EXPLORING THE TRANSIENT PHENOMENA OF ELECTROMAGNETIC INDUCTION

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We present here a case study of two students working as a team to explore the simple construct of a coil and a magnet. There are three objectives of this article, first is to describe a task which involves students designing, constructing and conducting quantitative experiments with focus on the collecting, representing and analysing large, real-world sets, second to establish the coil as an exemplary model system which allows for easy parameter manipulation, and third to make a case for use of computers for data collection and constructing graphs to bring out peculiar features which would be otherwise invisible in what is essentially a qualitative demonstration.

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 analysed 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. 2000).

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. The *emf* generated in the coil due to this action will cause the LED to fire. What kind of learning is possible with a construction as simple as this? Can any *quantitative* experiments be done with this set-up? We seek to answer this question in this article through a case study.

The Students: The two participating students in this study had just appeared for their class 10 exams, and were selected for doing a summer project 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 others answers, often citing examples to support and clarify each other.

As an introduction to the task the students were shown one of the simple demonstrations for 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. The answers to these questions, through the discussions helped us to understand the conceptual framework of the students.

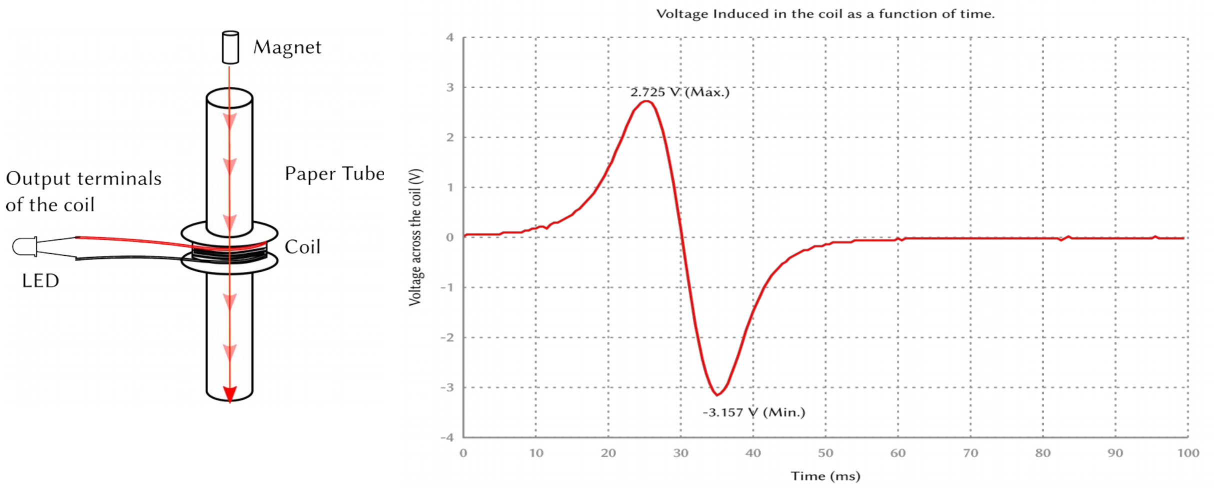

Figure 1: *Left:* A schematic drawing of the basic setup of the demonstation. We can attach LED to the output terminals of the coil. The LED lights up if the emf generated in the coil is above the threshold voltage. *Right:* A typical curve which shows emf generated in the coil as a function of time,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

CAPTURING, VISUALISATING 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 fraction of a second returns back to zero. To find the maximum voltage generated using the multimeter is not possible. This is a transient phenomenon, with the action taking place in within a fraction of a second. To address this issue we used a data-logger, *expEYES* to capture the phenomenon (Kumar 2011). expEYES is a free harware, free software project which has a millisecond resolution and can take readings in the millivolt range. 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 is programmable.

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 100 readings. The total time required for the voltage generated is about 60 *ms, which* is a very short time from a human observers perspective and explains why we see a flicker on the multimeter. Another interesting thing to notice is that there are *two* peaks of voltages. This is not at all evident from the lighting of the LED or the flicker of the multimeter.

The presence of data in the form of a graph for this phenomenon opens up for entirely different kinds of studies. To start: *How does one now 'fit' this curve in the explanation of the phenomenon that was given earlier? Why were there two peaks?* Since now we can measure the induced voltage, we can ask this question: *What are the different parameters in this setup that will affect the induced voltage?* The task given to the students was to seek answers to this question.

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 that since the magnet is falling under gravity the speed with which the magnet comes towards the coil is smaller than the speed with it goes away, hence the second peak is larger.

TASK, PARAMETERS, DESIGN AND CONSTRUCTIONS

With this background the students returned to the original question: *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 will 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, desi for the experiments with the hypotheses to be tested.

For the purpose of constructions the students were provided with raw materials and tools for making the coils. Students constructed a total of nine coils for the experiments. The construction of the coils was one of the things they enjoyed in this activity. They explained how they made the coils in details. The students were told that these experiments should be repeatable by others, and for that how they constructed the coils should be known.

EXPERIMENTS, RESULTS AND ANALYSIS

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. For each set-up experiments were repeated multiple times. In our case the students were instructed to use *gnuplot* plotting program once they collected the data. Gnuplot is a versatile plotting free software programme with many features included for analysis (William and 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?* In the demonstration of the setup, this question cannot be answered completely. The LED lighted when the magnet is reversed, in fact we cannot make any noticeable change in the output by just looking at it. But the data 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 is opposing the change in the magnetic field. This is a direct demonstration of this fact. Thus we see that the presence of graphs from data of experiments by the students in this case opens up an entirely new dimension.

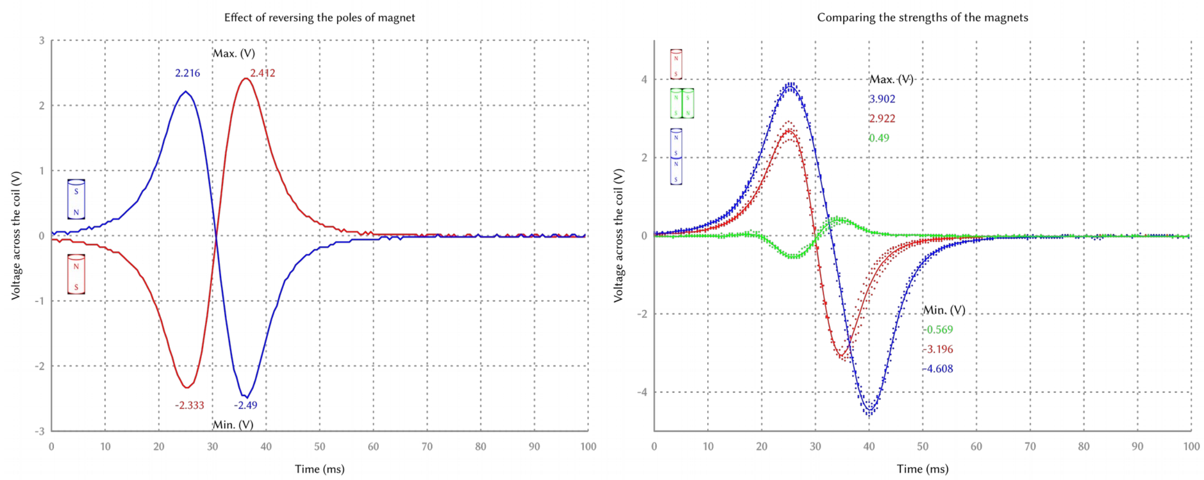

Figure 2. *Left:* Effect of inversion of magnets. In this the two graphs were obtained by inverting the magnet. *Right:* Comparing strength of magnets. The pole to pole configuration provides the maximum induced voltage, while side-by-side the least.

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

Experiments with coils

In case of coils the students constructed nine coils and performed experiments on them. Some of the coils can be seen in the bottom right of Figure 3. Each time the same magnet was used in these experiments so that the results would be comparable.

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 hypothesised 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 this 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.

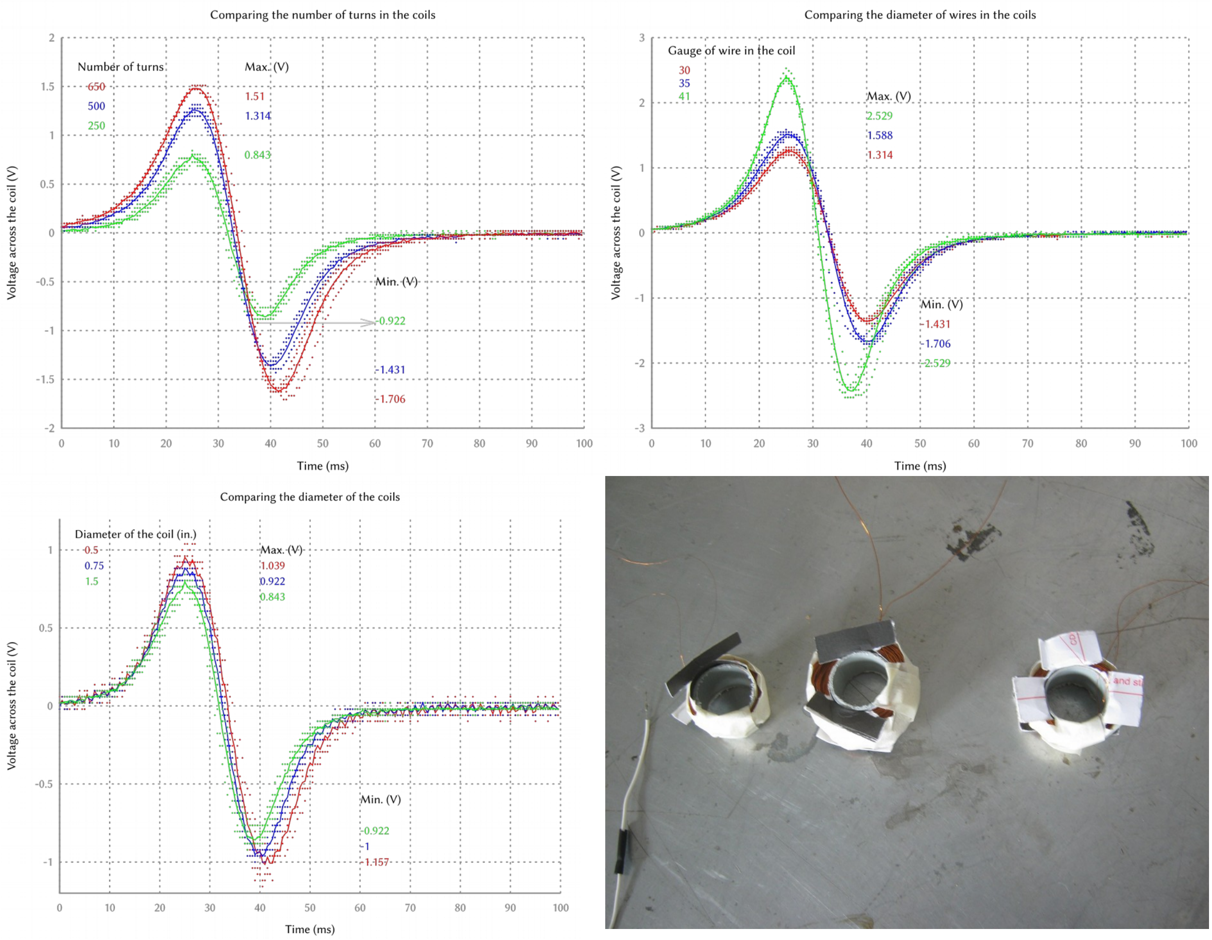

Figure 3. Results of experiments with coils. *Top Left:*Comparing number of turns in the coil. More turns (650) produce more induced voltage. *Top right:*Comparing diameter of the wires of the coil. Thinner wire produces more induced voltage, this was against the hypothesis made by the students. *Bottom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

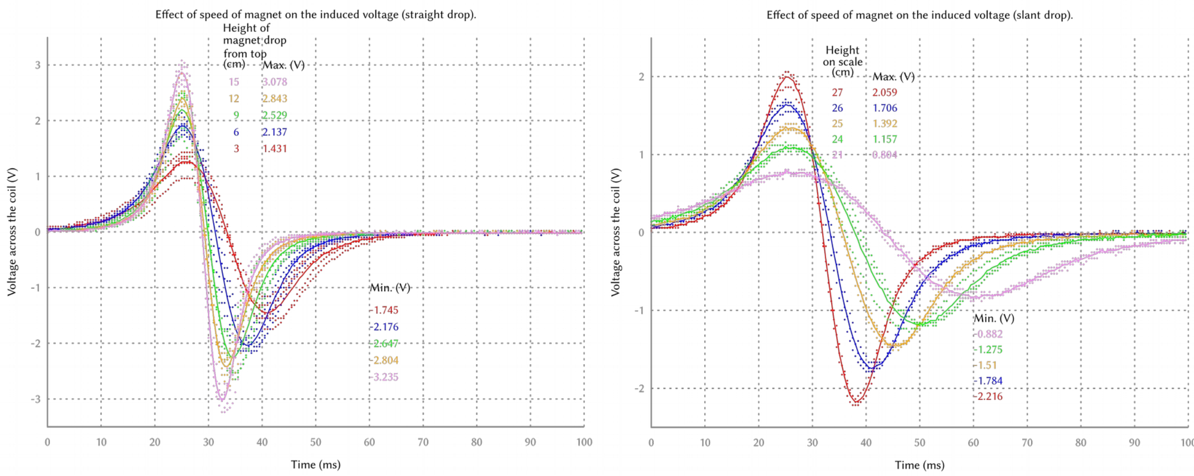

Figure 4. Results of experiments with speed. The induced voltage is directly proportional to the speed of the magnet. *Left:* The results from the straight drop method. Notice how the voltage peak intensifies (pink graph) as speed increases. *Right:* The results from the slant drop method. Notice the 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. It is interesting to note that in this graph as the speed of the magnet is reduced, the time range in which the voltage is induced also increases.

DISCUSSIONS

Process of investigation

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. Schematically the process can be represented as below and closely follows the method of scientific experimentation:

Prior Knowledge + Reasoning => Hypothesis => Variables => Design => Construction

=> Measurements => Graphical representation => Analysis => Inferences => Test of Hypothesis + New Knowledge/Insights

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 (for example, thicker wires would produce more voltage). 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 clearly.

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 and 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 controled 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 visualised 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, analysing 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 intented 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 and 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 and Nagarjuna 2011). Neither there is any emphasis given to seeing it as a 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.

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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