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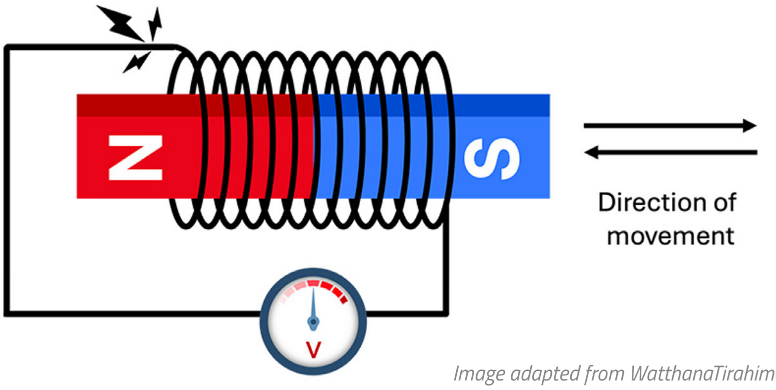

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Generating induced currents

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Three simple experiments illustrating Faraday's law of induction and the different ways induced currents may be generated.

In this article, we present a series of simple classroom experiments that allow students to observe magnetic induction phenomena directly and apply their knowledge of induced currents to explain them.

When students are able to interact directly with the subject matter, they are more engaged, involved and motivated. This leads to a more gratifying and effective learning and teaching experience for students and teachers. As the old Chinese proverb goes, "I hear and I forget; I see and I remember; I do and I understand".

The activities are aimed at students aged 16 to 19. We recommend that students carry out the experiments in groups of three and then discuss their results before presenting them to the whole class.

After completing this activity, students should

- understand Faraday's law of induction from an experimental point of view;
- understand Lenz's law from an experimental point of view;
- understand the relationship between variations in magnetic flux and the induced electromotive force (EMF);
- know how induced currents can be generated.

Historical background

Back in 1831, the English scientist Michael Faraday discovered that it was possible to generate electricity by means of motion in a magnetic field. He also demonstrated how a current in one circuit could induce a current in a neighbouring circuit. He soon explained this phenomenon in terms of variation in magnetic flux. The following year, in 1832, the American scientist Joseph Henry made similar observations independently.

These findings eventually led to the formulation of Faraday's law of induction, which is now one of the four fundamental laws of electromagnetism. This law states that the electromotive force ε induced in a circuit is proportional to the rate of change of the magnetic flux through the circuit. Faraday's law is expressed mathematically as follows:

$$\varepsilon_{induced} = -\frac{\Delta\phi}{\Delta t} \qquad \text{(Eq. 1)}$$

The minus sign on the right-hand side of the equation indicates that the direction of the induced current generates a field that opposes the change in the magnetic flux that caused the current in the first place (Lenz's law).

There are different ways to change the magnetic flux through a circuit and, consequently, various ways in which a current can be induced. We will explore these in the proposed activities.

Magnetic flux

The magnetic flux ($\emptyset$) through a given surface can be thought of as the number of magnetic field lines that pass through it.

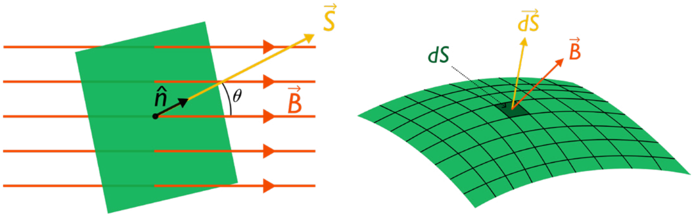

Figure 1: a) The magnetic field $\vec{B}$ penetrates a closed flat loop with the surface vector $\vec{S}$. b) The magnetic field $\vec{B}$ penetrates a differential surface element d$\vec{S}$ on a curved surface.

Images: a) Image courtesy of the authors; b) Image adapted from Maschen/Wikimedia Commons, CC0 1.0

Consider a flat loop described by a surface vector $\vec{S}$, where the magnitude of this vector is equal to the loop's surface area and the vector's direction is perpendicular to the loop. In the presence of a uniform magnetic field $\vec{B}$, the flux through the loop is expressed as the scalar product of $\vec{B}$ and $\vec{S}$:

$$\emptyset_m = \vec{B}\cdot\vec{S}\cdot\cos\Theta \qquad \text{(Eq. 2),}$$

Where Θ represents the angle between $\vec{B}$ and $\vec{S}$ (see figure 1a).

If we have a coil of N turns instead of a closed loop, the magnetic flux will increase N-fold, as the magnetic field penetrates each of the loops forming the coil:

$$\emptyset_m = N\cdot\vec{B}\cdot\vec{S} \qquad \text{(Eq. 3).}$$

When the magnetic field is non-uniform and the surface through which the flux must be calculated is not flat, the surface can be divided into small parts represented by d$\vec{S}$. This so-called differential surface element, d$\vec{S}$, is small enough that we can consider that the magnetic field through it to be constant (see figure 1b). The flux differential $d\emptyset$ through d$\vec{S}$ is therefore:

$$d\emptyset = \vec{B}\cdot d\vec{S}.$$

The flux through the entire surface is equal to the sum of all the flux differentials $d\emptyset$ through their respective differential surface elements and can be obtained by integrating:

$$\emptyset_S = \int \vec{B}\cdot d\vec{S}.$$

Combining this equation with Faraday's law, we can see that a current can be induced in a closed loop in any of the following ways:

- by varying the magnitude of the magnetic field B;
- by varying the size of the coil (i.e., S);
- by varying the relative orientation of $\vec{B}$ and $\vec{S}$.

Activity 1: Varying the magnetic field

In this activity we will induce an electrical current by changing the magnitude of the external magnetic field.[1,2]

Materials

- Three PVC tubes (length: 53 cm; outer diameter: 3.9 cm; inner diameter: 3.2 cm)
- Three stacks of three cylindrical neodymium magnets (magnet size: 28.5 mm × 10 mm)
- Coils made from enamelled copper wire (wire diameter: 0.5 mm; coil diameter ca. 4 cm). See supplementary materials for tips on how to assemble the coils.
    - 3 x coil of 110 turns
    - 1 x coil of 230 turns
    - 1 x coil of 400 turns
- Three 3 V flashlight bulbs
- Three lightbulb sockets
- One red LEDs
- One green LED

Figure 2: a) Set-up for experiment A: PVC tube with three identical coils attached to its top, middle and bottom. The coils have been assembled using cardboard. b) Set-up for experiment B: PVC tubes and attached coils with different number of turns.

Image courtesy of the authors

Procedure

Experiment A

1. Take the three coils that have the same number of turns.
2. Connect the ends of each coil to the light bulb sockets, then screw in the 3 V bulbs.
3. Attach the coils to the ends and the middle of the PVC tube, as shown in figure 2a.
4. Hold the tube upright and drop a magnet through the tube.

Observation: As the magnet falls through the tube with the three coils, the light bulbs are observed to flash one after the other. The intensity of each successive flash increases.

Explanation: Due to the uniform accelerated motion of the falling magnet, its velocity – and therefore the change in flux through each successive coil – increases as it falls.[3]

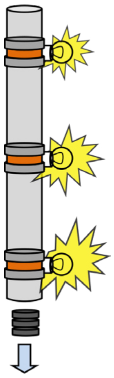

Figure 3: The diagram shows that the intensity of flash increases with the velocity of the falling magnet in experiment A.

Image courtesy of the authors

Experiment B

- Take three PVC tubes of the same length and attach a different coil (400, 230 or 110 turns) to the bottom of each tube, as shown in figure 2b.
- Connect the ends of each coil to the light bulb sockets and then screw in the 3 V bulbs.
- Holding the tubes upright, drop a stack of magnets through each tube simultaneously.

Observation: The falling magnets produce flashes of different intensity in each of the three tubes. The greater the number of turns, the more intense the flash.

Explanation: The magnetic flux, and therefore the induced current and the intensity of the flash, is proportional to the number of turns in the coil.

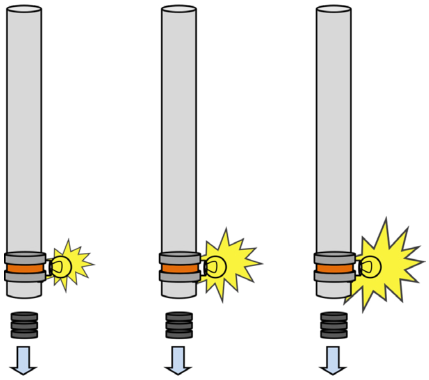

Figure 4: The diagram shows that the intensity of flash increases with the number of turns of the coils in experiment B.

Image courtesy of the authors

Experiment C

- Attach the coil with 230 turns to the bottom end of the PVC tube.
- Connect the coil to a red and a green LED in parallel, but in opposite orientations.
- Drop the stack of magnets through the tube.
- Drop the stack of magnets through the tube again, this time orienting the magnet stack in the opposite direction. Mark one side of the stack with a marker or sticker to keep track of the orientation.

Observation: When the magnet is dropped through the tube, the red and green LEDs flash quickly in succession, not simultaneously. When the orientation of the magnet is reversed, the order of the flashes changes (red-green vs green-red).

Explanation: The change in flux is positive (i.e., flux increases) when the magnet approaches the coil, and negative (i.e., flux decreases) when it moves away from it. Therefore, the induced current first flows in one direction, allowing only one of the LEDs to flash, and then in the other direction, causing the other LED to flash (see figure 5). (The two LEDs are connected in opposite orientations).

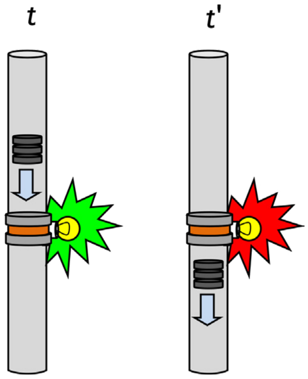

Figure 5: The diagram demonstrates what happens in experiment C. The LED flashes green (red) at time *t* as the magnet approaches the coil and red (green) as it falls away from it an instant later at *t'*.

Image courtesy of the authors

Discussion

The following questions can help you evaluate how well the students have grasped the concepts:

- Regarding experiments A and B:
  - Why do the light bulbs flash?
  - Do all the light bulbs flash with the same brightness?
  - Which light bulb flashes the brightest? Why?
  - What is the magnitude of the induced EMF?
- Regarding experiment C:
  - Do the red and green LEDs flash simultaneously?
  - Which LED flashes first? Why?
  - Does the orientation of the stack of magnets make a difference? Why?
  - What is the magnitude of the induced EMF?

A detailed discussion of the experiments can be found in the explanation sheet 1 in the supplementary materials.

Activity 2: Varying the coil surface

In this experiment we will induce a current by changing the surface area of a coil immersed in a magnetic field.[4]

Materials

We used the following materials to build the set-up shown in figure 6.

- Two 50 mm × 50 mm × 12.5 mm magnets
- A straight copper rod
- A copper rod bent into a U shape
- Clips to secure the rod
- Support on which to assemble the different elements, made of wood or particle board

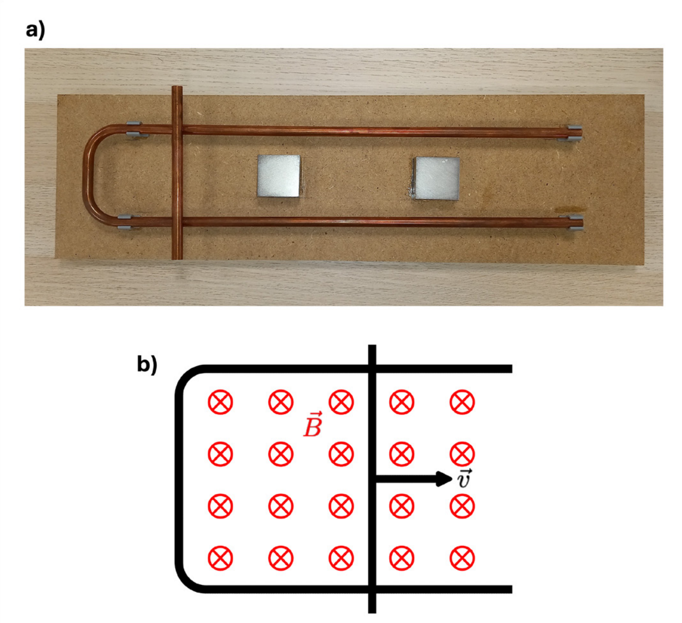

Figure 6: a) Set-up for Activity 2. b) Diagram of the set-up, showing a uniform magnetic field through the circuit loop and the bar of length L moving to the right at a velocity v. the area of the loop is $x \times L$.

Image courtesy of the authors

Procedure

Assemble the materials as shown in figure 6a.

1. The U-shaped rod should be positioned at a very slight incline on the board, just enough for the straight copper rod to roll down it.
2. The two magnet blocks under the rods generate a near-uniform magnetic field (B) perpendicular to the supporting wooden surface.

Observation: As the rod rolls over the rails, it appears to be slowed down.

Explanation: As the rod rolls to the right, the flux through the closed circuit formed by the rods increases, inducing an EMF. A current now flows through the moving rod. Being immersed in the magnetic field produced by the magnets, the current is subject to a magnetic force that opposes its motion.

Discussion

The following questions can help you evaluate how well the students have grasped the concepts:

- What is the induced EMF in this experiment?
- What happens when you let the rod roll towards the right?
- What is the direction of the current induced in the circuit in this case?
- What causes the rod to slow down as it travels over the magnets?
- What is the direction of the force slowing down the rod?
- What about if you roll the rod towards the left?

A detailed discussion of the experiments can be found in the explanation sheet 2 in the supplementary materials.

Activity 3: Varying the relative orientation of the magnetic field and the coil's surface

In this last activity we will explore the effect of the relative orientation of the coil and the magnetic field on the induced current.[4]

Materials

- Coil A: Small copper coil (diameter of 8.5 cm and 10 turns)
- Coil B: Larger copper coil (diameter of 10–15 cm and about 20 turns) connected to an LED
- 12 V halogen transformer
- Switch

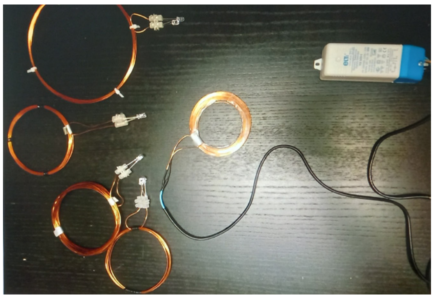

Figure 7: Materials for Activity 3 are shown, including coil A, which is connected to the transformer, and several coils B, which are connected to LEDs.

Image courtesy of the authors

Procedure

1. Connect the 8.5 cm coil (coil A) to the transformer and switch, then plug it into the outlet.
2. Turn on the switch.
3. Bring the coil connected to the LED (coil B) close to coil A so that they are parallel and their surfaces overlap.
4. Then, holding coil B over coil A, slowly rotate it until the coils are perpendicular.

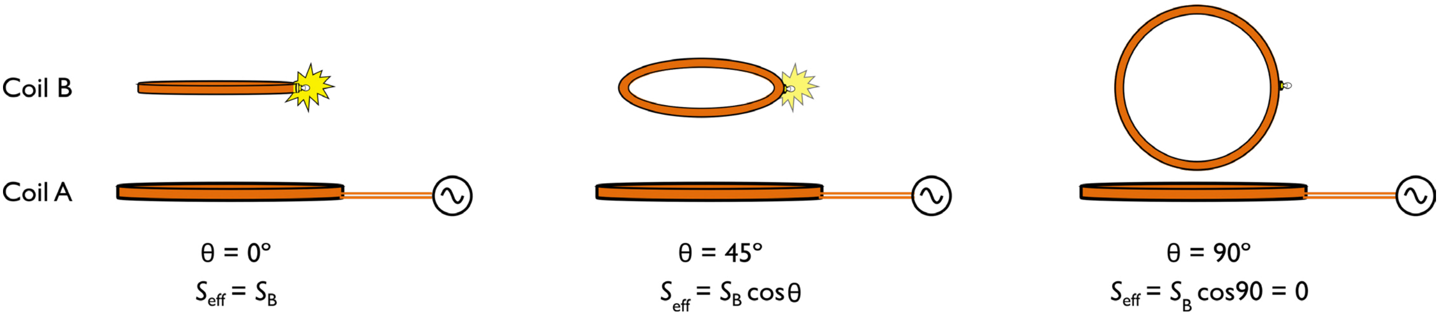

Figure 8: The diagram illustrates Activity 3. Coil A is connected to an AC power source. When coil B is parallel to coil A (θ = 0°), the flux through coil B is at its maximum and the LED intensity is at its highest. As coil B is rotated with respect to coil A, the flux through it decreases, as evidenced by the lower LED intensity. When θ = 90°, the flux through coil B is zero and the LED does not light up.

Image courtesy of the authors

Observation: When coil B is placed above coil A, the LED lights up. When coil B is parallel to coil A (θ = 0°), the LED intensity is highest. As coil B is rotated with respect to coil A, the intensity decreases continuously until it disappears completely when coil B is perpendicular to coil A (θ = 90°).

Explanation: The alternating current (AC) in coil A produces a flux variation in coil B, which induces an AC current in coil B. As coil B rotates, the flux through it decreases until it reaches 0 when the coils are perpendicular.

Discussion

The following questions can help you evaluate how well the students have grasped the concepts:

- What happens when we turn on the power?
- Why do the LEDs light up when we bring coil B near coil A?
- What happens as we rotate coil B with respect to coil A?
- What would we see if we used direct current in this experiment?

A detailed discussion of the experiments can be found in the explanation sheet 3 in the supplementary materials.

Conclusion

The activities proposed in this article will help students develop an intuition with regards to Faraday's law of induction and Lenz's law by means of three hands-on experiments exploring the concept of magnetic flux. The three different experimental set-ups allow students understand the dependence of the magnetic flux on the magnetic field, the circuit's surface area and the relative orientation of the two. «

References

[1] Del Mazo A (2002) Experiencias en electromagnetismo. *Didáctica de las Ciencias Experimentales* **34**: 94–103.

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[3] Amrani D (2005) Electromotive force: Faraday's law of induction gets free-falling magnet treatment. *Physics Education* **40**: 313–314. doi: 10.1088/0031-9120/40/4/F02

[4] Tipler PA ; Mosca G (2010): Ley de Lenz. In Casas-Vázquez J (eds) *Fisica: Para La Ciencia Y La Tecnologia* pp 965-972. Editorial Reverté. ISBN: 978-84-291-4430-7

Resources

- Watch a video performance of experiments 1 and 3 done by the authors.
- Watch a video showing the author performing the experiment described in Activity 2.(in Spanish)
- Check out another video by the authors showing a series of experiments related to induction, including experiments from activity 1 and 3. (in Spanish)
- Learn how to make convection currents visible using mist: Lim ZH, Shu A, Ng YH (2023) A misty way to see convection currents. *Science in School* **64**.
- Show students how to evaluate Planck's constant using simple equipment: de Amorim e Sá Ferreira André MR, de Brito André PS (2014) Classroom fundamentals: measuring the Planck constant. *Science in School* **28**: 28-33.
- Build a simple setup to convert the energy from water waves into electricity: Dimitriou L (2025) Electricity from sea waves. *Science in School* **72**.
- Teach electromagnetism using an induction hob: André P, Bastos AR, Ferreira R (2021) Faraday's law of induction: from classroom to kitchen. *Science in School* **52**.