

Scanning for Time: Science and Art on a Photocopier

Eric Muller, Exploratorium Teacher Institute, Pier 17, San Francisco, CA

What do you get when you cross a rubber band with a photocopier? You get a whole series of physics lessons and some great images! It's easy to get this activity up and running, be amazed, and apply it to any number of scientific concepts. It lends itself to a whole host of investigations. This easy-to-do activity can also be aligned to NGSS outcomes and three-dimensional learning. It's science, art, and fun, and your results may be surprisingly.... well, surprising.

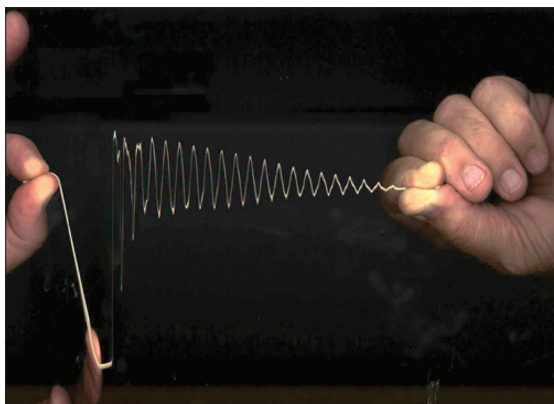


Fig. 1. Copier image of a loosely stretched rubber band.

What you'll need:

- A thick, long rubber band (like a standard #64, but also try an assortment)
- High-speed photocopier/scanner (found in most offices, schools, or copy shops)

Make sure your copier scans documents or pictures by moving a lighted bar across the scanner bed. If your copier can scan an image in a second or two, you're in business. If needed, adjust the dpi (dots per inch) to get the machine scanning faster. Some machines scan at different rates for color vs. black/white vs. scan-only modes. Scan quality might also differ from manufacturer to manufacturer. (*Note:* home/office photocopiers might not be fast enough to produce useful results).¹

- Scissors
- Partner
- Cellphone or digital camera
- Metric ruler
- Optional:
 - Bungee/elastic cord
 - Fidget spinner
 - Soda can or other cylindrical object
 - Guitar or other stringed musical instrument (see the "Musical Sidebar")



Fig. 2. Cut the rubber band.

Here's what to do:

1. **Cut** the rubber band with scissors (Fig. 2) so that it is a linear strand.
2. **Have** a partner help you with this:

- a. Stretch the rubber band across the high-speed copier bed (Fig. 3) and perpendicular to the axis of the scan bar (usually held left to right).

(*Note:* The photocopied image in Fig. 1 was the result of a loosely stretched rubber band and Fig. 4 shows the output when the same rubber band is stretched more tightly.)



Fig. 3. Stretching the rubber band on copier.

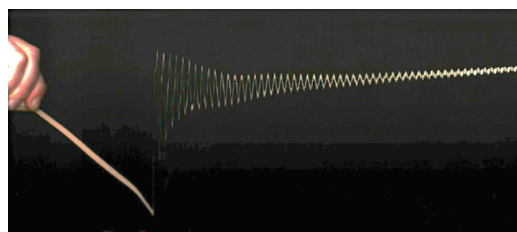


Fig. 4. Same rubber band used in Fig. 1, but stretched more tightly.

- b. The rubber band should be held very close to the glass but not touching it, so that it is free to vibrate.
 - c. Pinch and pull the rubber band to one side and be ready to release.
 - d. Press the start button on the photocopier.
 - e. When the lighted scanner bar moves under the rubber band, release the rubber band so that it can vibrate back and forth.
3. **As soon** as the copier's light turns off, you're done!
 4. **Remove** the copy from the tray and see what was recorded.

What's going on?

Cool, right? And all from a vibrating rubber band and

photocopier! A photocopier is designed to record stationary flat objects. It doesn't work like your eye/brain system. It doesn't randomly scan a scene for important locations and events and try to put everything in context. A photocopier only records what it "sees" directly above the optical scan bar and that's it.

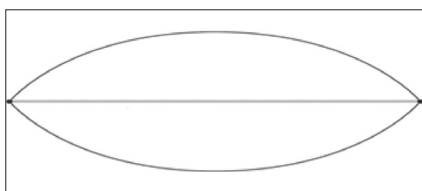


Fig. 5. Harmonic waveform.

A photocopier contains a host of electronic and mechanical systems that all need to be in sync. After the start button is pressed, a scanner or scan bar moves at a set and constant rate beneath a glass bed.

When plucked, your rubber band really vibrates back and forth as a fundamental harmonic waveform (1/2 wavelength), just like a guitar string (Fig. 5). Pluck your rubber band and prove that to yourself!

What is recorded happens over the course of a few seconds. But because there are two perpendicular moving parts that combine to make the image (the vibrating rubber band and, 90° to that, the scan bar), you don't see a simple harmonic. What is recorded looks like a sine-wave pattern that's bigger on one end and flattens out to a line on the other.

To the right (Fig. 6) is a hypothetical series of images you might see if you were able to look up and through the glass scanner bed. Here are 10 frames or 2-1/4 cycles of back and forth (or up and down in this view) motion of the rubber band (pink). The scan bar moves sideways frame by frame at a constant velocity (green) and records the view at each instance (black dot). The image is a continuous recording (light blue).

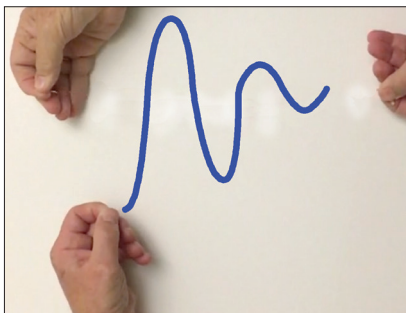


Fig. 7.

What is produced is a composite of both motions over time (dark blue) (see Fig. 7). Since the scan bar moves a certain distance in a certain amount of time, the copy you see is a graph—a time and distance graph! Each

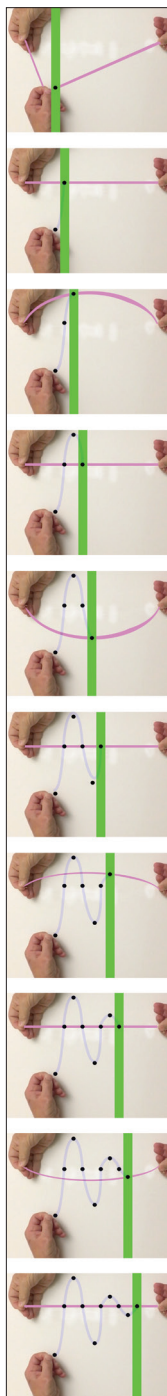


Fig. 6.

wave crest represents one full cycle of back and forth motion of the rubber band, but in a different location or moment in time.

Each wave crest is **equidistant**, because the rubber band vibrates at a **constant rate**. You can hear the **frequency or pitch** of the plucked band. If you change the **tension, length or mass (thickness)** of the rubber band, you change the frequency or rate of back and forth motion and therefore the distance from wave to wave or **wavelength**. The scan bar is moving from the region where you plucked it (antinode) to where you're holding it (node), and the oscillation also naturally dampens with time. You can see the combined effect of these two factors by the successive decrease in wave height. If you listen, you may notice that the rubber band does indeed get quieter over a short period of time. The vibration **decays**, and the **amplitude** of each successive wave gets smaller and smaller. All this is seen because both phenomena, the moving rubber band and the scan bar, take time.

A similar effect happens with digital cameras, like those on cellphones. If you take a picture of a very fast moving object, such as a spinning propeller (Fig. 8), you'll get a recorded image that looks distorted. Most cellphone cameras scan the scene just like photocopiers do. Although the scan is all electronic (no moving parts) and it happens much faster, it still takes time. And on a digital camera it can happen when taking a still shot or movie. This phenomenon is known as the "Rolling Shutter Effect."²⁻⁴



Fig. 8. A spinning propeller image taken with a cellphone; the rolling shutter effect causes the propeller to appear warped.

Want to do some math?

You can do some interesting calculations with your photocopier, since it's a graph of events that happened over a plate of glass. Here's one to try: find out the frequency at which your rubber band is wiggling.

First figure out the speed of your scanner.

All scanners scan documents at a constant rate, but figuring this speed accurately can be a challenge unto itself. There are several ways to figure this out, but here's my favorite:

1. **Use a cellphone** or digital camera to make a video recording of your photocopier in action (see Fig. 9). Using the standard recording speed of 30 frames⁵ per second (fps), record the machine as it scans from one side of the bed to the other. Most beds are either tabloid size, 17.0 in (43.20 cm) long in the United States or Canada, or A3 size (420 mm or 16.54 in) in other countries.
2. **Play back** your video on a computer or video system that lets you step through every individual frame. (Note: Make sure your software doesn't "drop" or remove any frames due to digital compression!)

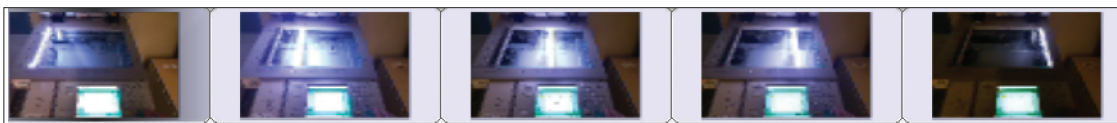


Fig. 9. A video recording of photocopier in action.

3. **Count the number** of frames from when your scanner starts to when it stops scanning.

Here are a couple of things to know to make a better frame count:

- Many photocopiers give the scan bar a short distance to “run up” to speed.
 - Be mindful that determining the first and last frame is made more difficult due to the extreme brightness of the scan bar.
4. **Compute the speed**, which is just the scan bed length divided by the time for the scan (number of frames times 0.0333 s).

Here’s an example from the Exploratorium’s office scanner.

From beginning to end, our video shows that the scan took 53 frames to cover the 17.0 in or 0.432 m scan bed.

$$53 \text{ frames} \times 0.033 \text{ s} = 1.75 \text{ s.}$$

The speed of the scanner is therefore

$$0.432\text{m}/1.75 \text{ s}$$

$$\text{or } V = 0.25 \text{ m/s.}$$

Figure out wavelength (λ) of your copied waveform.

Photocopiers are designed to scan and print documents incredibly close to the original document’s dimensions. (*Note:* make sure your copier is set to 100% copy ratio.) This means you can directly measure the distance from wave crest to wave crest. However, it is better to measure the distance of multiple waves and divide by the number of waves. This average will give you better data than measuring an individual wave.

1. **Use a** metric ruler to measure the distance of multiple waves (Fig. 10).

- Number of waves = _____
- Distance from first crest to last = _____ m

2. **To get** the average wavelength of the copied image, divide the distance by number of waves.

$$\text{Wavelength} = \text{_____ m/wave.}$$

For our example:

We measured 15 waves over a distance of 7.0 cm or 0.070 m.

So, the graph has a wavelength of 0.070 m/15 waves

or

$$\lambda = 0.0047 \text{ m/wave.}$$

Note: This is not the wavelength of the standing wave fundamental. The captured waves and associated wavelengths are an artifact of how the scanner records the moving fundamental wave. Each crest to crest (or trough to trough) recorded wave of the vibrating rubber band represents a different time and location of the scan bar as it moves under each cycle of the actual fundamental wave.

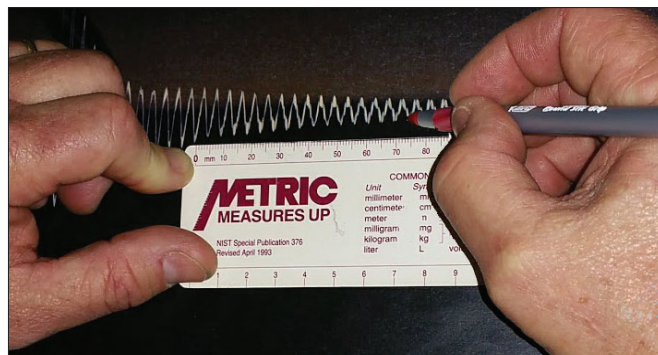


Fig. 10. Measuring the crest-to-crest distance.

Finally, figure out the frequency (f) of your vibrating rubber band. Although the rubber band is really moving at a fundamental harmonic, its multiple waveform recording was created by moving a scan bar of known velocity (V), tracing waves of a known wavelength (λ). You can use the wave equation:

$$f = V / \lambda.$$

Therefore, our example has a frequency of:

$$f = 0.25 \text{ m/s} / 0.0047 \text{ m/wave}$$

or

$$f = 53 \text{ waves/s or } 53 \text{ Hz.}$$



Fig. 11. Here’s our setup of recording and then plucking a rubber band. Note the external microphone to help with recording.

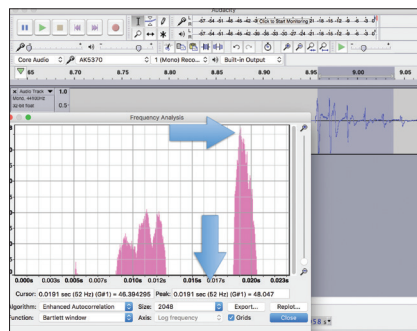


Fig. 12. Shown here is Audacity, a free audio analysis program.

And the best part, this can be confirmed with sound analyzing software!! (See Figs. 11 and 12.)

Our calculated frequency was 53 Hz and our audio sample of the same plucked rubber band was 52 Hz ... pretty good. Con-

sidering all the small precision errors and these numbers still agree within an error of less than 2% ... that’s amazing!

A Musical Sidebar: How to tune a guitar with a photocopier!

1. Place guitar upside down on a scanner bed. Don't let the strings touch the glass.
2. Guitar strings should be strummed once as the photocopier scan bar passes underneath. Strumming an area not on the glass scan bed, like the over-hanging neck, might lead to a clearer image.
 - a. Strum all strings.
 - b. Pluck individual strings.
 - c. Strum a chord.
3. Check out your copy...cool!
4. Measure your waves, just like your rubber band example above.
5. Calculate each string's frequency using the wave equation.
6. Compare your results from a guitar tuner or audio analysis software.

We need to tune our guitar, but we won't fret about it! Other things to notice:

- Which string was strummed first?
- Can you see overtones in the strings?
- Are there differences between nylon and metal strings?

Here's how we did:

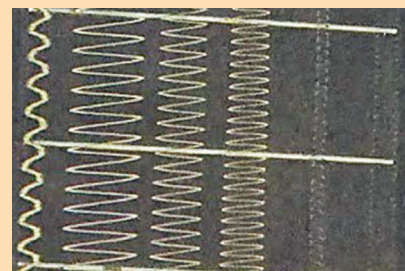
Frequency	String 1	String 2	String 3	String 4	String 5	String 6
Photocopier result	79 Hz	109 Hz	143 Hz	193 Hz	244 Hz	315 Hz
Audio tuner result	79 Hz	107 Hz	141 Hz	189 Hz	242 Hz	320 Hz
Standard tuning	82.4 Hz	110 Hz	147 Hz	196 Hz	247 Hz	330 Hz
Name of note	E	A	D	G	B	E



Electric Guitar



4-String Electric Bass



Close-up of strings on guitar neck.

Going further⁶

Here are some things to try:

- If you know the frequency of your vibrating rubber band (by using an audio analysis program), you can figure out the scanning speed of other photocopiers.
- Experiment with tension, mass, and length of your rubber band. How would it affect your photocopied outcome?

$$f_1 = \frac{\sqrt{\frac{T}{m/L}}}{2L}$$

T = string tension
 m = string mass
 L = string length

- Use this activity to spark a variety of sound and wave investigations and experiments.
- Find things that spin, roll, or move. Predict what you will see from the copier. Just by pressing "start," you can

confirm your guess and make some great images! A few of our favorites are shown in Figs. 13 and 14; for more images, see Ref. 6.

Teacher Tips

Here are some ideas to make your activity more palatable to others that don't share your interest in physics and art:

- Make sure to clean the glass scan bed after use.
- Printing your scans in black and white is usually cheaper than color.
- Scans sent digitally to your computer are cheaper and less resource intensive than printing (you will save on ink costs).

So, don't ignore tension in your physics class; cut it with a knife and see what happens to the frequency! And always re-

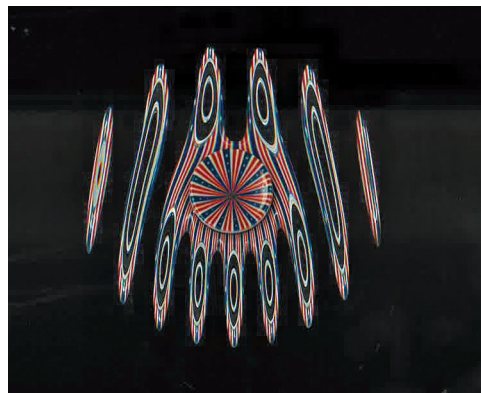
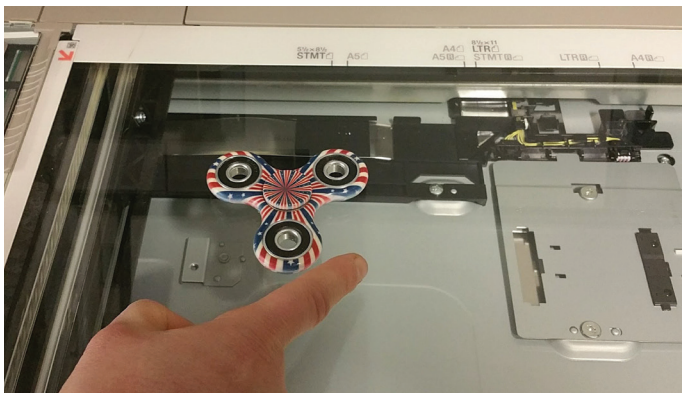


Fig. 13. Fidget spinner and results on the copier.



Fig. 14. Rolled carton and results.

member to have fun, learn something, and promote copying in science!

Acknowledgments

Thanks for the help and support from the Exploratorium, especially Don Rathjen. I would also like to thank Zeke Koss-over and the rest of the Exploratorium Teacher Institute crew.

References and online resources

1. Matt Parker, "Rolling Shutter Explained on the Cheap," YouTube, standupmaths Channel (July 12, 2017), <https://www.youtube.com/watch?v=nP1eMR5qjc>.
2. Destin Sandlin, "Why Do Cameras Do This? (Rolling Shutter Explained) - Smarter Every Day 172," YouTube, Smarter Everyday Channel (June 30, 2017), <https://www.youtube.com/watch?v=dNVtMmLlnoE>.
3. Dan MacIsaac, "Smartphones in a guitar redux," *Phys. Teach.* 53, 190 (March 2015), <https://doi.org/10.1119/1.4908097>.
4. Udi Tirosh, "Everything You Wanted to Know About Rolling Shutter," DIY Photography (Sept. 24, 2012), <https://www.diy-photography.net/everything-you-wanted-to-know-about-rolling-shutter/>.
5. Eric Muller, "Falling for Gravity," Exploratorium Science Snacks (Sept. 9, 2016), <https://www.exploratorium.edu/snacks/falling-gravity>.
6. You can find examples and photos of additional activities at *TPT Online*, <http://dx.doi.org/10.1119/1.5084918>, under the Supplemental tab or at <http://www.exo.net/~emuller/copierscience/>.

Eric Muller, seen here "blowing a raspberry" of 54 Hz, is a Sr. Science Educator at the Exploratorium Teacher Institute in San Francisco. emuller@exploratorium.edu

