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Faraday's law of induction: from classroom to kitchen

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Explore electromagnetic induction and of one of its well-known applications – the induction hob – with these hands-on activities.

Many modern devices are based on electromagnetic induction. Faraday's law of induction, formulated in 1831, describes how a variable magnetic field induces an electromotive force (EMF). Applications of this law include:

- generators, which produce most of the electrical energy consumed around the world magnetic
- levitation trains
- induction hobs in kitchen
- electric guitar pickups
- wireless power transmission pads used to charge mobile devices.

Teaching Faraday's law of induction in high school is challenging. Students aged 16–19 are required to apply both mathematical calculations and conceptual understanding to explore the science behind electromagnetic induction, and to investigate its application in daily life.

In this activity, students gain some direct experience of electromagnetic induction at work. The activities are suitable for physics students aged 16–19, and together take around an hour to complete, although additional time is required to prepare for activity 2 before the lesson.

An induction hob
PxHere - CC0

At the end of the activity, students should be able to:

- understand, from an experimental perspective, Faraday's law of induction
- identify the parameters that affect the application of Faraday's law of induction
- investigate the relationship between the variations in the magnetic flux and the induced electromotive force
- construct an electric generator, using a coil and an induction hob to power an LED

Faraday's law of induction

Faraday's law of induction states that a change in the magnetic environment of a wire coil will induce an electromotive force (EMF), represented by ε :

$$\varepsilon = -N\frac{d\Phi}{dt} \qquad (1)$$

where N is the coil number of turns and Φ is the magnetic flux across the coil.

If the timescale is small,, the derivative term $d\Phi/dt$ can be approximated to $\Delta\Phi/\Delta t$. This approximation is particularly useful if the students are not sufficiently familiar with differential calculus.

The magnetic flux depends on the coil area A, the magnetic field intensity B, and the angle θ formed between the magnetic field lines of force and the vector normal (at 90°) to the coil plane:

$$\Phi = B\,A\cos(\theta) \qquad (2)$$

Any change in the magnetic field intensity, coil area, or in the angle results in an induced EMF that can be measured with a galvanometer and used to demonstrate the principles of induction. This setup is shown in figure 1.

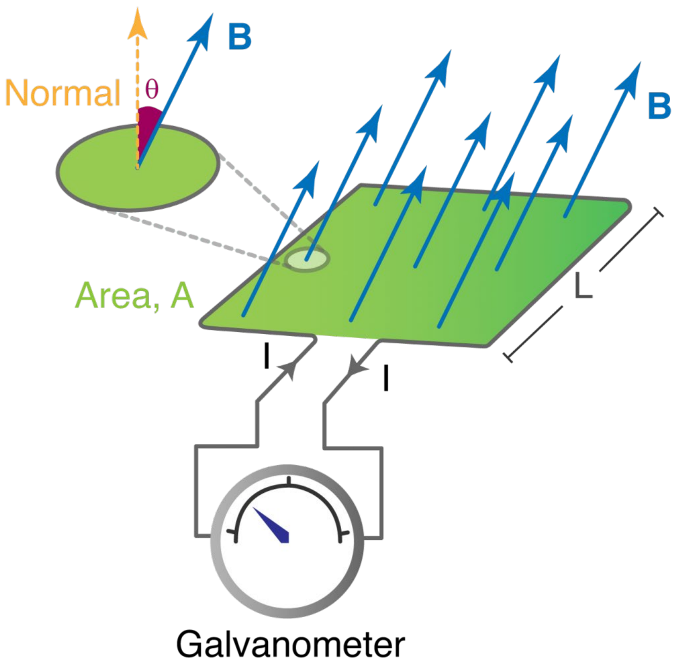

Figure 1 An electrical circuit with a galvanometer and square coil, under a magnetic field with intensity B and direction.
Image courtesy of Paulo André

Activity 1: Free-falling magnet

In this experiment, to be carried out by the students, a magnetic dipole is dropped through a coil, inducing an EMF by causing a transient change in the intensity of the magnetic field. To observe the EMF change, the coil can be connected to a galvanometer or a light-emitting diode (LED). Using an LED (figure 2) has the advantage of producing a visible output (flash of light) when the induced EMF rises above a threshold value (~1.5 V).

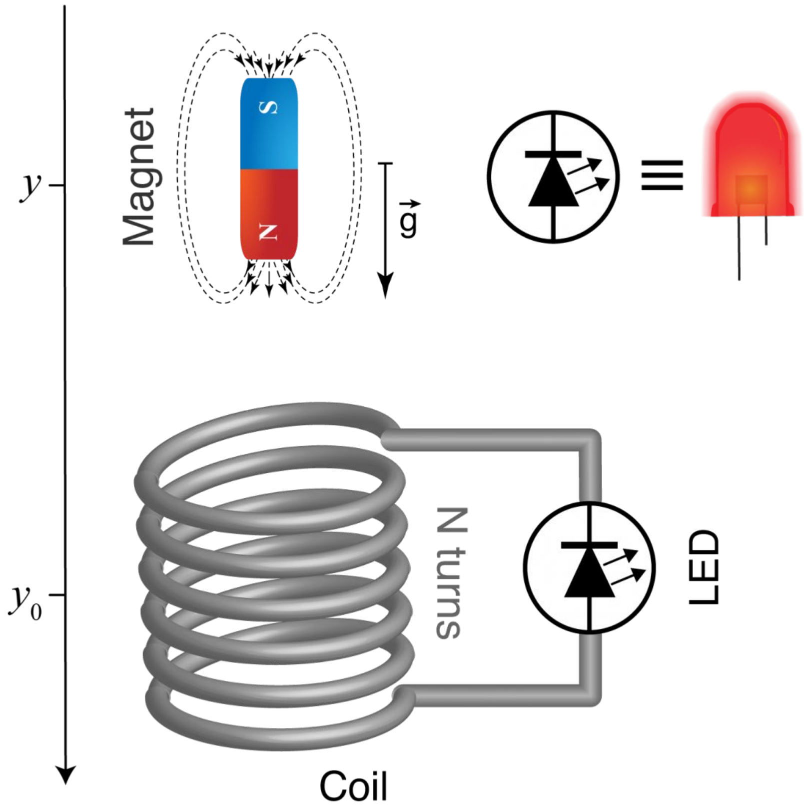

Figure 2 The free-falling magnet experiment using a LED
Image courtesy of Paulo André

Materials

- Coil with N > 10 000 turns
- Small bar magnet
- LED
- Ruler
- Smartphone (to film the free fall)

Procedure

1. Connect the coil terminals to the LED contact pads. If soldering is required, this step should be done by the teacher in advance.
2. Use the ruler to place the magnet at 20 cm above the coil centre (and aligned with the coil centre).
3. Set up the smartphone camera to record the event, preferably in slow motion.
4. Release the magnet and observe the LED (figure 3).
5. Experiment with releasing the coil from different heights above the coil. What differences, if any, do you notice?
6. Now rotate the coil through 180° and repeat the experiment. Is any change observed?

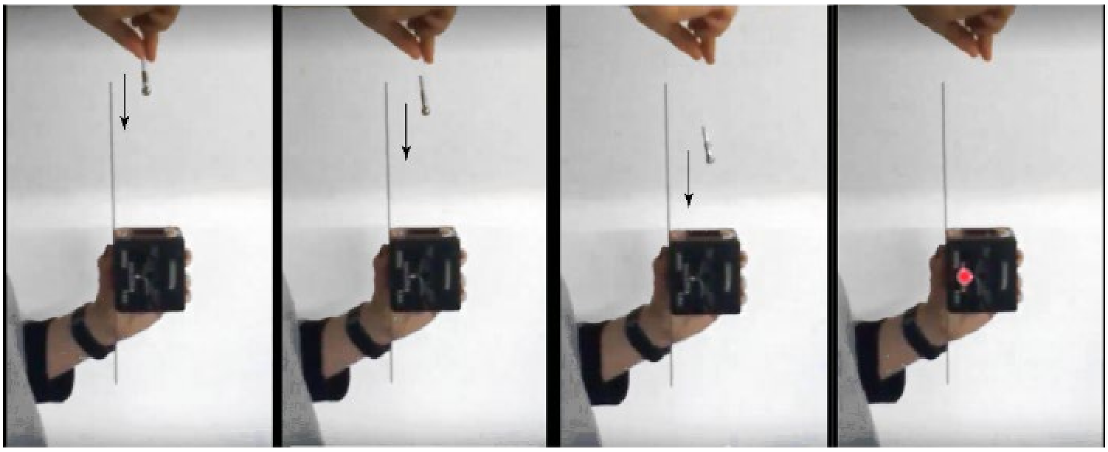

Figure 3: Frames of a video showing the free-falling magnet. The last frame is when the magnet is inside the coil and the LED is emitting (red).
Image courtesy of Paulo André

Discussion

Teachers can discuss the following questions with the students to explore key concepts:

- How does the LED emission intensity depend on the distance at which the magnet is released?
- For the same falling distance, does rotating the coil 180º result in different LED emission intensities?

Students can watch their videos of the experiment to find evidence for their answers, or watch the provided video. The process happens very fast in real life, so a slow-motion video is needed to clarify the details.

Explanation

The experiment should show a clear difference in the intensity of the LED emission as the initial distance between magnet and coil increases, resulting in increased magnet velocity and a greater rate of magnetic flux change.

The LED is a polarized device, which means that it only emits light if the applied EMF is positive (when the electrical current can flow). Whether the EMF is positive or negative depends on the direction of travel of the magnet (which pole of the magnet is currently moving through the coil) and which way round the coil has been connected to the LED contact pads.

We can see this in more detail in the simulation shown in figure 4e. Here, the EMF is positive for only approximately half of the time period for which the magnet is inside the coil, and that the positive EMF has a higher maximum value than the negative EMF due to the magnet accelerating as it falls through the coil.

Activity 1 extension: mathematical modelling

While the flashing LED provides an indication of an induced EMF resulting from the changing magnetic flux, it provides no quantitative values. We can find out more precisely the varying values of magnetic flux as the magnet falls through the coil by using a further equation:

$$\Phi(t) = B_{max}\, A \exp\left(-\frac{(y(t) - y_0)^2}{\sigma}\right) \tag{3}$$

where y represents the magnet coordinate, y_0 the coil centre coordinate, B_{max} the maximum value of the magnetic field intensity, and σ is a parameter describing the magnetic field intensity decay.

Here we make the following assumptions or approximations:

- the magnet's length is small relative to that of the coil
- its magnetic field vector is aligned with its longitudinal axis
- Φ (the magnetic flux across the coil) is at a maximum when the geometric centres of the coil and magnet coincide.

The parameter σ (distance for B ~ 37 % of B_{max}) can be assumed to be in the 5 – 10 mm range, the complete procedure for experimental determination can be found in Ref. [1].

For a magnet in free fall, the displacement y of the magnet at time t is related to gravitational acceleration, g via equation 4:

$$y(t) = 0.5\, g\, t^2 \qquad (4)$$

Table 1 provides an example of the parameters used.

Parameters	Symbol	Value	Unit
Coil area	A	250	mm^2
Coil number of turns	N	12000	
Magnetic field maximum intensity	B_{max}	3	mT
Magnetic field decay	σ	10	mm
Coil centre coordinate	y_0	200	mm

Table 1. Example values for the parameters used to obtain the results of Figure 4.

Using the values in table 1, equations 3 and 4, and the attached spreadsheet, we can produce a mathematical model that shows these variations graphically, as seen in the results and graphs in figure 4.[2] Here, the magnetic flux through the coil and the induced EMF are shown as a function of position and time. The magnet is released at y = 0 and t = 0, and it falls in the positive direction of the axis. The coil is centred in position y_0.

Discussion

Using figure 4 and the spreadsheet, teachers can discuss the following questions with the students:

- How does the magnetic flux change as the magnet approaches the coil centre? (It increases, followed by a decrease after passing the centre – see Fig. 4b.)
- In figure 4c, what happens to the EMF as the magnet passes through the coil centre? (There is a change of sign from negative to positive.)
- In figure 4e, is the shape of the EMF curve symmetrical before and after the magnet passes through the coil centre? (No, it is asymmetrical, because the magnet is in free fall, so its velocity is increasing with time and the rate of change of the magnetic flux and induced EMF also increases with time.)

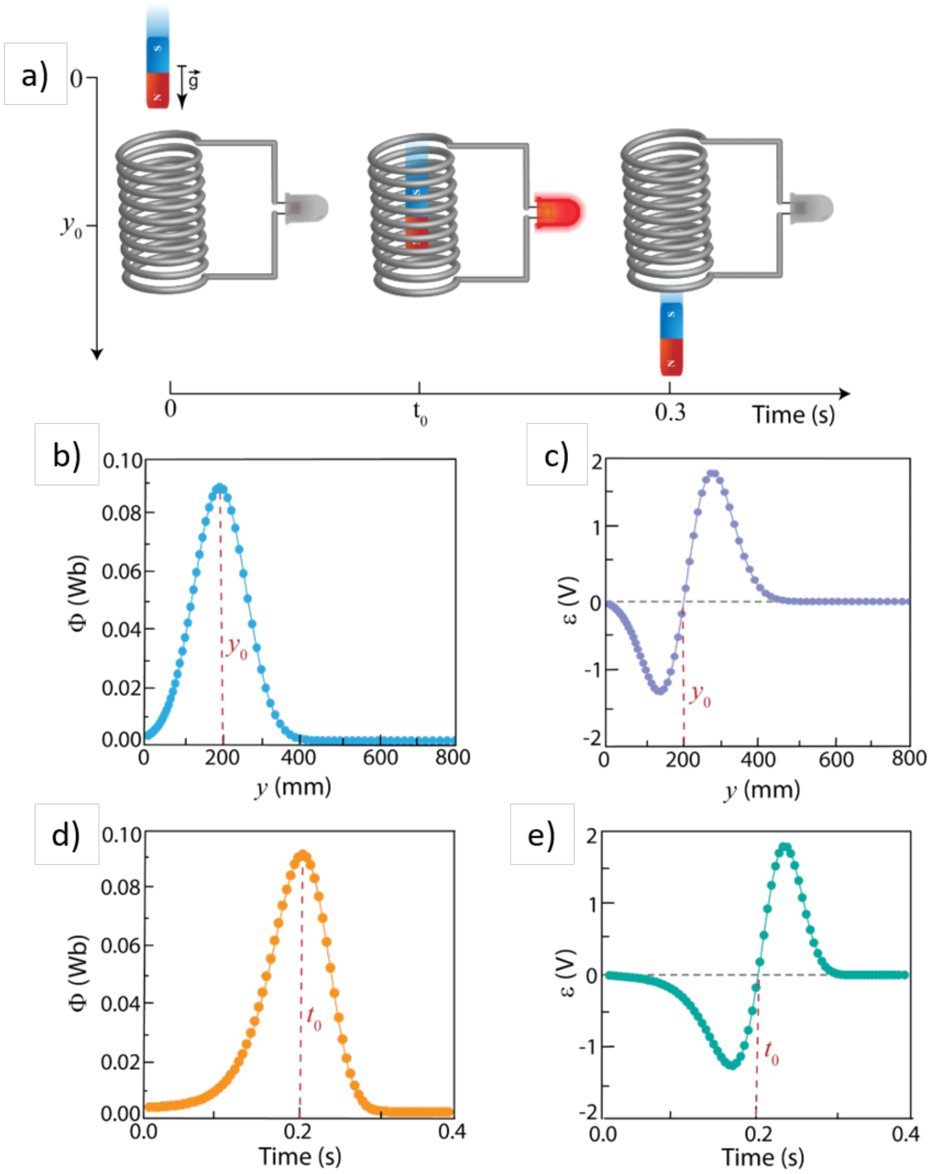

Figure 4: a) Experimental scheme. b–e) Simulated values for a magnet in free fall: magnetic flux as a function of position (b) and time (d), and EMF as a function of position (c) and time (e)

Image courtesy of Paulo André

Activity 2 - Induction hob

A real-life application of Faraday's law is cooking using an induction hob, where a pan is heated by electrical induction, rather than via thermal conduction from a flame or electrical hotplate. Induction hobs generate heat within the pan itself, making this cooking method more efficient. However, all pans need to be made from a ferromagnetic metal (usually cast iron or stainless steel).

An induction hob has a coil, powered by an alternating electric current, underneath a ceramic plate. The alternating current produces an oscillating magnetic field, which induces an oscillating magnetic flux in the base of a pan placed on the hob. This produces an electric current (called an eddy current) in the pan base, heating it up.

In induction hobs, the magnetic field intensity is typically small (~100 mT), but it oscillates at a high frequency (27 kHz). This means that the rate of change of the magnetic field intensity is very high, resulting in high values for the induced EMF and thus for the heating produced.

In this activity, students investigate the induced EMFs around an induction hob, again using an LED connected to a coil.

Materials

- Kitchen induction hob
- LEDs (different emission colours)
- 0.2 mm diameter copper wire to produce the coil
- Pencil
- Paper
- Adhesive tape

Safety note

Although the induction hob doesn't get hot, the cooking pan and water will, so students should be warned not to touch it and care should be taken that the pan handle is out of the way and can't be easily knocked while carrying out the experiment. Special care should be taken if the students are to carry out the soldering step themselves, and this should only be done under close supervision by the teacher.

Procedure

1. Take a pencil, cover it with a piece of paper (this will be the interior of the coil), and wind 300–400 turns of the wire onto it.
2. Apply tape to cover the wire and keep it in place; then remove the pencil.
3. Remove the enamel from the copper wires at each end of the coil.
4. Solder two LEDs to the copper wires in anti-parallel (parallel but with their polarities reversed relative to each other). The teacher may perform this step or the students may do so under the teacher's supervision.
5. Place a pan with water in the centre of the induction hob.
6. Place the coil near to the pan.
7. Switch on the hob, starting with low intensity (figure 5).
8. Move the coil along the surrounding regions of the hob. Try to work out what changes cause the LED to become brighter or dimmer.

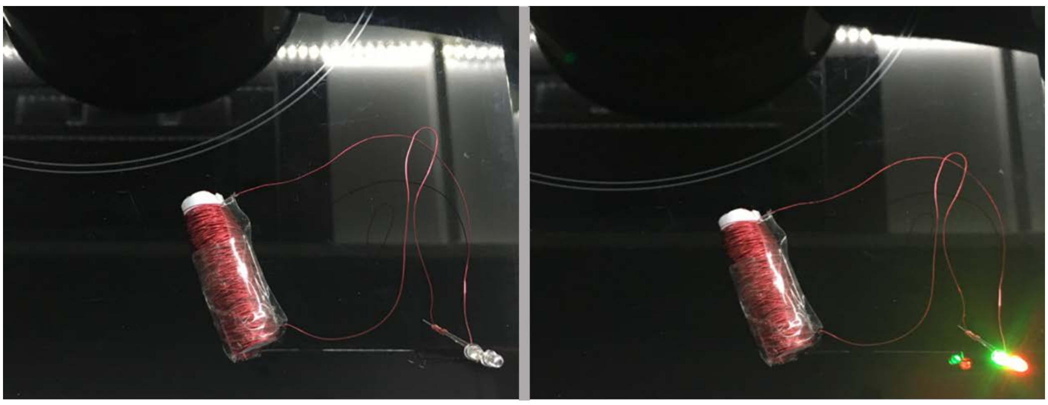

Figure 5. The coil near the induction hob, with the hob switched off (left) and switched on (right)

Image courtesy of Paulo André

Discussion

Teachers can discuss the following questions with the students to explore the key concepts.

- How does the LED's intensity depend on the distance from the hob?
- For the same position, will turning the coil result in a change in the LED intensity?

Students should find that the magnetic field is largely confined to the pan region, and the field intensity decreases rapidly with distance from the hob. Rotation of the coil results in a change of the EMF, according to equation (2), due to the changing angle between the coil and the magnetic field line of force.

Michael Faraday (1791–1867)

Portrait of Michael Faraday by Thomas Phillips (1842)
Public domain

Michael Faraday was a British scientist who set out the principles underlying electromagnetic induction. Although Faraday received little formal education, he became one of the greatest scientific discoverers in history. The unit of electrical capacitance, the farad (F) is named in his honour, and it was largely due to Faraday's efforts that electricity became practical for widespread use. Several concepts that he derived from experiments, such as magnetic force lines, became important theoretical ideas in physics, giving rise to modern electromagnetic theory.

Faraday worked in the laboratory of the Royal Institution in London. In 1831, he demonstrated the principle of induction: this enabled the development of the dynamo (or generator), which produces electricity by mechanical means. In 1845, Faraday also established that an intense magnetic field can rotate the polarization plane of light (now known as the Faraday effect), showing an underlying relationship between magnetism and light.

Faraday ceased research work in 1855, but he continued as a lecturer until 1861.

Acknowledgements

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[1] Enrique A et al. (2015) Measurement of the magnetic field of small magnets with a smartphone: A very economical laboratory practice for introductory physics courses. *European Journal of Physics* **36**:1–11. doi: 10.1088/0143-0807/36/6/065002

[2] 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

Resources

- Find out more about induction hobs: https://edisontechcenter.org/InductionCooking.html
- Discover how to use Faraday's law to build a loudspeaker: Anta A, Goiri E (2018) Hearing waves: how to build a loudspeaker. *Science in School* **45**:38–42.
- Find out more about the use of Faraday's law in seismographs: Bazanos P (2012) Building a seismograph from scrap. *Science in School* **23:**25–32
- A detailed video explaining Faraday's law: https://www.youtube.com/watch?v=zRmfNvTzIhk&ab_channel=PhysicsHigh
- Watch a fun demonstration of Faraday's law: https://www.youtube.com/watch?v=txmKr69jGBk&amp%3Bab_channel=Veritasium&ab_channel=Veritasium

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