Chapter 1

Introduction

Education is an essential civilizational activity and science education is especially relevant in today’s times, with science impacting society in various spheres and at all levels. Our aim in contributing to science education in a developing country like India is two-fold: to attract those bright students who have talent and potential to become scientists to take up science as a career irrespective of their social or financial background and to provide an empowering tool and methodology which will get integrated into the thinking of individuals who can then employ these methods of rational scientific enquiry in any field they choose to work in, be it science policy, environmental law or activism. Science education is an expanding sphere of research in India and several institutions are being setup in order to enlarge the community of working scientists and to build a large base of scientific manpower. This thus provides a novel platform for researchers active in the field to explore new ideas in science education.

The role of experiments in physics has been well delineated by Feynman and we begin by quoting him, "The principle of science, the definition almost, is the following: The test of all knowledge is experiment. Experiment is the sole judge of scientific "truth". But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalizations - to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess" (Feynman (1963)).
1. Introduction

1.1 Motivation for Physics Education Research

Science has been described as the study of phenomena and their underlying mechanisms (King (2001); Squires (1963); Whitehead (1967)). After the turmoil of the nineteenth and twentieth centuries, science has also emerged as a cornerstone of civilization, a replacement of older beliefs and value systems and a benchmark by which nation-states mark their progress and their achievement indices. The basic motivation of physics education research (PER) is to understand the learning difficulties of physics students and to develop physics teaching methodologies to address these concerns (Eisenkraft (1989, 1999); Eisenkraft et al. (2006); Heller et al. (1992); Heuvelen (1991); McDermott (1998); McDermott & Redish (1999)).

The objective of physics teaching is to bridge the gap between a phenomenon in the physical world and the theory explaining it. Experiments in physics provide not only the confirmation of theories, but also act as a vital tool for facilitating the formation of concepts in the minds of the students. Despite extensive research and development in physics teaching laboratory experiments, there are concepts which remain confusing to students.

There is also a need to assess effective depth up to which a student is able to probe a given concept in a particular experiment. Further, teaching labs have not been able to keep pace with research and development in physics. Demonstration experiments which once enjoyed a privileged position in academics and played a pivotal role in science popularization are no longer so popular. The culture of bringing equipment to a physics classroom has almost disappeared. Computers can be used to circumvent some of these problems as they can provide simulation of different physical systems and can be configured as laboratory instruments (Redish et al. (1997); Reif & Scott (1999)). However, they cannot replace the lab equipment. Therefore, to improve physics teaching, there is a need to do research in physics teaching methodology itself, with a strong emphasis on laboratory experiments and demonstrations. A good laboratory experiment helps the students to develop the following:

- A habit of observation and description.
- A useful practical knowledge of technology.
- An appreciation of the quantitative and its presentation.
- A skeptical, doubting, questioning attitude appropriate to our world.
- Stimulus to the imagination, realistic rather than fantastic.
Just as it is commonly believed that a picture is worth a thousand words, we believe that doing a good physics experiment goes a long way in helping a student start evolving into a true physicist. Becoming a physicist is not just about getting good grades and doing the requisite course work; it is about developing a rational thought process, reducing a complex problem to its essential elements, theoretically modeling physical phenomena and comparing theoretical predictions with experiments. All these are in essence “mind games” and playing these games time and again makes a physicist’s expertise valuable in many disciplines of science and many realms of societal activity. It has been noted previously that physics is uniquely poised to contribute to human knowledge in the twenty-first century and it is the need of the hour to have dynamic physics education initiatives in society. However, given the manner in which science is usually taught by remaining un-connected with daily experience, the subject is not able to engage most students at the deepest level or arouse their curiosity and stir their imagination. Excellence in fundamental physics research cannot be achieved unless innovations in physics teaching are introduced into the curriculum, starting from the primary school onward. Often students find it difficult to translate the problem solving ability learnt in dealing in textbook problems to more realistic problems encountered in physics laboratories. Furthermore, several concepts seem to pose difficulties to generations of physics students. Examples of common misconceptions are the fact that a battery of a particular strength always produces the same amount of current irrespective of the circuit it is connected to or that current can never flow in an open circuit. The concepts of “interactive engagement” and “active learning” are fast gaining ground in physics education research, wherein all efforts are made to see that learning physics concepts becomes an efficient process and students continuously probe their own understanding during the learning process.

1.2 Quantitative aspects of PER

A large variety of rigorous methods have been developed in PER to quantify student understanding of physics concepts, their latent abilities and their creative ideas. Multiple research methodologies such as written questionnaires on quizzes or exams, individual student interviews and specially designed diagnostic tests to identify problem areas in physics teaching can aid researchers in developing a model for students patterns of logic and reasoning.

The statistical analysis of the distribution of student responses to a set of
1. Introduction

questionnaires or interviews can then be used for curriculum development (Buffler et al. (2001); Redish (1999); Redish et al. (1998)).

Another PER method is to collect data on how students use their common sense/intuition about the physical world to connect with their textbook physics courses and problem solving. Several PER groups work on identifying specific areas in physics such as quantum mechanics, special relativity or superconductivity and then work with students and teachers to evolve a methodology that helps students improve their grasp of fundamental concepts in these areas. Other PER groups take a broader position and focus on the general types of logical reasoning that students evolve to understand a large set of phenomena (Duggan & Gott (2002); Hammer & Elby (2003); Reif & John (1979)).

1.3 Trends in PER

Physics education research (PER) is a well developed and wide-ranging field with threads ranging from the popularization of physics, curriculum development, research on exposition of physics concepts, building classroom demos to aid in classroom teaching, the use of computers in physics teaching, and the design of novel physics experiments to convey concepts in physics. A wide variety of physicists across the globe are engaged in all these sub-fields of PER. All over the world leading physics departments have physics education research groups who identify the problems associated with the learning of physics and devise methods to improve it. In India the physics community is becoming increasingly sensitive to this field and a number of groups have started research in this area. PER is an integral part of curriculum development, dissemination of knowledge, building conceptual models, developing novel experiments and several physics departments worldwide have recognized the need to have active PER groups working in this field. There is a growing realization that while science and technology have made enormous progress in the past few decades, cumulative and systematic progress in physics education and developing a scientific temper has not occurred simultaneously. Hence PER groups have gone beyond merely documenting lacunae in student understanding of physics and traditional teaching methods. The goal now is to be able to apply the same rigor and scholarship to issues related to physics education as are applied in traditional physics research. With this in view, several systematic investigations of student learning and physics teaching have been carried out and the data carefully analyzed. Such studies have served
as the basis for other researchers to incorporate these findings in curriculum development and compiling non-traditional instructional materials. Several other researchers have then evaluated and documented the learning gains from the use of such materials in actual physics courses. Hence the cycle of data collection and analysis, model building, curriculum development and testing of the new curriculum is established as PER methodology (Sere et al. (1993); Thornton & Sokoloff (1990); White (1996)).

We now summarize the current and emerging research trends in PER. A well-trodden path in PER focuses on student ability to grasp concepts covered in typical undergraduate physics courses and develop their problem solving skills. A more recent trend is to focus on specific areas of physics such as quantum mechanics or special relativity and evolve specific teaching aids for such courses for physics majors. Quantifying problem solving skills and developing mathematical abilities is another active area of physics education research. The field of computer-based teaching aids such as simulations, animations and multimedia conceptual representations is rapidly advancing. Concomitantly there is a PER focus on the effectiveness of computers and technology as a physics teaching aid and on using computers to understand abstract concepts and the relation of scientific models to the physical world. Finally, students’ epistemological beliefs (about the nature of knowledge in physics) and their influence on student learning curves in physics is an interesting and emergent research trend (Eisenkraft (2003); Hart et al. (2000); McDermott (1984); Mestre (1991); Palmer (1997); Reif (1986, 1995)).

1.4 Role of experiments in PER

For students to evolve into working scientists, they need to pick up skills related to produce, analyze and evaluate scientific evidence and build theories/models based on the data. However, such skills are typically never imparted in a theory physics course and therefore necessarily have to be taught to students in the laboratory context. The undergraduate physics teaching laboratory is typically the first place where students encounter a “real” physics experiment and therefore the curriculum for such lab courses is of prime importance in the context of science education (Saraf (1979)).

The goals of any laboratory experiment course should include

- Making precise measurements and being able to estimate the uncertainty
1. Introduction

of the measurements.

- Using measurement techniques to improve reliability and accuracy of the data.

- Understanding the underlying physics concept behind the experiment and being able to negotiate through the lab manual without too much instruction.

- Using the basic experiment as a platform to explore open-ended questions and being able to design, fabricate and evaluate their own experimental setups in this direction.

The meta-level learning skills that bright students should be able to pick up from a well-designed laboratory course include connecting scientific principles with real life experiences, being able to logically reason out the implications of an idea, being able to use raw intuition to sketch out scientific theories and to be able to get a feel for what is a research hypothesis and how to design tools to verify or falsify it.

A radical innovation in physics laboratory organization is hence to do away with the traditional "cookbook" style lab manual wherein each experiment has a specific goal, and a well-defined procedure and all the student does is to take some measurements, plot graphs and estimate some quantities. Instead an open-ended lab would involve giving the student just one paragraph describing the research question to be answered and the student designs and performs an experiment to locate the answer to the question. The method, data and analysis are then written up by the student in the lab notebook which is then in the format of a scientific publication.

1.5 Guiding principles for our research

The focus of this thesis is to design new experiments for physics pedagogy. The parameters for research were set based on the following guiding principles:

1. Each experiment focuses on a concept which we thought required a laboratory experiment to be built around it. The level of the experiment was decided to be at the undergraduate physics laboratories.

2. The cost and simplicity of design was kept in mind so that the experiment can be easily replicated by physics teachers anywhere when required.
3. The visual appeal of each experiment was enhanced by seeing to it that there were no black box elements in the setup and the entire apparatus is "open" so that the student can see what is happening at every stage of the experiment.

4. The engagement of students with every experiment should occur at three different levels: familiarization with the apparatus leading to observations and results; understanding the underlying concepts; to go beyond and modify the apparatus to explore open-ended questions.

### 1.6 Summary of chapters

Once a set of ideas was generated, several students and colleagues were consulted and their inputs obtained about the relevance of the theme. The six experimental setups that finally emerged from the collation of all these ideas and discussions with students and teachers are arranged chapter-wise in this thesis and each chapter is summarized below.

In chapter 2 we describe an experiment to demonstrate normal modes and symmetry breaking in a two-dimensional pendulum. A simple pendulum hanging from a point suspension is actually a two-dimensional pendulum. The oscillation can be begun in any plane and the pendulum will oscillate in the same plane with a frequency dictated by its length and of course the acceleration due to gravity. It turns out that this is due to the fact that the pendulum suspensions used in the setup are not completely cylindrically symmetric and that the symmetry breaking leads to non-degenerate normal modes of oscillation. This experiment can be used to teach three concepts: normal modes, symmetry breaking and appreciating the difficulties associated with building a Foucault's pendulum.

In chapter 3 we describe a setup through which different aspects of the Coriolis force can be explored. We have designed a magnetic trap in which a bead-like oscillator, oscillates with a fixed frequency. The oscillator is placed on a rotating platform to see the effects of Coriolis force. As the platform rotates, the direction of oscillation of the bead changes in the frame of reference of the platform, observed by placing a small digital camera on the rotating platform. This is the first experiment where it is shown that while the direction of oscillation remains the same in the inertial lab frame, it rotates in the rotating frame, thereby reflecting the motion of the rotating frame. This experiment can be used to demonstrate the subtle interplay of geometry and Coriolis force. The experiment
1. Introduction

also nicely demonstrates the principle of magnetic trapping at the macroscopic scale where a metal ball is trapped in the potential of a magnetic field.

In chapter 4 we describe an experiment which is designed to demonstrate the novel aspects of a capacitor as a reservoir of charge. This experiment clarifies a common misconception about capacitance and AC circuits. A common belief is that current flows only when a circuit is complete, and typically AC circuits are completed by connecting one of the wires to ground (earth). If the circuit is not complete, the current is not supposed to flow. The setup consists of a variable frequency AC voltage source connected to a neon lamp. Instead of completing the circuit, if a large conductor with a certain capacitance is connected, the neon lamp glows a little demonstrating that there is current flowing in this open circuit. The amount of light emitted by the neon bulb is measured by an LDR based measuring circuit and calibrating it with known current sources, thereby providing a mechanism to measure the current. We quantitatively study the current in this open circuit as a function of capacitance and for different frequencies. The experiment demonstrates the notion of capacitance of a single object, its ability to act as a charge reservoir thereby opening up a possibility of current flowing through such open circuits, and the frequency dependence of this current flow.

In chapter 5 we turn to the study of a parallel plate capacitor after having looked at the notion of capacitance of a single capacitor in the previous chapter. A parallel plate capacitor is introduced very early on in physics courses, however most students do not get to see an actual parallel plate capacitor in a lab. To study a parallel plate capacitor using a DC source requires either very large plates or a very high voltage source (of the order of 10 kV or more). We demonstrate the properties of a parallel plate capacitor by using an AC source so that we do not require such large plates or high voltage DC sources. The quantitative measurements in this setup are facilitated by designing an appropriate current meter to measure very small currents through the parallel plate capacitor. The aim of the experiment is to explicitly show the working of the parallel plate capacitor to students and to verify the basic laws governing capacitors.

In chapter 6 we describe an experiment to demonstrate the role of probabilistic observations in physics. Despite the fact that most macroscopic physical systems are statistical in nature, the concept of probability and statistical treatment of data are not very well represented in physics curricula. We have designed an experiment in which we sample the instantaneous voltages across an AC source and generate a random time series of voltages. This time series is then subjected to various statistical analysis to extract information about the source. The setup
1.6 Summary of chapters

consists of a capacitor and a DC voltmeter that are used to randomly sample an AC voltage source. The resulting probability distribution is analyzed to extract information about the AC source. Different characteristic probability distributions arising from various AC waveforms are calculated and experimentally measured. The reconstruction of the AC waveform is demonstrated from the measured probability distribution under certain restricted circumstances. The results are also compared with a simulated data sample. The experiment has a two-fold advantage: firstly, the student is able to apply the concepts of electricity by measuring the potential difference across capacitor terminals and learn about the dependence of the measured values on impedance of the voltmeter being used, a concept which is not easily accessible from routine electricity experiments. Secondly, the experiment familiarizes the students with the probabilistic nature of collected data and its interpretation.

In chapter 7, we describe an experimental setup aimed at the study of molecules diffusing in a solvent. A glass tube filled with water is placed horizontally and KMnO₄ solution of a certain concentration is added at one end. As the KMnO₄ diffuses through water, the optical density changes because of the color change. We setup an LED and LDR arrangement at different points along the glass tube to measure the optical density. The detectors are calibrated with known KMnO₄ concentrations. The data allows one to understand the basic physics of diffusion. The square root \( t \) dependence is clearly seen and the experiment is also set up to measure the diffusion coefficient.

In chapter 8, overall conclusions about all the designed experiments and their pedagogy are described. Several of the setups developed in this thesis are already being used in different physics laboratories in India and we have received feedback from teachers and students on them. A future research direction is described, where we want to setup a system where we systematically work on a concept which evolves after discussions with students and teachers, design experiments, obtain feedback and finally produce a prototypical experimental setup which can be easily replicated.

In chapter A which appears as an appendix to the thesis we have given one sample manual for the random sampling experiment as actually used by instructors who implemented our experiments.
1. Introduction