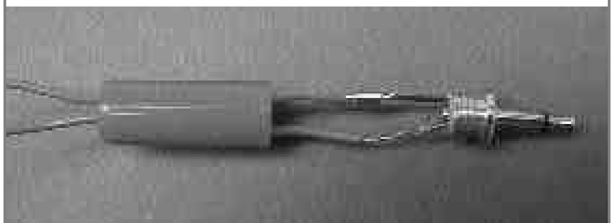
Be sure you have a mono plug. A mono plug can only be wired one way, and it will work with either a mono or stereo radio. A stereo plug can be wired in different ways, some of which may not work with particular radios (see figure 3 and step 6).

Figure 3

A mono plug (right) has one black band. A stereo plug (left) has two.

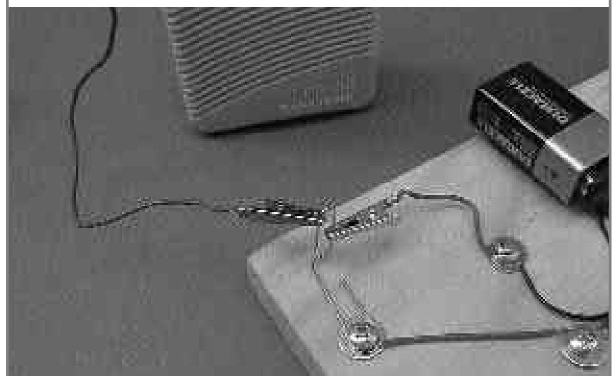
ASSEMBLY (continued)

Figure 4



Close-up of phone plug

Figure 5



Attach the alligator clips from the radio to the paper clips on the board.

5 Note where the battery lies on the board, and use the Velcro to hold it in place.

6 (NOTE: Skip this step if you are using the premade audio cables described in the Materials section.) Unscrew the plastic cover from one of the phone plugs (see Helpful Hint on page 52). Attach a 12-inch (30-cm) wire to the center terminal of the plug, and another 12-inch (30-cm) wire to the outer terminal (see figure 4). Slide the plastic plug cover onto the two wires and screw it back onto the plug. Be sure that the wire ends at the terminals don't touch each other—you may want to wrap a little tape around one of them to prevent contact. Attach an alligator clip to the other end of each of the wires. Repeat this process with the other phone plug, using two more wires, and two more alligator clips.

7 Insert one of the phone plugs into the input jack on the amplified speaker. Attach the two alligator clips to the contacts on the solar cell. Turn on the speaker and hold the solar cell toward the light. You should hear static from the speaker. Turn the speaker off while you finish the assembly process.

8 Turn on the radio and find a loud, clear signal. Attach the alligator clips of the second phone plug assembly to the paper clips on the board (see figure 5). It doesn't matter which alligator clip is connected to which paper clip. Plug the phone plug into the earphone jack on the radio. Once you insert the plug into the jack, you won't be able to hear the radio anymore. You may now be able to see the LED flickering, although it may fluctuate so quickly that you perceive it as a steady light.

➥ Helpful Hint

To test the solar cell and amplifier, turn on the amplifier and hold the solar cell in the light from a fluorescent bulb. If the system is working, you should hear a loud hum. Most fluorescent bulbs flicker on and off 120 times a second; the hum is produced by this fluctuation. (Some modern high-frequency fluorescent bulbs flicker on and off much faster and will not produce a hum.)

You can also test the solar cell by moving a comb back and forth between a small light source such as a glowing LED and the solar cell. Because of the spaces between the teeth, the comb alternately blocks the light and lets it pass. This creates pulses of electric current in the solar cell that, when passed through the amplified speaker, produces a "sawing" sound.

To Do and Notice

Hold the solar cell about 12 inches (30 cm) from the LED and point it directly at the LED. Turn on the amplified speaker again. You should now be able to clearly hear the radio signal coming from the amplified speaker. If you have difficulty, or if there seems to be significant static, block peripheral light from hitting the solar cell, or turn off the room lights if possible.

Put your hand or a piece of paper between the LED and the solar cell. The radio signal should stop.

Try reversing the connections on the LED, attaching the long leg to screw 5 and the short leg to screw 6. You will find that the LED won't light.

What's Going On?

The battery provides a steady DC current to light the LED. Under the influence of the battery alone, the LED glows with a fixed brightness. The resistor limits the current so the LED does not burn out.

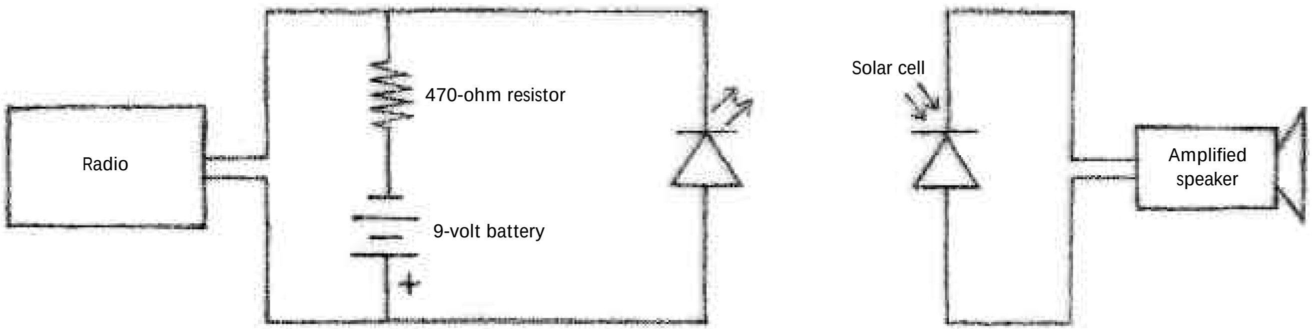


Figure 6 ***Circuit diagram with components labeled***

When the radio is turned on, the weak but fluctuating radio signal is added to the constant signal from the battery. The LED still glows, but now it flickers in synchronization with the radio signal, as the amount of current passing through it varies.

The flickering light hitting the solar cell causes it to generate electrical signals which again vary in synchronization with the original radio signal. These signals are amplified and fed to the speaker, recreating the original sounds from the radio. (The preceding process is represented in figure 6.)

Placing an opaque barrier between the LED and the solar cell cuts off the light, and the solar cell is unable to generate any electrical signals.

So What?

Modern communications systems, such as long-distance phone lines and high-bandwidth communication lines for computers, commonly use modulated signals carried on a beam of light. The relatively high frequencies of visual light can carry a lot more information than lower frequency radio waves. The light that is used is normally from a laser, not an LED, and the signals are carried by a clear fiber-optic cable, rather than through air, but the principle is the same.

Going Further

Which LED Works Best?

Try several different LEDs and find out which results in the clearest sound or transmits the sound farthest. Does the relative brightness of an LED affect the results?

Cancel the Noise

It can be hard to use your system in a room lit by fluorescent lights because the lights flicker on and off, producing an annoying hum. To get rid of the hum, you can make a noise-canceling receiver with two identical solar cells.

Hook the solar cells together in a series, attaching the positive side of one to the positive side of the other. Attach the amplifier to the two negative terminals.

Shine the light from the LED on only one of the solar cells while the room light shines on both. The signal from the LED is converted to electricity by one of the cells, and the signal from the room light is converted into electricity by both of the cells. Because the cells are hooked together so that they oppose each other, the two signals from the room light cancel each other. This allows you to hear the radio signal in a noisy environment.

In World War II, navy signalmen used flashing lights to send messages between ships.

Credits & References

This snack is based on the Exploratorium exhibit Modulated Laser.

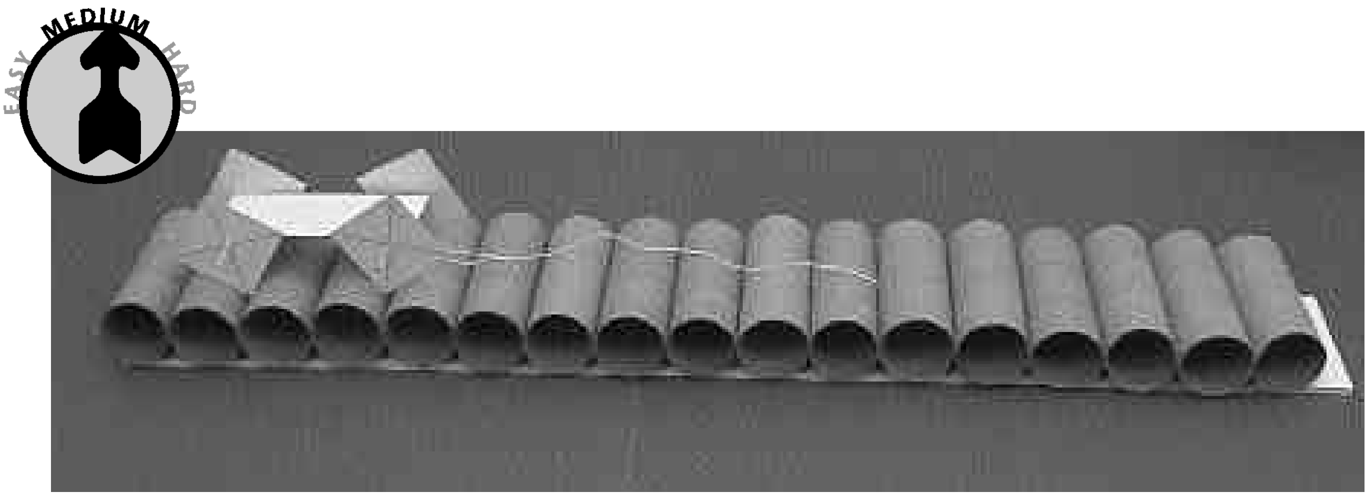
Macaulay, David. *The Way Things Work.* Boston: Houghton Mifflin, 1988.

Mims, Forrest M. III. *Getting Started in Electronics.* RadioShack, 2000. (RadioShack #62-5004)

Square Wheels

You may not be able to put a square peg in a round hole, but you can make a square wheel roll on a round road.

A square wheel will roll smoothly, with its axle at a constant height, on a surface with properly spaced bumps of the right size and shape.



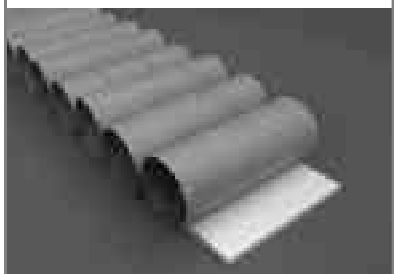
Materials

- hot glue gun and glue sticks
- about 20 cardboard toilet paper tubes (all approximately the same diameter)
- foam core, stiff cardboard, or mat board to serve as a base for the cardboard tubes, about 4 in × 30 in (10 cm × 75 cm)
- ruler
- poster board or mat board, approximately 8 in × 10 in (20 cm × 25 cm)
- pencil or pen
- pushpin
- scissors
- drinking straw
- 2 bamboo skewers
- paper clip
- string, about 12 in (30 cm)

A S S E M B L Y

1 Use hot glue to attach a cardboard tube at one end of the base. The length of the tube should be placed across the base, as shown in figure 1.

Figure 1



Toilet paper rolls glued to base

2 Continue gluing tubes to the base, with each tube just touching the one before it, until you reach the other end of the base.

3 Measure the diameter of three or four of the cardboard tubes. The diameters should be approximately $1\frac{11}{16}$ inches (4.3 cm). If this is the case, cut four square wheels from the poster board, with sides of 2 inches (5.1 cm). If the tubes you obtain have a significantly different diameter, then make the sides of the square wheels equal to 1.2 times the diameter (see Box o' Math at the end of this snack).

4 Locate the center of each square wheel by drawing two diagonals, as shown in figure 2.

Figure 2

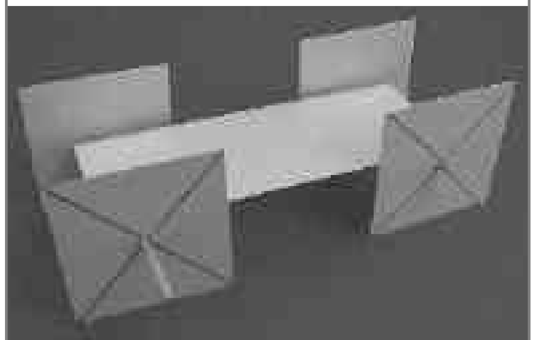
Using diagonals to locate the center of the square wheel

5 Poke a small hole in the center of each square wheel with a pushpin, taking care not to bend or crease the wheel.

6 From the poster board, cut out a 2- × 5-inch (5- × 12-cm) piece for the cart body.

7 Cut two sections of straw, each 2 inches (5 cm) long.

Figure 4



Cart with wheels

8 Hot glue the straw sections to the rectangular piece of poster board $\frac{3}{8}$ inch (1 cm) from each end, as shown in figure 3. This assembly will be the body of a small cart.

Figure 3

Drinking-straw axle holders

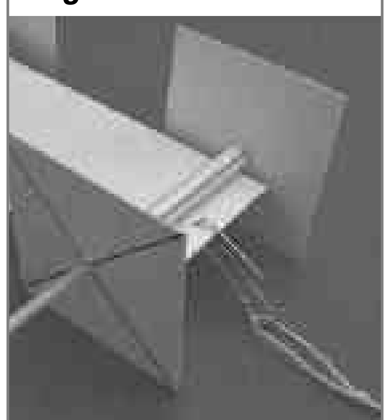
9 Cut the skewers into two 5-inch-long (12-cm) pieces, each with a point at one end. These will be axles. (If you are unable to cut the skewers with the scissors, just break the skewers or cut them with a utility knife.)

10 Slide one of the square wheels onto a skewer until it is about $\frac{3}{4}$ inch (2 cm) from the non-pointed end. Slide the pointed end through the straw, and then slide the other square wheel onto the skewer. Adjust the positions of the wheels so that they are aligned with each other and are fairly close to the edge of the cart. The wheel-and-axle assembly should turn freely in the straws. Assemble the other set of wheels the same way. When all the wheels are on, the cart should look like the one in figure 4.

11 Use the pushpin to poke a hole in the body of the cart between the straw and one end, equidistant from the edges. Put one end of the paper clip through the hole, and adjust until it is positioned as shown in figure 5.

12 Tie a loop in the end of the string, and place it on the paper clip as shown in figure 5.

Figure 5



Paper clip and string on cart

➥ Helpful Hint

When you place the cart on the road, the wheels on each axle should be aligned with each other, as shown in figure 6. Also, be sure that the wheels are reasonably perpendicular to the axles and are not excessively wobbly. If you have trouble keeping the wheels on the same axle aligned, or if they are too tilted or wobbly, use a small amount of hot glue to hold them in place on the axle.

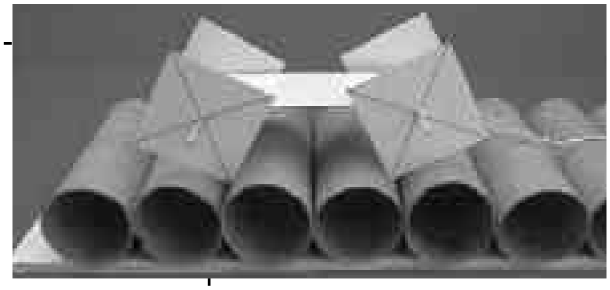


***Figure 6** Square wheels on the rounded road*

To Do and Notice

Place the cart at one end of the cardboard-tube “road” and pull gently on the string so that the cart travels along the road. Notice that the cart rolls along smoothly and that the axles stay at a reasonably constant height.

What’s Going On?

The cart rolls smoothly along the bumpy road because the vertical distance from each axle to the horizontal base of the road is always about the same. Each axle moves from a point above a low spot between two tubes (see figure 7) to a point above a high spot on a tube (see figure 8). The increasing height of the point on the circular tube where the tube contacts the wheel is compensated for by the decreasing distance on the wheel between the axle and the edge of the square where it contacts the tube. The same thing happens in reverse as each axle moves from a position above a high spot to a position above a low spot.

A special shape called a *catenary curve* (see Did You Know?), not a circle, is the curve that will give an absolutely level ride with square wheels. A road made with circles is a reasonably close approximation, however, and is easier to build from commonly available materials.

Figure 7

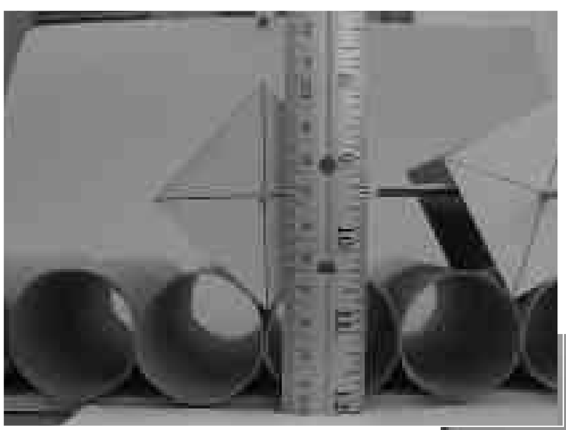
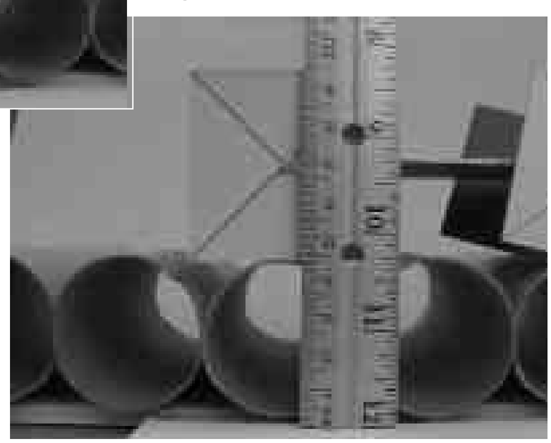


Figure 8



The height of the axle always remains about the same distance from the base (6.8 cm in figure 7 and 6.9 cm in figure 8). In figure 7, the vertical distance between the axle and the bottom of the wheel is maximum; because the wheel is in a depression, however, the remainder of the distance to the base is minimum. In figure 8, the situation is reversed. The vertical distance between the axle and the bottom of the wheel is minimum, but the remainder of the distance to the base is maximum.

On a flat road, this would be the ultimate exercise bike! Mathematician Stan Wagon was inspired to build his square-wheeled tricycle after seeing the Exploratorium’s Square Wheels exhibit.

So What?

A key problem in designing automobile transmissions involves gear teeth. Gear teeth must mesh together without slipping, because slipping results in frictional wear. In order for gears to mesh smoothly, engineers must design teeth that have matching shapes—a problem that’s quite similar to designing the particular bumpy road that will provide a smooth ride for square wheels.

Box o' Math

Calculating Wheel Size

To travel smoothly over the array of tubes, the sides of the square wheels have to be 1.2 times the diameter of the tubes. The equations below explain how this relationship is derived; the diagram shows you how the math applies to the square wheels and the "road." Note that *l* is the side of the square and *d* is the diameter of the circle (which represents the tube). The circumference of the tube = $2\pi r$.

$$\cos 45 = \frac{AC}{AB}, \text{ or } AB = \frac{AC}{\cos 45} = \frac{r}{\cos 45}$$

$$AD = r$$

$$DB = AB - AD = \frac{r}{\cos 45} - r = r\left(\frac{1}{\cos 45} - 1\right) = r\left(\frac{1}{.71} - 1\right) = r(1.41 - 1) = 0.41r$$

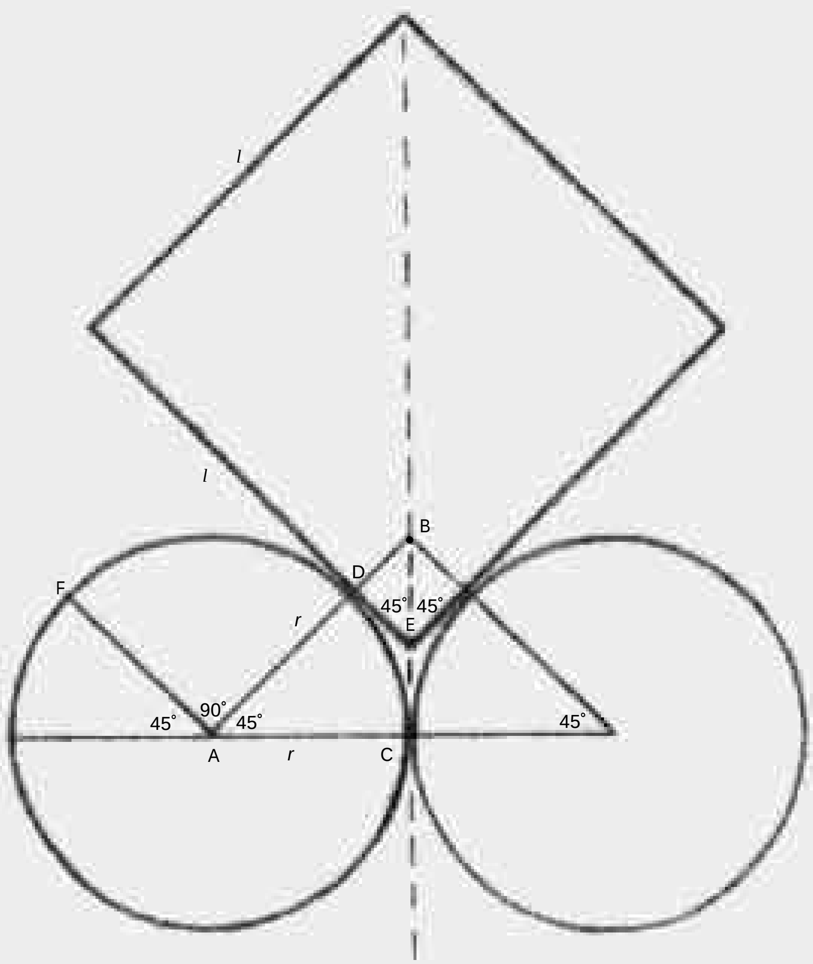
$$l = \widehat{DF} + 2DE$$

$$\widehat{DF} = \frac{2\pi r}{4}$$

$$DE = DB = 0.41r$$

$$l = \frac{2\pi r}{4} + 2 \times 0.41r = 0.5 \times 3.14r + 0.82r = 1.57r + 0.82r = 2.4r$$

$$r = \frac{d}{2}, \quad l = 2.4 \times \frac{d}{2} = 1.2d$$



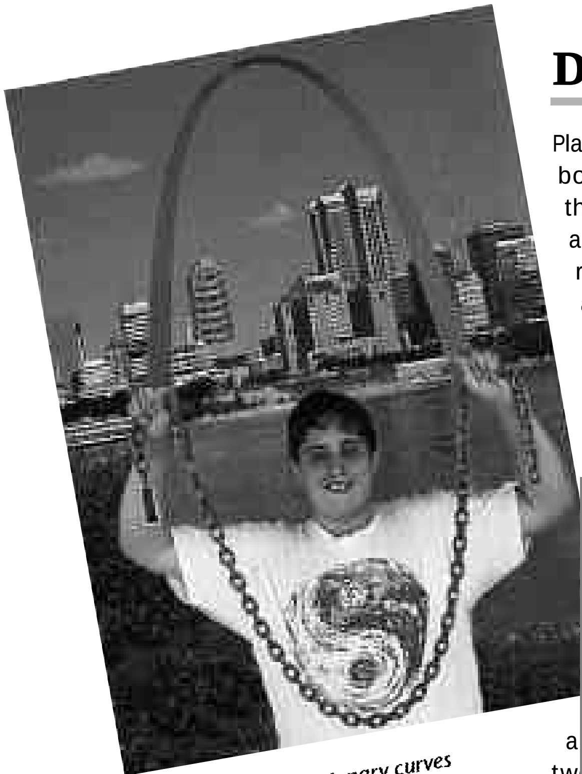


Figure 9 Two catenary curves

Do and Notice

Place the cart at one end of the cardboard-tube "road" and pull gently on the string so that the cart travels along the road. Notice that the cart rolls along smoothly and that the axles stay at a reasonably constant height.

What's Going On?

a

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above a high spot on a tube (see figure 8). The increasing height of the point on the circular tube where the tube contacts the wheel is compensated for by the decreasing distance on the wheel between the axle and the edge of the square where it contacts the tube. The same thing happens in reverse as each axle moves from a position above a high spot to a position above a low spot.

A special shape called a *catenary curve* (see Did You Know?), not a circle, is the curve that will give an absolutely level ride with square wheels. A road made with circles is a reason-

To

Credits & References

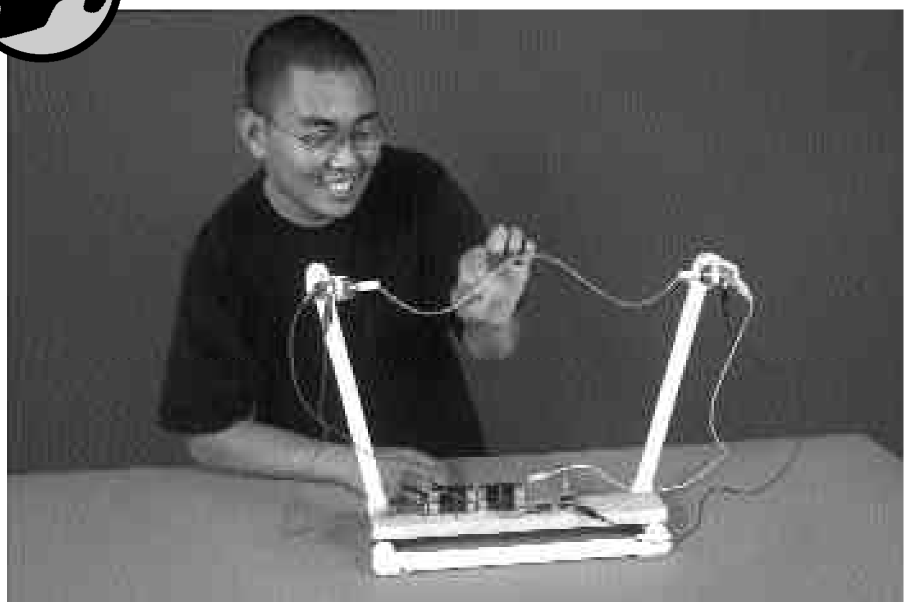
This snack is based on the Exploratorium exhibit of the same name.

Regester, Jeffrey. "A Long and Bumpy Road." *The Physics Teacher,* April 1997. (Also reprinted in *Apparatus for Teaching Physics: A Collection of "Apparatus for Teaching Physics" Columns from The Physics Teacher,* 1987–1998, edited by Karl Mamola, American Association of Physics Teachers, 1998, pages 46–47.)

String Machine

Waves you never node about.

Waves are everywhere. They break on the shores of the ocean, bring music to your ears, and carry the signal of your favorite radio station. This snack—essentially a string attached to two small electric motors rotating in the same direction—allows you to create and play with a special class of waves called standing waves.



Materials

- $\frac{1}{2}$-in PVC pipe, 1 piece, 4 ft (1.2 m) long
- PVC shears (or hacksaw)
- electric band saw (or hacksaw)
- 8 each, $\frac{1}{2}$-in PVC 90˚ elbows
- hammer
- 6 finishing nails, $1\frac{1}{2}$ in long
- $\frac{3}{4}$-in standard pine shelving, $2\frac{1}{2}$ in × 15 in (6 cm × 38 cm); a 15-in-long piece of “1-×-3” board meets these dimensions
- 2 D-cell batteries
- 1 brass cup hook (or 1 additional nail)
- Velcro, 5 in (13 cm) long
- 25-ohm potentiometer (e.g., RadioShack #271-265); the potentiometer provides continuously adjustable speed control; if you want to omit it, you can still have two speeds—see Helpful Hint
- drill
- $\frac{1}{16}$-in drill bit
- $\frac{3}{8}$-in diameter wooden dowel, 2 segments, each $\frac{3}{4}$ in (2 cm) long
- 2 motors, 1.5–3 volts (e.g., RadioShack #273-223)
- 2 rubber bands
- piece of string, 18 in (46 cm) long (Braided string works significantly better than ordinary twisted string because it won’t unravel. Wellington brand Braided Nylon Chalk and Mason Line works well and is available at some hardware stores; if you use regular twisted string, you will have to manually “retwist” it if it unravels.)
- masking tape
- 4 alligator-clip leads, 2 ft (60 cm) long (e.g., RadioShack #278-1157)

ASSEMBLY

1 From the half-inch PVC pipe, cut two 2-inch-long pieces, two 4-inch-long pieces, and three 12-inch-long pieces (two 5-cm-long pieces, two 10-cm-long pieces, and three 30-cm-long pieces). Use PVC shears, a hacksaw, or an electric chop or band saw (PVC shears are an amazingly handy tool for cutting PVC pipe).

2 Use a hacksaw or band saw to slice the top portion off two PVC elbows, as shown in figure 1. These modified elbows will serve as cradles for the motors.

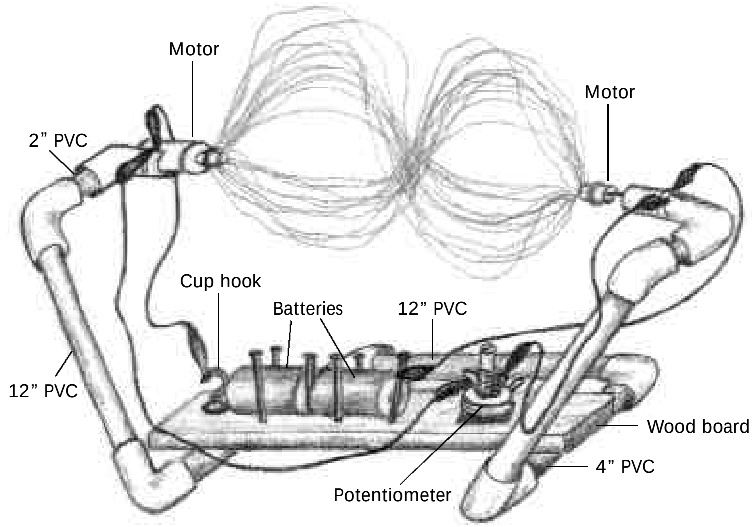
Figure 1

Cut the top off the PVC elbow to make the motor mount.

3 Using the PVC pipe pieces and elbows, create the PVC part of the structure shown in figure 2. Other parts will be added in succeeding steps. NOTE: Do not use glue to hold the PVC pieces together! You will need to adjust the joints when the String Machine is running, and the lack of glue allows the machine to be taken apart for storage.

4 Hammer the six nails into the board as shown in figure 3 to form a holder for the two D-cell batteries. One of the nails goes between the two batteries.

Figure 2



The completed string machine (with rotating string) will look like this.

Figure 3

Notice the nail placed between the two batteries in the battery holder.

5 Screw the cup hook into the board so that when it’s in the position shown in figure 3, it contacts the flat end of the battery and holds it tightly in place. If you don’t have a cup hook, you can use a seventh nail instead, but a nail sometimes doesn’t make good contact with the flat end of the battery.

6 Stick 2-inch (5-cm) Velcro strips to the ends of the board and to the short PVC pieces in the base so that the board can be attached to the base.

7 If you are using the potentiometer for speed control, stick 1-inch (2.5-cm) pieces of Velcro to it and to the board to hold the potentiometer in place on the board as shown in figure 2.

➥ Helpful Hint

Simple Speed Control

If you want to omit the potentiometer, you can get two different speeds by attaching the alligator clip (see step 13) to the end nail of the battery holder (two-battery speed) or to the middle nail (one-battery speed).

ASSEMBLY (continued)

1 From the half-inch PVC pipe, cut two 2-inch-long pieces, two 4-inch-long pieces, and three 12-inch-long pieces (two 5-cm-long pieces, two 10-cm-long pieces, and three 30-cm-long pieces). Use PVC shears, a hacksaw, or an electric chop or band saw (PVC shears are an amazingly handy tool for cutting PVC pipe).

2 Use a hacksaw or band saw to slice the top portion off two PVC elbows, as shown in figure 1. These modified elbows will serve as cradles for the motors.

3 Using the PVC pipe pieces and elbows, create the PVC part of the structure shown in figure 2. Other parts will be added in succeeding steps. NOTE: Do not use glue to hold the PVC pieces together! You will need to adjust the joints when the String Machine is running, and the lack of glue allows the machine to be taken apart for storage.

Figure 4

Motor, dowel, string, rubber bands, and alligator clip leads

4 Hammer the six nails into the board as shown in figure 3 to form a holder for the two D-cell batteries. One of the nails goes between the two batteries.

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6 Stick 2-inch (5-cm) Velcro strips to the ends of the board and to the short PVC pieces in the base so that the board can be attached to the base.

7 If you are using the potentiometer for speed control, stick 1-inch (2.5-cm) pieces of Velcro to it and to the board to hold the potentiometer in place on the board as shown in figure 2.

8 Use a $\frac{1}{16}$-inch drill bit to drill a hole $\frac{3}{8}$ inch (1 cm) deep in the center of the end of each piece of dowel. (The $\frac{1}{16}$-inch drilled hole is slightly smaller than the diameter of the motor shaft.)

9 Hold one of the motors so that the short end of the shaft (which

To Do and Notice

Adjust the tension in the string (by adjusting the spread between the ends of the motor arms) and the motor speed (by turning the potentiometer knob) until you obtain a relatively stable pattern in the string. See if you can get the pattern to change to a different stable pattern by gently "pinching" the string: Hold your thumb below the string pattern and your forefinger above it, and slowly compress the pattern without actually making your fingers touch. Play with the machine for at least a few minutes to see how many different behaviors you can produce in the string.

While the machine is running, gently pull the motor ends of the two arms apart to increase the tension in the string. At some point, the string should snap into its simplest behavior mode, in which it looks something like a high-speed jump rope. This behavior is shown in figure 5. (Once you have this pattern, moving the arms back together a little usually helps to stabilize it; you can try further adjusting string tension or motor speed to get the best and most stable pattern.)

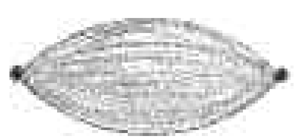

Figure 5 ***The simplest wave pattern has two nodes.***

Notice that the string moves very little near the ends, but quite a lot in the middle. In wave language, a place in a wave with little or no movement is called a *node,* and a place with maximum movement is called an *antinode.*

Gently pinch the string near the middle—or just press down on it with a pencil. With a little practice (and perhaps some adjustment of string tension or motor speed), you should be able to make the string jump into a mode with three nodes (one at each end, and one in the middle), and two antinodes (one in the middle of each loop) as shown in figure 6.

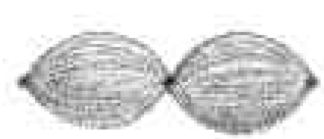

Figure 6 ***This wave pattern has three nodes and two antinodes.***

Double-Dutch rope jumpers make patterns like those made by your string machine.

To Do and Notice

Adjust the tension in the string (by adjusting the spread between the ends of the motor arms) and the motor speed (by turning the potentiometer knob) until you obtain a relatively stable pattern in the string. See if you can get the pattern to change to a different stable pattern by gently "pinching" the string: Hold your thumb below the string pattern and your forefinger above it, and slowly compress the pattern without actually making your fingers touch. Play with the machine for at least a few minutes to see how many different behaviors you can produce in the string.

Figure 7 ***Try making a more complicated wave pattern with four nodes and three antinodes.***

While the machine is running, gently pull the motor ends of the two arms apart to increase the tension in the string. At some point, the string should snap into its simplest behavior mode, in which it looks something like a high-speed jump rope. This behavior is shown in figure 5. (Once you have this pattern, moving the arms back together a little usually helps to stabilize it; you can try further adjusting string tension or motor speed to get the best and most stable pattern.)

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Now try pinching the string about one-third of the way across. With a little practice, you should be able to make the string jump into a more complicated pattern with three loops. This pattern, shown in figure 7, has four nodes and three antinodes.

Put the string back into the mode with three nodes and two antinodes as shown in figure 6. Spread the fingers on one of your hands slightly apart so you can see between them, and wave this hand back and forth between the string and your eyes so that you can see the string between your fingers. Can you make the string seem to stand still? If not, reduce the motor speed and try again. (Closing one eye may also help.) Eventually you may be able to see a single wave, rather than the blurred pattern.

What's Going On?

As the dowel turns on the motor shaft, the end of the string that is taped to the edge of the dowel moves in a circle. If you think of circular motion as a combination of vertical and horizontal motion, you can visualize the string as being shaken up and down at the same time as it is being shaken right and left. The shaking of the string causes wave pulses to travel along the string.

You and a friend can produce wave pulses in a jump rope that are very similar to those in the string. If the person holding the other end of the rope holds the rope tightly while you shake the rope, the pulses you make will bounce off the person's

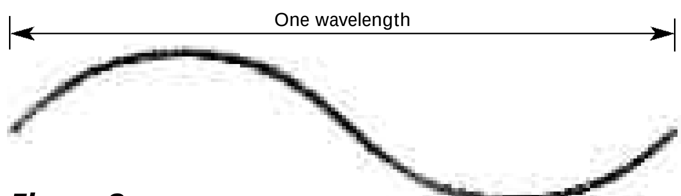

Figure 8 ***One wavelength***

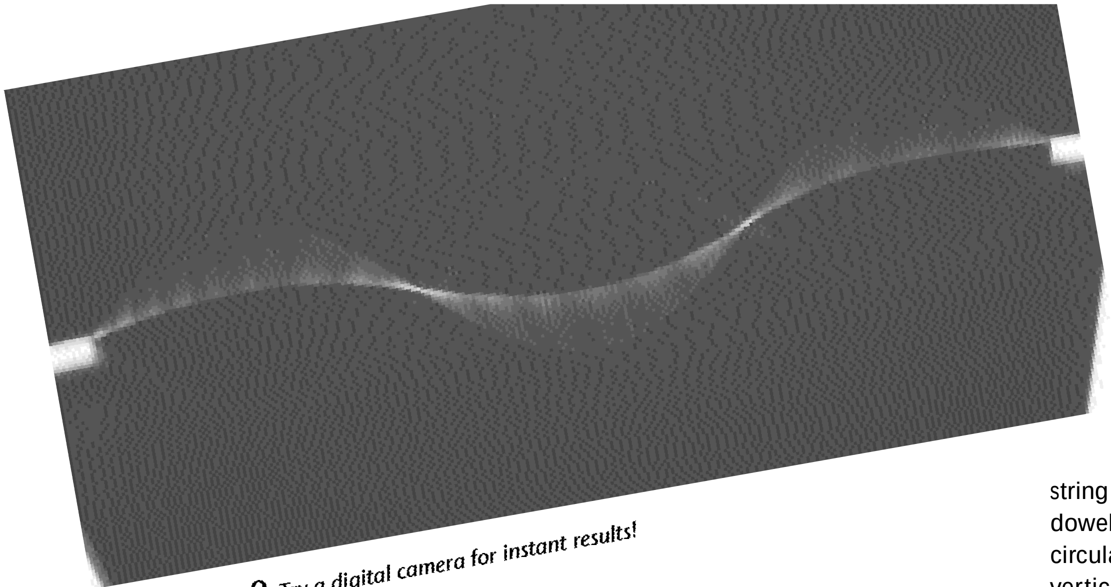

Figure 9 Try a digital camera for instant results!

To Do and Notice

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You and a friend can produce wave pulses in a jump rope that are very similar to those in the string. If the person holding the other end of the rope holds the rope tightly while you shake the rope, the pulses you make will bounce off the person’s hand and travel back toward you. These returning pulses will travel through the ones you continue to make. Since any particular piece of the rope can only be in one place at one time, the two waves traveling in opposite directions combine with each other, adding together to produce a

Credits

The String Machine is a low-budget, black-and-white version of the commercially available, full-color String Ray.

Don Rathjen, Tien Huynh-Dinh, and Guillermo Trejo-Mejia contributed to the design of this snack.