

EXPLORING THE TRANSIENT PHENOMENA OF ELECTROMAGNETIC INDUCTION

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The main objective is to demonstrate that coil-magnet system with a data-logger becomes an exemplary experimental model system to teach science as well as the method of science. We first describe a task which involves designing, constructing and conducting quantitative experiments by students with a focus on collecting, representing and analyzing large, real-world data sets. Second to establish the coil-magnet as an exemplary model system which allows for easy parameter manipulation, and third to make a case for the use of computers for data collection and constructing graphs to bring out salient features of scientific investigation.

INTRODUCTION

The phenomenon of electromagnetic induction was discovered by the brilliant work of Faraday (Faraday, 1832), in which empirical data was gathered with careful design and experimentation and analyzed to arrive at path breaking conclusions. It is often demonstrated qualitatively in the school classroom in many different ways, e.g., Chapter 8 of Class 8 (MSBSHSE, 2011a) and Chapter 5, Class 10 (MSBSHSE, 2011b), Chapter 13 Class 10 (NCERT, 2012). The demonstrations can be fun and enjoyable, for example, see the section on activities of electromagnetic induction on Arvind Gupta's excellent website Toys from Trash (Gupta, 2015), which is incidentally an inspiration for this study. But most of the demonstrations are qualitative in nature and in some cases the complete analytical description of the phenomena may involve calculus, which can be demanding for school students, for example, see (Kingman et al., 2002).

In some cases the transient nature of the phenomena prevents one from making any quantitative studies of the same, for example firing of a LED attached to a coil, when a magnet is passed through it. Even when we vary the number of turns, or diameter or length of the wire the effects we notice in this setup are not visibly very different. To make the effects visible we introduced an electronic data-logger connected to a computer to the traditional coil-magnet setup. Could this addition transform a demonstration setup into a complete experimental setup? Amrani and Paradis (2005) and Bonanno et al. (2011) used data-loggers in the study of electromagnetic induction. In our study we extend this approach so that it also provides sufficient scaffolding to learn electromagnetic induction, and also for the method of science for school students. We seek to demonstrate in this case study the pedagogical potential of the setup for learning the content as well as the method of science.

The Students: The study was conducted with two students who had just appeared for class 10 exams, and were part of the study for a week. They were from an urban Indian school with English as medium of instruction. One of the students was well versed with the use of computers and had experience in hobby electronics. The other student had not used computers much and was not aware of electronics. The interactions with the students were in the form of

semi-structured interviews taken before, during and after the activities and were video recorded. The students already had a knowledge of the Faraday's law of electromagnetic induction, Ohm's law and Newton's laws of motion. At the end of a week the students presented their work to other students and mentors. During the interviews the students reinforced each other's answers, often citing examples to support and clarify each other.

To begin with the students were shown a simple demonstration of electromagnetic induction by passing a magnet through a copper coil. An LED attached to the terminals of the coil lights up when the magnet is passed. A paper tube is passed through the coil to facilitate the magnet movement through the coil. A schematic of the set-up is shown in left of Figure 1. The students were asked to explain this phenomenon, which they did correctly. The students were asked probing questions to elicit their conceptual framework.

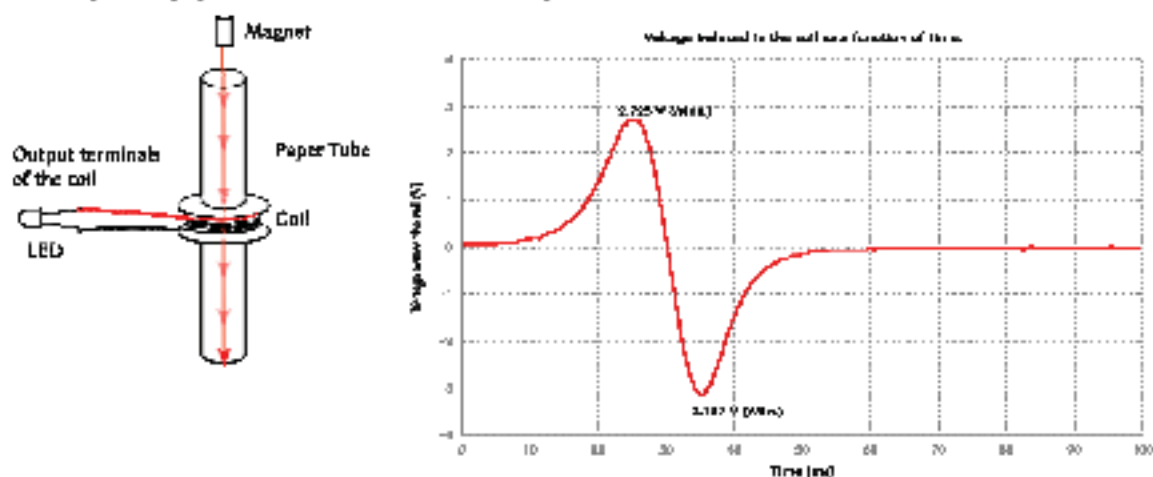


Figure 1: *Left:* A schematic drawing of the basic setup of the demonstration. We can attach LED to the output terminals of the coil. The LED lights up if the emf generated in the coil is above the threshold voltage. *Right:* A typical curve plotted using the data-logger which shows emf generated in the coil as a function of time, when magnet is passed through it.

CAPTURING, VISUALISING THE PHENOMENON THROUGH A DATA-LOGGER

The students were then asked to attach a digital multimeter to the coil to read off the voltage generated by passing the coil. The multimeter registers a surge in voltage and in a fraction of a second returns to zero. This being a transient phenomenon, which takes a fraction of a second, voltage cannot be measured using a multimeter. To address this issue we used a data-logger, *expEYES* to capture the phenomenon (Kumar, 2011). *expEYES* is non-proprietary device with millisecond and millivolt resolution. The cost of the current version of device is about Rs. 2000 (< USD 35). The software interface for the device has many in built programs, and can be reprogrammed. The *expEYES* kit displays a graph and saves the data into a text file once the experiment is performed. The data has two columns, time and the corresponding voltage across the coil. This data can be used to plot the graph with any other graphing software.

The students were introduced to use of *expEYES* and to the specific programme in the software interface which can capture the required phenomenon. When our experimental setup of the coil and magnet is attached to *expEYES* instead of a LED, we can not only measure the peak of the voltage but also observe the waveform of the phenomenon. The output from the

data logger is in the form of voltage across the terminals of the coil along with a time stamp. A plot of typical output voltage as a function of time, resulting from passing of the magnet through the coil is shown in the right side of Figure 1. The graph consists of a total of about 100 voltage readings in 60 ms. The graph clearly shows *two* peaks of voltages, which cannot be noticed through either the LED or multimeter.

The availability of data and the possibility to plot it as graph opens up the possibility for more inquiry. How does this curve explain electromagnetic induction? Why were there two peaks? What are the different parameters in this setup that will affect the induced voltage? The students were asked to seek answers to these questions by designing experiments.

Prior to the experiments the students gave explanation of the two peaks along the following lines: The first peak is due to the approach of the magnet *towards* the coil, while the second peak is due to the magnet moving *away* from the coil. The students also noted that the peak voltages in the first and the second peak are not same.. They reasoned with help of Newton's laws of motion since the magnet is falling under gravity it gains speed with time. Hence the speed of the magnet is greater when it goes away from the coil.

DESIGN, CONSTRUCTION AND INVESTIGATION

What parameters affect the induced voltage in the coil and how do they affect it? For this purpose the students were asked to design experiments to test their hypotheses. Three major categories of the parameters were finalised after prolonged engagement with the researcher: coils, magnets, speed of approach. Table 1 shows the different variations of these parameters, their variations and designs and constructions required for testing the hypotheses regarding these.

Parameter	Variation	Design/Construction	Hypothesis
Coils	Number of turns	250, 500, 650 with 30 gauge wire	Induced voltage will increase with number of turns.
	Diameter of wires	30, 35 and 41 gauge wires with 250 turns	Induced voltage will increase with diameter of the wire.
	Diameter of coil	0.75, 1 and 1.5 inch, with 35 gauge wire and 450 turns.	Induced voltage will decrease with diameter of the coil.
Magnets	Reversing polarity	Using magnet in obverse and reverse directions.	The induced voltage will change polarity.
	Magnet strength	Using magnets in three different configurations.	Induced voltage will increase with magnet strength.
Speed	Straight drop	Moving the coil along the paper tube.	Induced voltage will be largest for lowest position of the coil.
	Slant drop	Slanting the paper tube along a scale.	Induced voltage will be largest for the straight drop.

Table 1: Parameters and their variations, design for the experiments with the hypotheses to be tested.

Students constructed a total of nine coils for the experiments. The construction of the coils was found to be engaging and enjoyable. They were asked to explain and document how they made the coils in detail.

EXPERIMENTS, RESULTS AND ANALYSIS

For each set-up experiments were repeated multiple times. The students were instructed to use a non-proprietary graph plotter (*gnuplot*), is a versatile plotting programme with many features included for analysis (William & Kelley, 2014). *Note:* The graphs presented here in Figures 2, 3, and 4 have been redrawn and labelled for clarity. The data used in these graphs is from students' experiments.

Experiments with Magnets

Change in orientation of magnets: The basic question that was addressed in this part was: *Will changing the orientation of the magnet cause any change in the induced voltage?* The LED glows in both cases, but graphs obtained in the two cases present a dramatically different case (Figure 2. *Left*). We not only see the reversal in the waveforms (red and blue curves), but also note they are almost symmetric. In terms of conceptual understanding, this explains the '–ve' sign in the law, which says that the induced voltage opposes the change in the magnetic field.

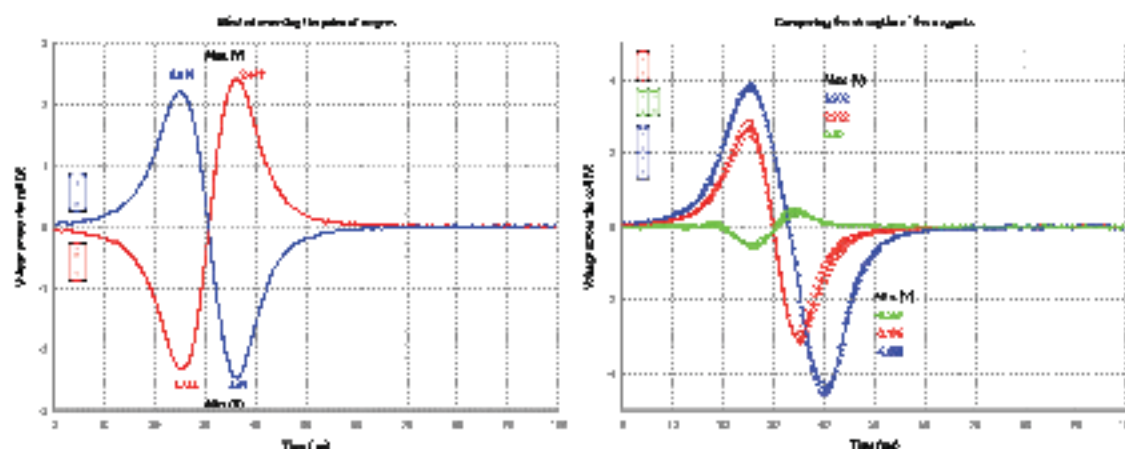


Figure 2: *Left:* Effect of inversion of magnets. In this the two graphs were obtained by inverting the magnet. *Right:* Comparing strength of magnets. The pole to pole configuration provides the maximum induced voltage, while side-by-side the least.

Magnet Strength: The students repeated the experiments with *single magnet (red curve)*, *two magnets attached pole to pole (blue curve)*, *two magnets attached side by side (green curve)*. The results are shown in the right side of Figure 2. The hypothesis that the induced voltage would increase as the magnet strength increases was tested as well.

Experiments with Coils

In case of coils the students constructed nine coils and performed experiments using the same magnet. Some of the coils can be seen in the bottom right of Figure 3.

Number of turns in the coils: Students constructed three coils with 250, 500, 650 turns with gauge 30 wire. The results from these experiments are shown in the top left of Figure 3. In this case the hypothesis that the induced voltage is directly proportional to the number of turns was also verified.

Diameter of wires: Students constructed three coils with 30, 35 and 41 gauge with same number of turns. The results are shown in the top right of Figure 3. In this case the students hypothesized that induced voltage is proportional to the thickness of the wires. They argued that in thicker wires the resistance would be lesser than in thinner wires, and hence thicker wires will have more induced voltage. But the results of the experiments were against their hypothesis.

Diameter of the coils: Students constructed three coils with 0.5, 0.75, 1.5 inches with 250 turns of 30 gauge wire. The results are shown in lower left of Figure 3. In this case the hypothesis that induced voltage is inversely proportional to the diameter of the coils was tested.

Experiments with Speed

Straight Drop: For the straight drop students did the experiments by moving coil relative to the paper tube by equal amounts. The results of this experiment are shown in left of Figure 4. This confirms the hypothesis that the induced voltage is directly proportional to the speed of the magnet.

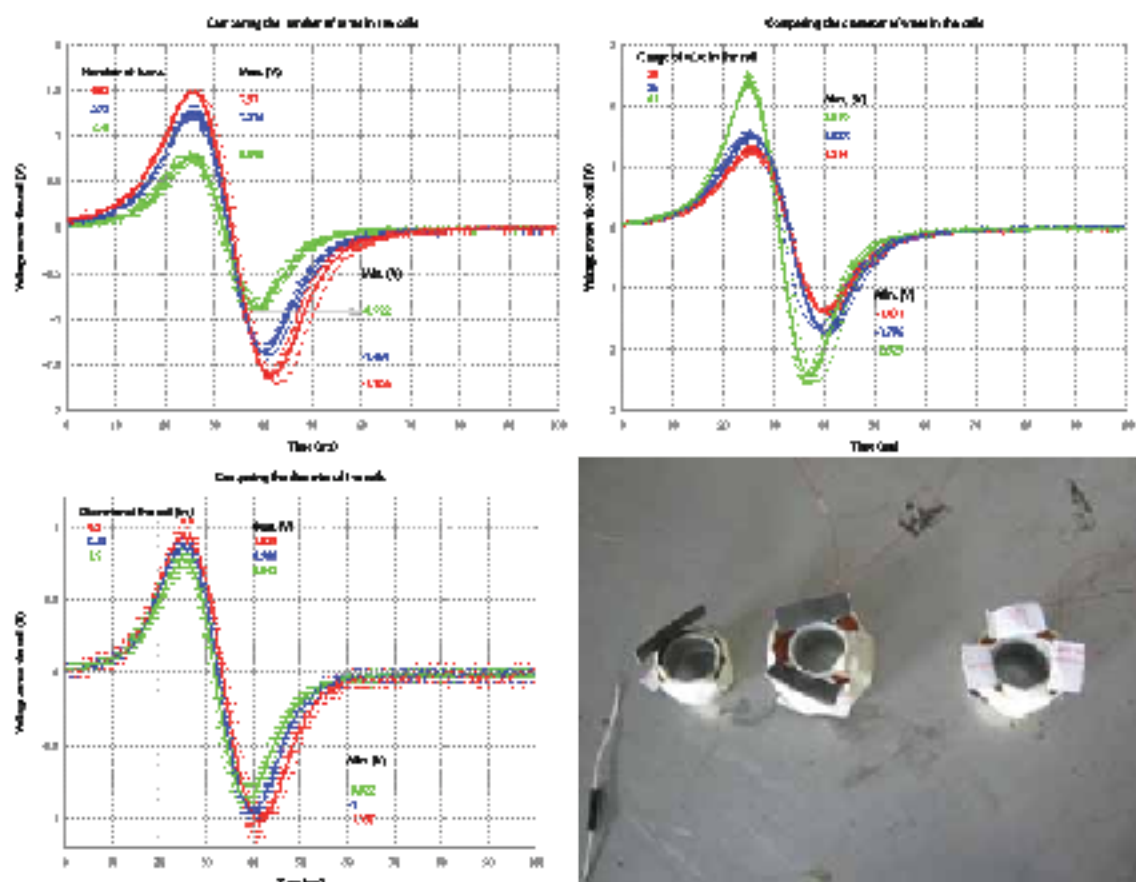


Figure 3: Results of experiments with coils. *Top Left:* Comparing number of turns in the coil. More turns (650) produce more induced voltage. *Top right:* Comparing diameter of the wires of the coil. Thinner wire produces more induced voltage, this was against the hypothesis made

by the students. *Bottom Left*: Comparing diameter of the coils. Smaller diameter produces more induced voltage. *Bottom Right*: Some of the coils made by the students.

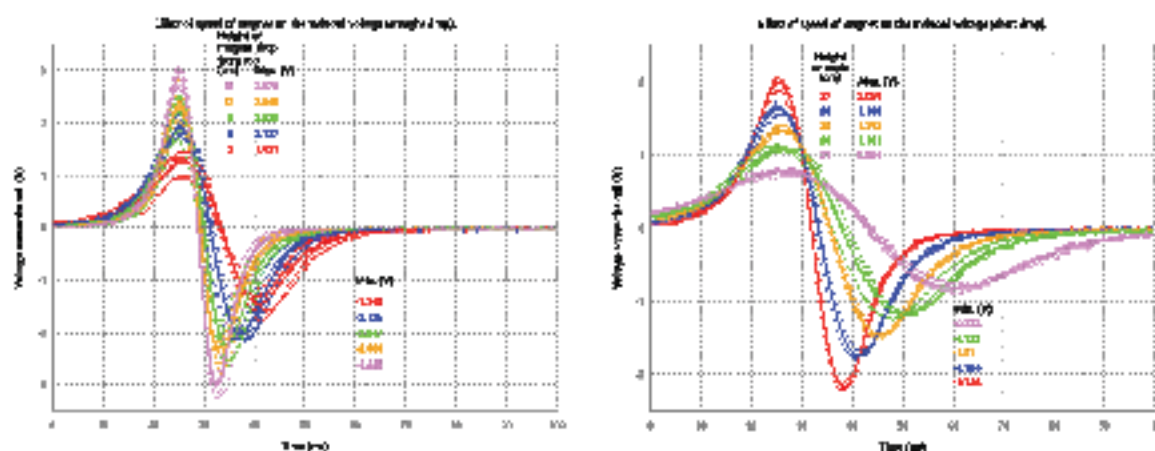


Figure 4: Results of experiments with speed.

The induced voltage is directly proportional to the speed of the magnet. *Left*: The results from the straight drop method. Notice how the voltage peak intensifies (pink graph) as speed increases. *Right*: The results from the slant drop show the spread in the voltage peak as the speed decreases (pink graph).

Slant Drop: For the slant drop the students tilted the paper tube to form an incline at different angles. The results are shown in right of Figure 4. The hypothesis is confirmed again in this case.

DISCUSSIONS

Real-World Data and Use of Computers

The electromagnetic induction can be seen in a variety of applications in everyday life and hence is a close-to-life context in which investigations were carried out. The task gave students a better understanding of basics of the phenomenon under study and experience in collecting real-world data which is an important skill (Curcio, 1987). In the task students collected and handled large data-sets, arising from repeated experiments. The use of technology in the form of a data-logger and computer for plotting data opened an avenue for collecting and analysing large real-world data. Without use of computers tools the experiments were almost impossible to perform. Though there are works which report use of data loggers, for example see (Wood & Sebranek, 2013), they differ from our work in the sense that construction and design of experiment by the students was not part of their study.

A single observation from the data logger had 100 data points and was instantly displayed while taking the observations. With multiple readings each of the graphs have thousands of data points. Using computers to plot such large data sets becomes essential. So this task gave them experience in collecting real-world data, which included many trials and errors during experimentation. As this happens in any science lab, we consider this as a good exposure to the nature of science. The concept of dependent and independent variables, and controlled experimentation was concretely presented in this engagement.

Coil as an Exemplar Model System

The coil with different parameters can be seen as an exemplary model system for the study. Historically what was pendulum to the classical mechanics, coil was to the electro-dynamics. It forms a bridge between the theoretical learning from the textbooks and the real-world applications of the phenomenon. It provided a low-cost, easily manipulable system in which different parameters can be changed and the effects of the change can be easily observed. This was made possible by the use of data-logger, but the entire construction process can be carried out easily with minimal raw materials and tools. The construction of a variety of coils based on the designs by students added another dimension to the investigation. The students could relate to what and why they were doing. The design of the activity created a base for any further investigations that students might do in the future.

Multiple Representations

The entire task can be seen as an exercise in multiple representations. Multiple representations are required in tasks that involve decision-making and problem-solving skills (Ainsworth et al., 1997). The phenomenon (the magnet passing through the coil) itself is a concrete and experiential one. The students can perform the phenomenon and experience the lighting of the LED when the magnet passes through it. The phenomenon can be described verbally, explaining the cause and effect. The table of numbers containing the time and voltage across the coil from the data-logger is an abstract representation of this same phenomenon. And when these same numbers are visualized in the form of graphs it is yet another abstract representation of the same phenomenon. The task of changing the parameters concretely during the design of the experiments and observing the resulting change in the form of graphs enables one to move between representations. At the end of the task the students were already familiar in reading information directly from graphs, analyzing and inferring from them. In case of scientists interpreting the graphs the movement between abstract and concrete is not just one way, but appears to be simultaneously from concrete to abstract and from abstract to concrete (Roth, 2006). Providing students with meaningful opportunities where they have to deal with multiple representations is helpful in developing ability to move between abstract and concrete representations.

Developing Graphicacy

Students usually face problems in comprehending and constructing graphs. The ability to read and make graphs forms one of the core competencies in doing science. One of the intended aims of this task was to develop opportunities for *graphicacy*, which has been defined as an “ability to understand and present information in the form of sketches, photographs, diagrams, maps, plans, charts, graphs and other non-textual, two-dimensional formats” (Aldrich & Sheppard, 2000). The representation of large data sets by graphs, provided the students a platform by which they could answer many questions, while gaining new insights into already known facts. The students had the exposure to develop the skill of reading graphs and relating the features on the graphs to physical phenomenon that they represent. This goal was inherent to the design of the task. The design of the task was such that the abstract representation of graphs and change in them, always had a concrete analogy which the students could relate to (the parameters that they had changed). Thus students could learn the skill in a context they were familiar with and was close-to-life.

Graphicacy does not have an emphasis even though it is an important skill in science, mathematics and everyday life. In *Critical Graphicacy* Roth et al. show that textbooks do not provide students with enough opportunities to read scientific texts critically (Roth et al.,

2005). In the context of Indian school textbooks graphicacy is a neglected area (Dhakulkar & Nagarjuna, 2011). Neither there is any emphasis given to seeing it as an interdisciplinary skill which needs continuous nurturing through exposure of students to activities which involve graphs. Activities like this can build upon prior knowledge of the students, allow students to design experiments, collect data, and test hypotheses take them to a different level, in terms of qualitative and quantitative investigations, will perhaps help fill this gap.

Method of Science

The students while performing these experiments followed a path which started with their prior knowledge, led to forming hypotheses and test them by designing experiments.

The selection of parameters and hypotheses regarding them were informed by prior knowledge of the students. This led to designing of experiments and constructions required to execute them. The measurements aided by the data logger and graphical representation of numerical data was done with computers. The analysis of graphs led to answers to questions concerning the hypotheses. In some cases the hypothesis was validated by the experiments, while in other cases the hypothesis was proven to be incorrect. This led to new knowledge about the phenomenon under observation. In some cases a new insight about known facts (for example, effect of inversion of polarity of magnet) and new knowledge emerged (for example, the second peak being slightly larger than the first). Thus the students were able to design experiments, investigate the relations between the variables and test their hypotheses. At the end of the investigation the students presented their findings to other students in the project camp. During this presentation they could talk about the phenomenon by presenting the graphs and could explain the ideas about the design of experiments. Thus this activity also had reporting element as well.

Schematically the process can be represented as below and more or less follows the method of scientific experimentation:

Prior Knowledge + Reasoning \Rightarrow Hypothesis \Rightarrow Design \Rightarrow Construction

\Rightarrow Measurements \Rightarrow Graphical representation \Rightarrow Analysis \Rightarrow Inferences \Rightarrow Test of Hypothesis + New Knowledge/Insights \Rightarrow Reporting

Considering the richness of the coil engagement, which brings to the foreground the several desired goals of science education, we recommend such use of technology. As Papert says “the kind of knowledge children most need is the knowledge that will help them get more knowledge” (Papert, 1993). We hope that this activity fulfils this aspiration.

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