

Open the simulation at **activities.zornscience.org/faraday-lab/**. A neodymium magnet falls through a vertical 1.00 m tube while an identical magnet falls freely beside it. You can change the tube material and the magnet strength, reverse the poles, slow the motion down, and reveal the eddy currents and induced magnetic fields in the tube. The ruler beside the tube reads height above the bottom of the tube. You will also need a stopwatch (a phone timer works).

**Learning goals.** I can...

1. Explain how a changing magnetic field (changing magnetic flux) induces an electric current in a conductor.
2. Use Lenz's law to predict the direction of induced currents and fields and the force they exert on a moving magnet.
3. Investigate how tube material, magnet strength and pole orientation affect the induced current and braking force.
4. Describe the energy changes for a magnet falling through a conductor.
5. Evaluate whether your data are reliable evidence for the link between changing magnetic fields and current.

**Key ideas**Magnetic flux:  $\Phi_B = BA \cos \theta$ Faraday's law:  $\varepsilon = -N \Delta \Phi_B / \Delta t$ Lenz's law: the induced current makes a magnetic field that opposes the *change* in flux.Average speed:  $v = d/t$  Free fall:  $\Delta y = \frac{1}{2}gt^2$ Energy:  $PE = mgh$   $KE = \frac{1}{2}mv^2$   $g = 9.81 \text{ m/s}^2$ **NGSS alignment**

HS-PS2-5: a changing magnetic field can produce an electric current.

HS-PS3-5: model two objects interacting through magnetic fields, with the forces and energy changes.

**Predict (before you touch the simulation)**

1. Copper is not attracted to a magnet the way iron is. Predict how the fall time of a strong magnet dropped through a copper tube will compare with an identical magnet dropped through air. Explain your reasoning.

**Part A: Comparing Tube Materials**

Set the magnet strength to 1.0x with N down. For each tube, press **Release magnets** and time the magnet in the tube from release until it lands in the catch tray. Do three trials and average them. If a fall is too quick to time, turn on **Slow motion** ·  $\frac{1}{4}$  **speed**, time it, then divide your time by 4.

2. Record your fall times.

| Tube             | Trial 1 (s) | Trial 2 (s) | Trial 3 (s) | Average (s) | Compared with free fall (slower, about the same, faster) |
|------------------|-------------|-------------|-------------|-------------|----------------------------------------------------------|
| Copper · intact  |             |             |             |             |                                                          |
| Copper · slotted |             |             |             |             |                                                          |
| Plastic          |             |             |             |             |                                                          |

3. The free-falling magnet drops about 1.13 m from release to the catch tray. Use  $\Delta y = \frac{1}{2}gt^2$  to calculate its fall time. Does this agree with your timing for the plastic tube?
  
4. Copper and plastic are both not attracted to a magnet. What property of copper explains why only the copper tube slows the magnet?
  
5. The slotted tube is the same copper with one lengthwise cut. Turn on the eddy currents and explain why the slot almost eliminates the braking.

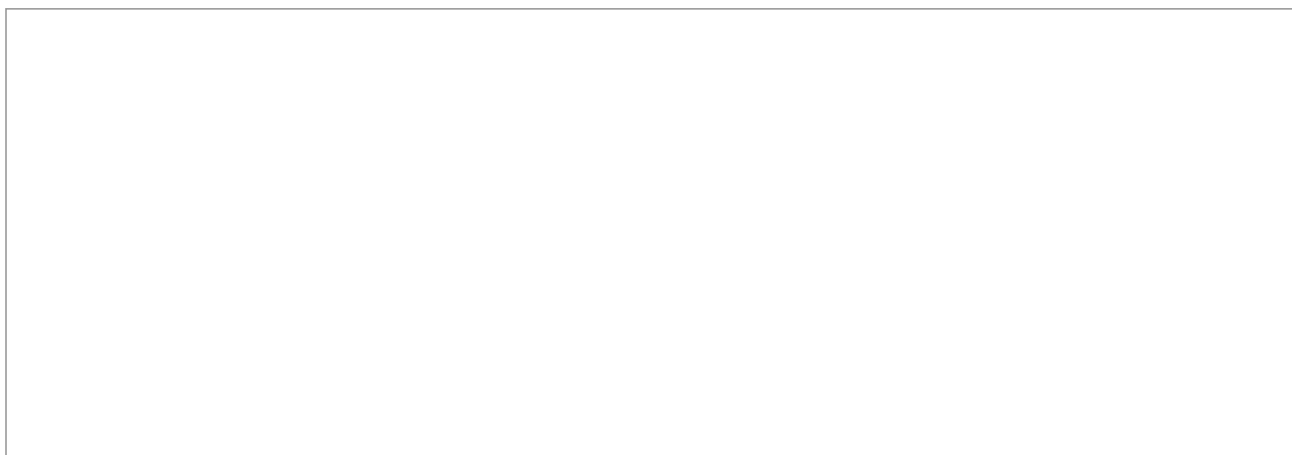
## Part B: Seeing Lenz's Law

Choose **Copper · intact**, strength 1.0×, N down. Turn on Tube cutaway, Eddy currents, Induced fields and Force arrows. Release, then press **Pause** while the magnet is near the middle of the tube. The arrows on the cyan loops show conventional current. Picture the loops as if you were looking straight down the tube from above. Then press **Reverse poles** and repeat with S down.

6. Record what you see.

| Pole facing down | Loop             | Magnet moving toward or away from the loop? | Current viewed from above (CW or CCW) | Induced field in the tube (up or down) |
|------------------|------------------|---------------------------------------------|---------------------------------------|----------------------------------------|
| N                | Above the magnet |                                             |                                       |                                        |
| N                | Below the magnet |                                             |                                       |                                        |
| S                | Above the magnet |                                             |                                       |                                        |
| S                | Below the magnet |                                             |                                       |                                        |

7. In the box, sketch the magnet (N down) and the two current loops. Label the magnet's poles. Each current loop acts like a small magnet: label the N and S ends of each loop and draw an arrow for the braking force.



8. Use your sketch to explain how *both* loops push the magnet upward, even though their currents flow in opposite directions.
9. When you reversed the poles, the currents reversed. Did the direction of the braking force change? Did the fall time change? Use Lenz's law to explain why.

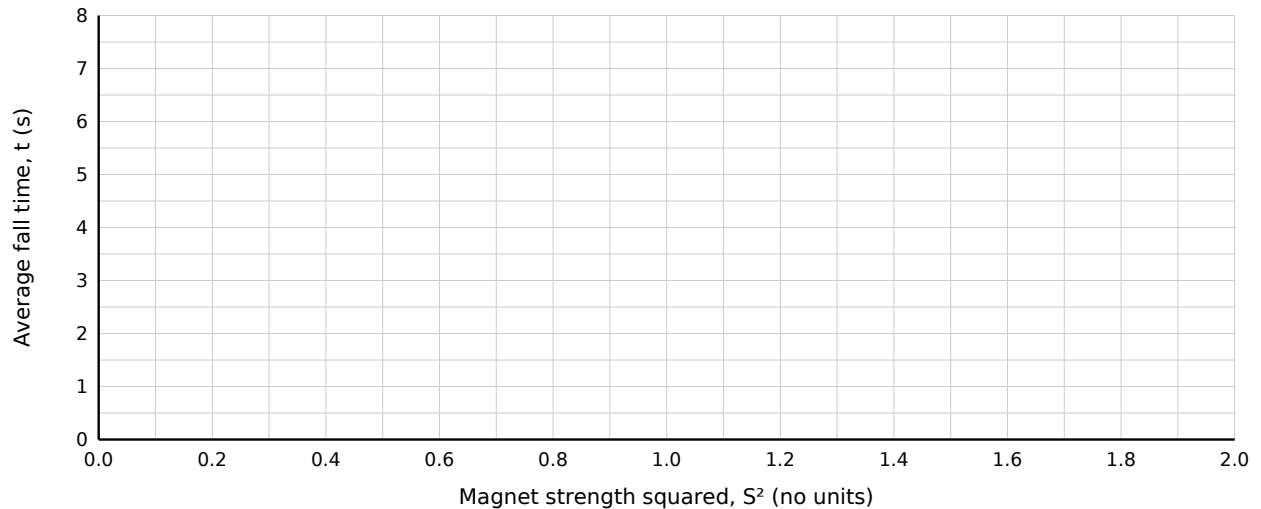
### Part C: Magnet Strength and Terminal Speed

Use **Copper · intact**, N down, real time. For each magnet strength  $S$ , time three falls from release to the catch tray and average them. Then find the average speed through the 1.00 m tube,  $v \approx 1.00 \text{ m} \div t$ .

10. Record your data.

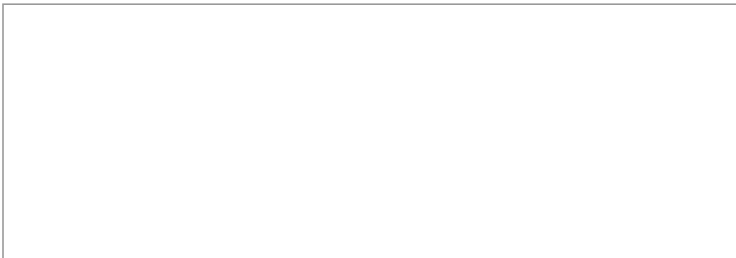
| Strength $S$<br>(x) | $S^2$ | Trial 1 (s) | Trial 2 (s) | Trial 3 (s) | Average $t$ (s) | $v \approx 1.00 \text{ m} \div t$ (m/s) |
|---------------------|-------|-------------|-------------|-------------|-----------------|-----------------------------------------|
| 0.6                 |       |             |             |             |                 |                                         |
| 0.8                 |       |             |             |             |                 |                                         |
| 1.0                 |       |             |             |             |                 |                                         |
| 1.2                 |       |             |             |             |                 |                                         |
| 1.4                 |       |             |             |             |                 |                                         |

**11.** Graph average fall time (y-axis) against  $S^2$  (x-axis). Draw a best-fit line and calculate its slope.



**12.** Is the graph of  $t$  against  $S^2$  linear? What does that tell you about how the braking force depends on magnet strength? (Hint: the magnet spends most of its fall at constant speed, so  $t$  is roughly proportional to  $1/v$ .)

**13.** Inside the copper tube the magnet quickly reaches a constant speed. Draw a free-body diagram of the magnet at that point. How does the braking force compare with the magnet's weight?



**14.** In question 13 the braking force equals the weight at every strength, yet stronger magnets fall more slowly. Explain how both can be true.

**15.** Use your best-fit line to predict the fall time at  $S = 1.5\times$ . Then test it. What was your percent error?

## Part D: Where Does the Energy Go?

**16.** A 20 g (0.020 kg) magnet at strength 1.0× falls through the full 1.00 m length of the copper tube.

- a) Calculate the gravitational potential energy it loses.
- b) Use your average speed from Part C (1.0×) as its speed leaving the tube. Calculate its kinetic energy.
- c) What percent of the lost potential energy did *not* become kinetic energy? Where did it go?
- d) How fast would the same magnet be moving after falling 1.00 m in free fall?

## Conclusion

**17. Claim, evidence, reasoning.** How does a changing magnetic field produce an electric current, and how does that current affect the magnet that caused it? Use specific data from Parts A, B and C as evidence.

**18.** Identify one source of error in your timing data, explain how it affected your results, and describe how to reduce it. Were your three trials close enough to trust the pattern in Part C? Explain.

**19.** Some roller coasters and trains use magnetic brakes: magnets pass close to copper or aluminum fins. Explain why these brakes get weaker as the vehicle slows down, and why they do not wear out like friction brakes.