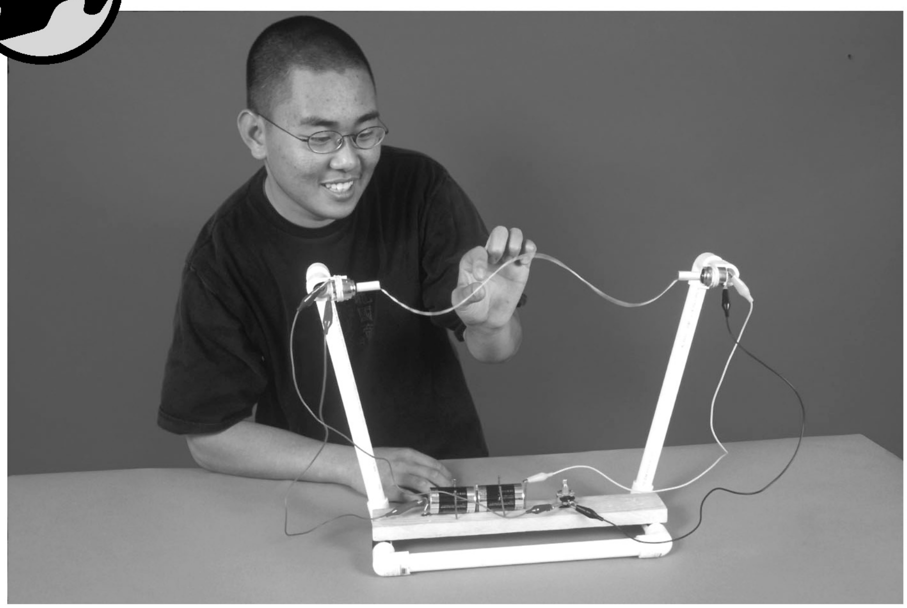
String Machine

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

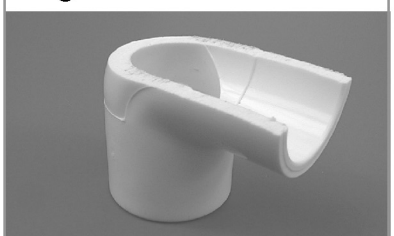
- $\frac{1}{2}$-in PVC pipe, 1 piece, 4 ft (1.2 m) long
- PVC shears (or hacksaw)
- electric band saw (or hacksaw)
- 8 each, $\frac{1}{2}$-in PVC 90° elbows
- hammer
- 6 finishing nails, $1\frac{1}{2}$ in long
- $\frac{3}{4}$-in standard pine shelving, $2\frac{1}{2}$ in × 15 in (6 cm × 38 cm); a 15-in-long 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).

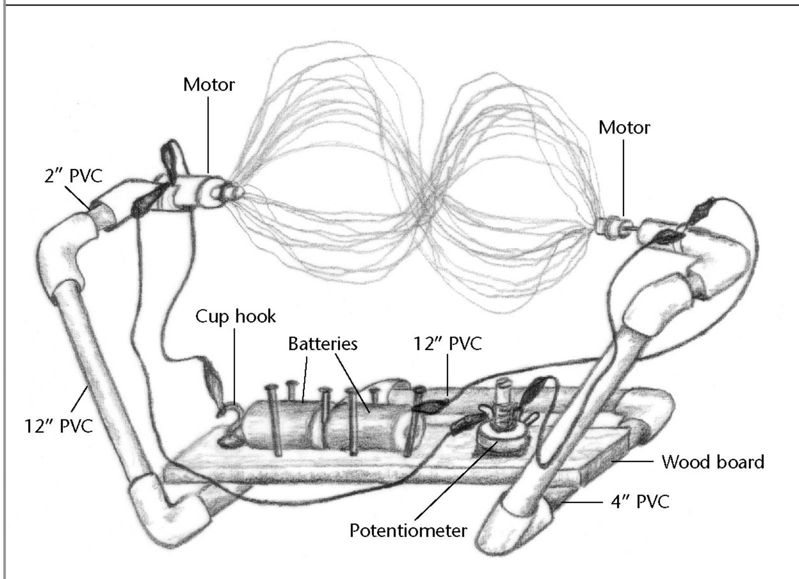
2 Use a hacksaw or band saw to slice the top portion off two PVC elbows, as shown in figure 1. These modified elbows will serve as cradles for the motors.

Figure 1



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

Figure 2

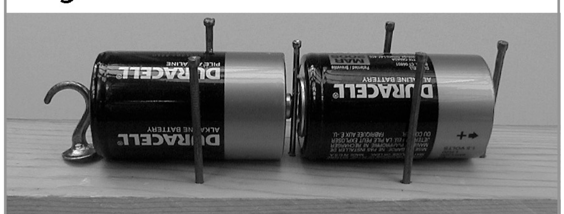


The completed string machine (with rotating string) will look like this.

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 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)

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 protrudes from the plastic end-cap) is touching a hard surface and the long shaft on the other end is sticking straight up from the motor. Press the dowel down onto the motor shaft so that the shaft fits into the hole—it's a tight fit, but you want it to be tight so it won't slip. **Note: Do not try to push the motor shaft down into the dowel—you are likely to pop the motor right out of its casing.** Repeat this step for the other motor and other dowel piece.

10 Use rubber bands to hold the motors in place in the cradles you made when you sliced off the tops of the two elbows (see figure 4).

Figure 4

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

11 Attach the ends of the string to the wooden dowels by laying each end of the string along a dowel and then wrapping masking tape around both (see figure 4).

12 Adjust the spread between the ends of the motor arms so that the string hangs in a loose curve.

13 Connect the alligator-clip leads as shown in figure 2, leaving one clip unattached. If you are using the potentiometer, connect one clip to its middle contact and the other clip to either one of the outer contacts. If you aren't using the potentiometer, just connect the two clips together.

14 Briefly touch the remaining unattached clip to its contact point to see if both motors are turning in the same direction. If they aren't, reverse the connections on one of the motors. (If neither motor turns, try turning the potentiometer knob. If that doesn't get them turning when you touch the clip to the contact point, check all the electrical connections carefully and make sure your batteries are working.)

15 Make the final connection, and adjust the potentiometer (if present) to obtain an intermediate speed.

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.

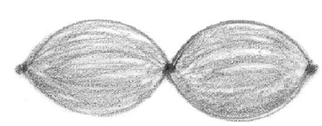


***Figure 6** This wave pattern has three nodes and two antinodes.*

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

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.

Figure 7 ***Try making a more complicated wave pattern with 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 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 single overall shape for the rope. This is still true even if both you and your friend shake the rope and each of you produce wave pulses. If you both shake the right way, you can produce an overall shape that is stable and exhibits nodes and antinodes. This stable overall shape is called a *standing wave.* The various stable patterns you produced with your String Machine are also standing waves.

The simplest standing wave that you produced was the fundamental, or first harmonic, as shown in figure 5. The fundamental is one-half of a whole wave, or one-half a wavelength (see figure 8). The second standing wave you made, the one with three nodes, is a second harmonic wave, and it is a whole wavelength. The third wave you made, with four nodes, is a third harmonic wave, which is one-and-a-half wavelengths.

For waves in a string, standing wave formation normally depends on a number of factors, including the frequency with which the string is shaken and the tension in the string. If any of these factors is changed, then the standing wave pattern changes. In your String Machine, however, it's possible to change the frequency (motor speed) and tension (spread between ends of the motor arms) *without* changing the pattern because of the circular motion of the string. This motion introduces forces on the string not present in waves generated in a single plane, as in the simple case of the jump rope being shaken up and down.

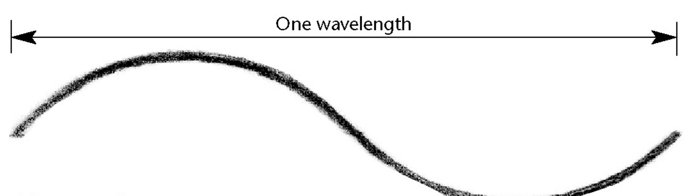


Figure 8 ***One wavelength***

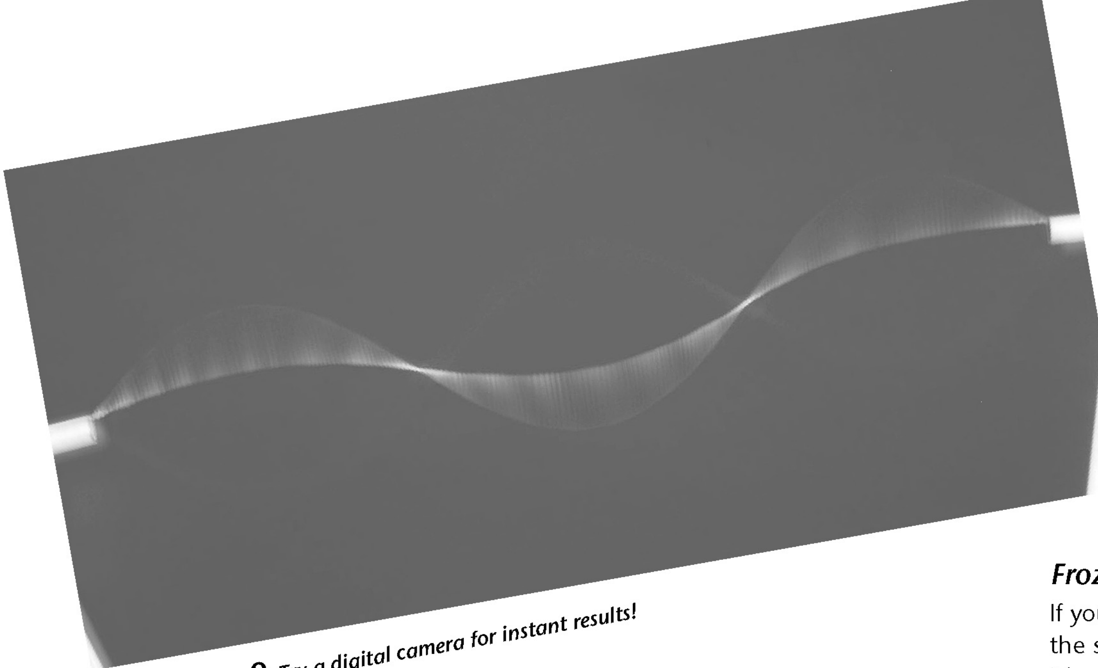


Figure 9 *Try a digital camera for instant results!*

When you "strobed" the string by waving your hand back and forth in front of it, you were able to get successive views of the string over short time intervals. If the time it took for adjacent spaces between your fingers to change places in front of your eyes was exactly the time it took for the string to go through one whole cycle (or any whole number of its cycles), then you saw the wave in the same position each time, and it appeared to be standing still.

So What?

Standing waves are at the heart of musical instruments. In wind instruments, standing waves are set up in an air column. At some locations, the density of air molecules is alternately very high and very low, creating large fluctuations in pressure. These locations are the antinodes of the air-pressure standing wave. At other locations, small pressure changes mark the nodes of the standing wave. When the length of the air column is changed, as with keys on a clarinet or the slide on a trombone, a different standing wave is formed, and you hear a different note. Standing waves are also formed on stringed instruments and drumheads.

Did You Know?

Getting in Tune

On occasion—possibly due to slightly different motor speeds—the moving string may seem to develop sub-patterns within the main pattern, which will vary slowly in a regular way. This behavior is the result of waves with slightly different frequencies interacting in a complex way to produce a regular alternating or oscillating pattern called a *beat.* Perhaps the simplest and most well-known example of a beat is the loud-soft-loud-soft tone produced when a musical instrument (or two different strings on the same instrument) are being tuned. The two instruments are in tune—each producing the same frequency note—when the variable tone is no longer noticeable.

Harmonics and Overtones

The second harmonic is also called the first overtone, the third harmonic the second overtone, and so on.

Going Further

Getting Loopy

What is the maximum number of loops you can produce in the string? You may try maintaining a continuous loose pinch or exerting continuous light pressure with your finger or a pencil.

Frozen Waves

If you have a strobe light, try strobing the string on your String Machine—it's spectacular! A good camera can produce images of a "frozen" string as well, as shown in the opening photo at the beginning of this snack and in figure 9. Using a digital camera will provide an instant picture of the string in mid-wave.

Rainbow Waves

Build a motorized color wheel, with transparent pie-shaped segments of a few different colors. If you shine a bright light through the rotating color wheel and use it to illuminate the string machine while the string is in motion, the results can be sensational.

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.