Subject Area(s) **physics**

Associated Unit

Associated Lesson

Activity Title **Falling Magnets**

Header

Grade Level **12 (11-12)**

Activity Dependency

Time Required **45 minutes**

Group Size **28**

Expendable Cost per Group US$0

Summary

The overall aims for this lesson can be divided into three parts. The first is to briefly review classical mechanics fundamentals, such as drawing free-body diagrams and recalling the relationship between speed and acceleration. Next, physical mechanisms responsible for magnetism and eddy currents are discussed, with a mention Maxwell's equations. The demonstration is concluded by discussing a few everyday examples of the use of eddy currents (especially induction heating and LED shake lights).

Engineering Connection

Mechanical and electrical engineers must be mindful of the dynamic interactions of electrical and magnetic fields, because the motion of a magnetic field near a conductor can have unexpected behaviors. Such is the case with eddy currents—not only can these induced currents slow down a moving conductor, they can generate unwanted levels of heating. Engineers, however, have even found ways to use seeming disadvantages for useful purposes, like stopping trains and cooking dinner.

Engineering Category = **#1**

Keywords

eddy current, induction, magnetism

Educational Standards

- ITEEA, Standard 16, Grades 9-12, J. Energy cannot be created nor destroyed; however, it can be converted from one form to another.
- ITEEA, Standarded 16, Grades 9-12, K. Energy can be grouped into major forms: thermal, radiant, electrical, mechanical, chemical, nuclear, and others.
- Texas Essential Knowledge and Skills (TEKS) §112.39. Physics, Beginning with School Year 2010-2011… (c) (5) (D) "Science concepts. The student knows the nature of forces in the physical world. The student is expected to… identify examples of electric and magnetic forces in everyday life;"

Pre-Requisite Knowledge

Understanding of kinematics, including free body diagrams (Texas Essential Knowledge and Skills (TEKS) §112.39. Physics, (c) (4) (B) "Science concepts. The student knows and applies the laws governing motion in a variety of situations. The student is expected to… describe and analyze motion in one dimension using equations with the concepts of distance, displacement, speed, average velocity, instantaneous velocity, and acceleration;" and (c) (4) (E) "Science concepts. The student knows and applies the laws governing motion in a variety of situations. The student is expected to… develop and interpret free-body force diagrams;").

Understanding of atomic nature of solids.

Basic knowledge of electricity and magnetism.

Knowledge of calculus.

Learning Objectives

After this activity, students should be able to:

- Draw free body diagrams for the falling magnet
- Predict time for a magnet to free fall
- Explain the physical origins of magnetism and eddy currents
- List Maxwell's equations and understand the meaning of each term
- Identify practical uses of eddy currents

Materials List

The instructor needs:

- High grade rare earth ring-shaped magnet (such as N42 neodymium-iron-boron) that is axially poled with thickness of approximately 1.27cm (½ inch), outer diameter of 1.9cm (¾ inch), inner diameter of 0.635 cm (¼ inch)
- Stopwatch
- Meter stick
- Shallow pan to catch falling magnet
- Mousepad, towel, or other soft, shock absorbing material to cushion magnet's impact
- Five tubes of roughly equal length (20cm (8 inches) works well) and 2.54cm (1 inch) inner diameter made of
    - schedule 40 PVC
    - thin walled PVC (such as a sink tailpiece)
    - galvanized steel (galvanized iron and black iron work well, too)
    - thin walled copper tubing (such as type L)
    - thick walled copper tubing (such as type K)

Introduction / Motivation

Sometimes it is difficult to predict which forces of nature are significant in a given situation. Magnetic effects, aside from posting notices on the home refrigerator, go largely unnoticed by the general public. The interaction of magnetic and electric fields, however, is critical in electric motors, magnetometers (metal detectors), and mag-lev transportation. The motion of a magnet near an electrical conductor can produce unanticipated effects.

Do you think dropping an object through a tube will change the velocity of the object? Let's see if this demonstration will make you change your mind.

Vocabulary / Definitions

Word	Definition
degaussing	Process of decreasing a magnetic field, typically by using a coil with an opposing magnetic field.
eddy	A current (either fluid or electrical) whose flow direction differs from that of the general flow
ferromagnetism	Property of certain materials that have an electronic configuration, which supports a net total magnetic dipole moment even when the magnetizing field is removed.
kinematics	Branch of classical mechanics that studies the motion of object without regard to the underlying forces
permeability	Degree of magnetization a material will experience when exposed to a magnetic field.

Procedure

Background

1. A free body diagram for a falling object can be represented by drawing a circle with a small arrow at the top pointing vertically upward (drag force) and a larger arrow at the bottom of the circle oriented vertically downward (gravitational force)
2. For the magnet geometry recommended in this activity, the viscous and pressure drag due to the object falling through air is negligible relative to the gravitational force
3. From kinematics, the students should recall that
    a. $\boldsymbol{v} = \int_{t_0}^{t_1} \boldsymbol{a}\, \mathrm{dt}$, where ***v*** is velocity, ***a*** is acceleration, and the integration occurs between two instants in time
    b. If the acceleration is due to gravity and the initial time is taken as zero, one obtains $\boldsymbol{v}=\boldsymbol{g}t$
    c. The distance *d* a body travels can be found by integrating its velocity in time, so $\boldsymbol{d} = \int_{t_0}^{t_1} \boldsymbol{v}\, \mathrm{dt}$ or substituting from above, $\boldsymbol{d}=½\boldsymbol{g}t^2$
    d. Solving the expression for time yield the final result $t = \sqrt{\frac{2d}{g}}$
4. Though we generally think of "ferromagnetic" materials and their behavior, all materials are influenced to a greater or lesser degree by the presence of a magnetic field. Physicists and engineers work with many different classes of magnetic materials—ferromagnetic, antiferromagnetic, ferrimagnetic, paramagnetic, diamagnetic… just to name a few!
5. The observed differences in magnetic behavior are dependent upon the atomic structure and electron configuration of the material. Generally, these characteristics can be captured by the relative permeability, a measure that is analogous to the dielectric constant. The relative permeability (κ_m) is formed by taking the ratio of the permeability of the material (μ) to the permeability of free space (μ_0); the permeability refers to the amount of magnetization a material will experience when introduced to a magnetic field.
    a. ferromagnetic materials: κ_m significantly greater than unity

b. paramagnetic materials: κ_m slightly greater than unity
c. diamagnetic materials: κ_m slightly less than unity

6. Sources of magnetization are the electrons' orbital angular motion around the nucleus and the electrons' intrinsic magnetic moment. Orbiting electrons can be thought of as extremely small current loops, so that the circulating electrons give rise to an orbital magnetic dipole moment. If one considers the spin of an electron to be an infinitesimal current loop, one sees that the spinning electron also forms an intrinsic magnetic dipole moment. The vector sum of the orbital and intrinsic momemts gives the total magnetic moment.
7. In most materials, the electrons are arranged such that their magnetic moments (both orbital and intrinsic) cancel out—these materials include diamagnetic materials. Paramagnetic and ferromagnetic materials, however, either spontaneously, or owing to an applied external magnetic field, will have electron magnetic moments that tend to align parallel to the magnetic field, thereby minimizing each moment's potential energy (the alignment is imperfect due to random motions associated with temperature). For ferromagnetic materials, a net magnetic dipole moment can persist after removal of the external field. If this is true a permanent magnet has been made. The term "permanent" is a bit misleading, however, because the magnetic dipoles can be re-randomized by increasing the material's temperature, mechanically impacting the material, or subjecting the material to a strong opposing magnetic field (degaussing).
8. Maxwell's equations
   a. Gauss' law for electricity: $\nabla \cdot E = \frac{\rho}{\varepsilon_0}$ (The electric flux through any closed surface is proportional to the enclosed electric charge: ε_0 is the electric constant)
   b. Gauss' law for magnetism: $\nabla \cdot B = 0$ (the magnetic field B has divergence equal to zero, in other words, that it is a solenoidal vector field. It is equivalent to the statement that magnetic monopoles do not exist)
   c. Maxwell–Faraday equation (Faraday's law of induction): $\nabla \times E = -\frac{\partial B}{\partial t}$ (electromotive force generated is proportional to the time rate of change of the magnetic flux)
   d. Ampère's circuital law (with Maxwell's correction): $\nabla \times H = J_f + \frac{\partial D}{\partial t}$ (relates the integrated magnetic field around a closed loop to the electric current passing through the loop)
9. Looking at the Maxwell-Faraday equation above, we see that moving and/or temporally varying magnetic fields (or more specifically, magnetic flux densities ***B***) can generate electromotive force (EMF). The equation also indicates that stronger applied magnetic fields, lower resistivity conductors, and greater variation in the applied field (either due to faster relative motion or more rapid change in time) will all result in higher EMF.
10. The induced EMF can cause electrons to move in a conductor, resulting in "eddy" (or Foucault) currents. The circulating eddies of current, in turn, induce magnetic fields that lead to repulsive, attractive, propulsive or drag effects.
11. The electromagnetic energy associated with the eddy currents is eventually converted to thermal energy, which can lead to a significant (and frequently undesirable) temperature rise in the conductor.
12. Eddy currents can be problematic in transformers, where they contribute to power loss.

13. Though eddy currents can cause significant heating of a conductor, scientists, engineers, and technologists have come to harvest this often undesirable side effect to great advantage in induction heaters and forges. These apparatuses generate very high, yet very localized, "hot spots" in a material. Induction cooktops can be found in many homes. Eddy currents are setup in the metal pots and pans placed on the range by passing time-varying currents through flat coils of wire underneath the cooktop. These cooktops heat food quickly without the gas-powered range's open flames and do not retain heat the way conventional resistively heated burners do.

Image 1 [left justified]

Image 1

ADA Description: Photograph of the surface of an induction cooktop set into a kitchen countertop

Caption: The cooking surface of an induction cooktop looks smooth and glassy

Image file: falling_magnets_image1.jpg

Source/Rights: Copyright © Erik1980, Wikimedia Commons http://en.wikipedia.org/wiki/File:Kookplaat_inductie.JPG

Image 2 [right justified]

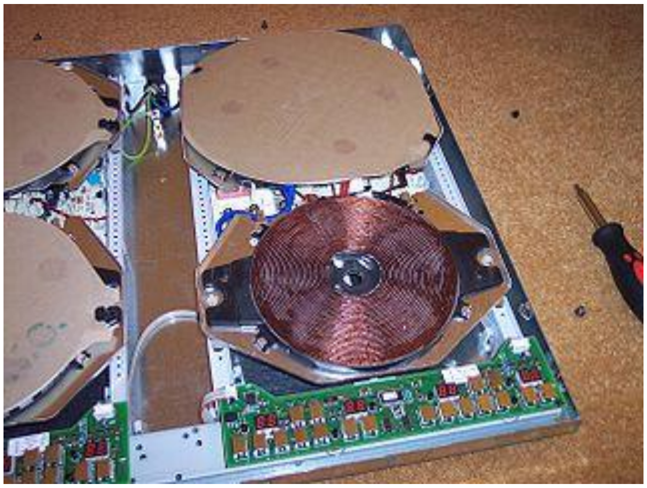
Image 2

ADA Description: Photograph of the underside of the induction cooktop shown in Image1. Three of the four heating coils are covered, but the fourth is exposed. The electronic connections are also visible

Caption: Behind the smooth top cover, the heating coils are visible, as are the electronic controls and connections

Image file: falling_magnets_image2.jpg

Source/Rights: Copyright © Twostaricebox, Wikimedia Commons http://en.wikipedia.org/wiki/File:Induction_Cooker.JPG



14. A couple of short videos showing industrial inductive heating are available at:
    a. http://www.youtube.com/watch?v=d7DBS2Is0ws
    b. http://www.youtube.com/watch?v=NofJswNBDBs&NR=1&feature=fvwp
15. Eddy currents can be used to provide non-contact braking. A conductor in the form of a rotating disc or translating bar is allowed to move freely past a series of electromagnets. When the magnets are not energized, the moving conductor feels no effects. However, when the electromagnets are turned on, eddy currents are generated within the conductor that tend to oppose the motion of the conductor. Thus the interaction of the magnetic forces causes the

conductor to slow down. The deceleration is dependent upon the electromagnet's strength and the speed of the conductor. The type of brake can be used as an emergency stopping mechanism for trains and rotating machinery. Because no physical contact is made, these brakes tend to be gentler on the mechanical system, offering longer life with less wear.

16. Induced EMF generated by sliding a magnet through a coil of wire can be harnessed to light an LED. This idea has been combined with rechargeable batteries (and a bit of circuitry) to make shake flashlights. The flashlight is an example of energy inter-conversion. The chemical energy liberated from metabolism of nutrients by cells allows a person to impart kinetic energy to a magnet. The motion of the magnet leads to eddy currents (electromagnetic energy) that can be converted to both thermal energy and radiant energy in a light emitting diode.
17. Directions for making a homemade shake light can be found by following the link to the K & J Magnetics blog in the "Activity Extension" and "Additional Multimedia Support" sections below.

Before the Activity

Gather materials. The various tubes required are available at most hardware stores. Magnets can be purchased online from K & J Magnetics.

With the Students

1. Show students the magnet, but don't yet tell them it is in fact a magnet.
2. Ask students to draw a free-body diagram for the falling "object"; the diagram should include gravitational force and drag force. Explain that the drag force should be negligible.
3. Ask students to estimate time for an object to fall—perhaps get a student to derive on the board
    a. As derived above, the final result should be $t = \sqrt{\frac{2d}{g}}$
    b. With a distance of 0.3048m (12 inches) and gravitational acceleration of 9.81 m/s^2, time to drop is just under a quarter of a second
4. Ask a student to drop "object" alongside a meter stick from the same height used in the calculation, 30cm (12 inches) works well. Be sure the magnet lands on shock absorbing material in a shallow pan. Rare earth magnets are quite brittle and can be cracked, so care is warranted to keep magnet from directly impacting the tabletop or floor and shattering.
5. Ask students whether drop time is as expected.
6. Ask a student to time the drop three to five times
7. Ask students to predict change in fall time if "object" is dropped through a PVC tube
8. Ask a new student to drop "object" through thin walled PVC tube (no noticeable change) and a new student to time the drop three to five times
9. Ask a new student to drop "object" through thick walled PVC tube (no noticeable change) and a new student to time the drop three to five times
10. Ask students to discuss reasons for variability in measured times and differences from calculated time (practicing Texas Essential Knowledge and Skills (TEKS) §112.39. Physics, Beginning with School Year 2010-2011 (c) (2) (H) "Scientific processes. …The student is expected to… make measurements with accuracy and precision and record data using scientific notation and International System (SI) units;" and (c) (2) (I) "Scientific processes. …The student is expected to… identify and quantify causes and effects of uncertainties in measured data;")
    a. possible reasons for variability between drops: magnet not always dropped from same height, different lag between observer registering start/stop of fall and activating stopwatch

   b. possible reasons for variation from theoretical value: not dropped from exact height, lag between observer registering start/stop of fall and activating stopwatch, value of ***g*** used is not the exact value at location of experiment, only gravitational force is included in calculation

11. Ask students whether the level of variation is acceptable
12. Ask students whether the “object” will drop differently through a steel tube
13. Drop the “object” through steel tube (magnet will attach to inner wall)
14. Ask students to theorize why the “object” sticks to this tube
    a. students should realize the object is magnetic
    b. explain origins of magnetism
15. Show students thin walled copper tube, tap magnet to side of tube (negligible ferromagnetism), and ask students for their estimates of fall time
16. Drop magnet through thin walled copper tube (magnet falls slowly)
17. Ask students for reasons why the magnet falls slowly in the tube
18. Explain eddy (Foucault) currents
19. Ask students to recall that thickness of PVC did not change fall time and to predict time for thick walled copper tube
20. Drop magnet through thick walled copper tube (magnet falls more slowly than in thin copper)
21. Discuss practical applications (Texas Essential Knowledge and Skills (TEKS) §112.39. Physics, Beginning with School Year 2010-2011… (c) (5) (D) “Science concepts. The student knows the nature of forces in the physical world. The student is expected to… identify examples of electric and magnetic forces in everyday life;”)
    a. Induction heating—remind students that this is an example of energy conversion. The thermal energy may appear to be magically created, but it arises from the electromagnetic energy associated with the eddy currents in the conductor. (ITEEA, Standard 16, Grades 9-12, J)
    b. Ask the students to name other major forms of energy; these include thermal, radiant, electromagnetic, mechanical, chemical, nuclear, and others. (ITEEA, Standard 16, Grades 9-12, K)
    c. Eddy current brakes—illustrate conversion of kinetic energy into electromagnetic and thermal energies. (ITEEA, Standard 16, Grades 9-12, J)
    d. LED “shake” flashlights—illustrate conversion of kinetic to electromagnetic to radiant energy. (ITEEA, Standard 16, Grades 9-12, J)

Attachments
<none>

Safety Issues
- Use caution around magnets to avoid pinching fingers
- Rare earth magnets are quite brittle and can be cracked, so care is warranted to keep magnet from directly impacting the tabletop or floor and shattering

Troubleshooting Tips

Investigating Questions

Assessment

Pre-Activity Assessment
Baseline
Ask students if they have ever heard of electromagnetic induction or eddy currents
Ask students whether dropping an object through a tube should change its velocity

Activity Embedded Assessment
Review of Classical Mechanics
Students are asked to sketch free-body diagrams, and derive an expression for time of free-fall

Post-Activity Assessment
Summarization
Students write one paragraph describing eddy currents and electromagnetic induction and one paragraph describing everyday applications of electromagnetic induction (topics may include those mentioned during the lesson)

Activity Extensions

Students can build their own LED shake flashlights. The directions and material list are available at http://www.kjmagnetics.com/blog.asp?p=shake-flashlight This activity could be used to address

- ITEEA, Standard 8, Grades 9-12, J. The design needs to be continually checked and critiqued, and the ideas of the design must be redefined and improved.
- ITEEA, Standard 11, Grades 9-12, Q. Develop and produce a product or system using a design process.
- ITEEA, Standard 11, Grades 9-12, R. Evaluate final solutions and communicate observation, processes, and results of the entire design process, using verbal, graphic, quantitative, virtual, and written means, in addition to three-dimensional models.

Activity Scaling

Additional Multimedia Support

The K & J Magnetics blog has a very nice step-by-step discussion of how to build a shake flashlight. The activity not only explains the concepts behind each step, but initially simple design is refined by adding components; this is a good example of the design and optimization process. The directions and material list are available at http://www.kjmagnetics.com/blog.asp?p=shake-flashlight

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Other

Redirect URL

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