Training in Practical or Experimental Physics

Ever since the dawn of history, man has been concerned with the universe around him. The study of the universe probably started when the early man noticed changes in the surroundings due to natural causes. Over a period of time this study, carried out to answer various questions about the behavior of nature gave birth to what was known as 'Natural Philosophy'. A variety of observations were made and patterns, rules and laws were formulated by a large number of individuals all over the world to comprehend the behavior of nature.

We may recall a quote by Albert Einstein, *"The most incomprehensible thing about nature is that it is comprehensible"*. This is probably the reason why man still feels the need to understand the universe around him, and uncover the cause and effect relationships, which will enable him to predict events and to a certain level, develop and control the world around him.

Physics, as we understand it today, was a part of natural philosophy a few centuries ago. It is a fundamental science, which provides a picture of how various systems in the universe behave and how the laws of nature operate under different conditions. It is no exaggeration to say that physics is the most quantitative of sciences. It is strongly based on observations, measurements, data collection, analyses and interpretations. Physics aims at explaining various systems in the universe in terms of quantitative relations between various physical quantities.

Introduction to Experimental Physics

In this modern age, there seems to be three divisions in the approach and tools physicists use to understand the behavior of nature, namely theoretical, experimental and the more recently established computational. Thus, fortunately or unfortunately, the discipline of physics has been compartmentalized into three branches, namely, theoretical physics, experimental physics and computational physics. However, all the three branches are intertwined in a complex manner and it is difficult to think of one without the other. Each one has an important role to play in the development of our understanding of the universe around us and predicting its behavour under different conditions. The basic approach and tools of experimental physics differ from those of theoretical and computational physics. Yet, most physicists as a community, would agree that physics has an underlying unity. All three are not just complementary, but integral aspects of physics as a discipline.

Theoretical physicists develop models and theories, and the validity of any model or theory is decided by the way in which its conclusions are supported by experimental evidence. An experimental physicist often starts by observing the behavior of nature or a system and records the observations (under different conditions) and measurements as data. With these raw data the physicists look for patterns and when the data obey simple mathematical rules, the patterns are termed as empirical laws. These empirical laws, when reconfirmed and well established, form the basis of our understanding about the behavior of nature.

We may surmise that a variety of careful observations about the behavior of nature and the universe, over a period of time, led man to the discovery of patterns in nature. This also paved the way for development of methods of experimental physics, which may be said to be the study of effects caused by known changes in the system.

The importance of experimental physics, however, came to be recognized only in the sixteenth century, when Galileo and Fransis Bacon introduced what we know as the scientific experimental method. The method was further developed and propagated by Newton, Boyle and others. The scientific experimental method is a procedure through which observations are made, hypotheses developed, experiments designed and conducted and conclusions drawn about a clearly defined physical problem. The two crucial assumptions underlying the method are reproducibility and causality. Through the scientific method, physicists try to develop or validate a theory, which has to be both, self-consistent and consistent with all known experimental observations and data. The scientific experimental method is an important tool in experimental physics, which should be emphasized and developed through the laboratory training in physics.

Importance and Role of Laboratory Training

People all over the world have now accepted the fact that the teaching and learning of physics is incomplete and inadequate, unless students gain a significant experience in experimental physics through a well-planned laboratory training. The physics laboratory training is supposed to develop in students, a variety of important cognitive and psycho-motor abilities related to experimental physics.

One may ask, how physics laboratory training with a set of simple experiments can be used to provide an introduction to experimental physics in general ? The answer is not so much in the set of simple experiments themselves but in the attitude, the scientific experimental method and various (cognitive and psycho-motor) abilities, which are essential to solve real life experimental problems. The physics laboratory training offers an opportunity to work with simple experiments and develop the expertise, which will be required later, to work on complicated, real world, experimental problems.

The role of laboratory training is succinctly expressed in the words of the well-known educationist and psychologists David Ausubel (1968), *"The laboratory gives the students appreciation of the spirit and method of science…, provides students with some understanding of the nature of science…, promotes problem solving, analytic and generalization ability"*.

In the lecture-laboratory method of instruction, which is the most acceptable and feasible method of instruction for teaching science at the school/college level, laboratory training plays a very important role. It complements the classroom sessions by providing the student direct knowledge and understanding of the experimental evidence, processes and methods. It provides an opportunity for the student to learn to work independently and creatively and to develop the ability to organize, analyze and interpret experimental observations and data. Laboratory training helps the student to develop an appreciation for measurements, and an understanding of their role and limitations. It also provides an opportunity for the student to develop interest and curiosity, as well as to learn "how to think scientifically", which is one of the objectives of physics education. For many students, the laboratory can have a strong motivating influence towards a career in physics, as it gives the joy and thrill of *doing* physics. Hence, training in experimental physics has become an integral and indispensable part of physics education.

Objectives of Physics Laboratory Training

A number of objectives of laboratory or practical training have been listed by researchers, thinkers and teachers from all over the world that include the following.

1) Development of a better and long lasting understanding of facts, concepts, principles and laws of physics.
2) Development of procedural understanding/abilities related to designing experiments, planning measurements/observations and analyzing data.
3) Development of experimental skills for the use, alignment and handling of a wide range of laboratory instruments and tools.
4) Development of insights and expertise in scientific experimental method.
5) Fostering various cognitive abilities like hypothesizing, predicting, observing, classifying, interpreting and inferring.
6) Development of the ability to solve experimental problems on the basis of methods, processes and techniques commonly used in experimental physics.
7) Training in the handling of experimental data, making the students aware of the uncertainties involved in various measurements and development of abilities with respect to the treatment of data, error analysis and reporting of experimental activities.
8) Development of higher order abilities, such as careful and keen powers of observation, the ability to make accurate measurements, handle measured data for objective reasoning correctly, draw conclusions and make generalizations.
9) Development of interest, motivation, open-mindedness, creativity, curiosity, scientific thinking/attitude, self-activity and independent working habits.

It is desirable to keep in mind all the above objectives while teaching and developing laboratory courses in physics. We need to understand that the emphasis placed on various aspects and abilities should be decided by the level, method and the content of the course.

What is Procedural Understanding in Physics ?

For many years, it has been accepted that science education should be more than just teaching about 'things' that the scientists know or have discovered. It should also enable students to 'think like scientists' and understand the 'nature of science'.

Physics teaching / education should include elements of the procedural understanding in physics. To define procedural understanding, I refer to the research work of Richard Gott and Sandra Duggan, published in their book *Investigative Work in the Science Curriculum* in 1995.

They point out that the content of 'procedural understanding' is not well documented. In mathematics the term 'procedural understanding' refers basically to recall and the use of a set of rules, however, in science it has a deeper meaning in its own right. In science, one has to not only recall and apply the 'rules', but also relate these rules and associated concepts to experimental evidence. The validity of science essentially rests on experimental evidence. It is the collection and verification of data, which distinguishes procedural understanding in science from that in mathematics.

Procedural understanding is often 'implicit' and is necessary to plan and execute an experimental activity or experiment in order to systematically generate scientific knowledge from it. In other words, procedural understanding is that understanding, which enables a student to use experimental skills to verify theory or discover new knowledge. It plays a critical role in experimental physics, and is necessary to solve simple as well as complex real life experimental problems. Procedural understanding develops the ability to 'think scientifically' and is a cognitive understanding in its own right, which is essential to understand various systems in the universe around us.

It involves understanding a set of ideas or concepts (e.g., variable identification, fair test, sample size, variable types, relative scale, range and interval, choice of instruments), which may be termed as 'concepts of evidence', related to the 'knowing how' of science and required to implement science in practice. It is distinct from, yet complimentary to, conceptual understanding. It is the 'thinking behind the doing' or the decision-making that goes on in performing experimental activities.

For example, suppose a student is asked to study the motion of a freely falling body, with respect to its changing velocity; then the understanding required for planning the experiment, deciding which quantities are to be measured, the appropriate range of values, the accuracy with which they are to be measured, the intervals at which the measurements are to be carried out and how one may derive meaningful outcome from the measured data, constitute procedural understanding.

Thus, procedural understanding is the understanding of various 'concepts of evidence' associated with design, measurement, data handling and evaluation of the complete experimental activity.

What are Concepts of Evidence ?

Procedural understanding is based on the belief that there is a body of knowledge that underlies an understanding of scientific evidence. Certain ideas about the collection, analysis and interpretation of data have to be understood before we can handle scientific evidence effectively. These ideas have been called the concepts of evidence. It is these ideas and their application and synthesis that constitute the 'thinking behind the doing'.

These concepts of evidence have been structured around the four main stages of experimental work; namely, the design of the experiment, measurement, data handling and finally the most crucial, the evaluation of the complete experiment in terms of the reliability and validity.
By stages, one does not mean, stages in time, since these stages are often revisited. For instance, at the data handling stage a decision may be made to take more measurements. The evaluation of the

solution to the problem requires an understanding of all three stages; design, measurement, and data handling, and this understanding of evaluation is needed as much at the beginning as at the end of the problem or activity.

Gott, Duggan and Roberts have identified more than 50 concepts of evidence, which form the knowledge base of procedural understanding, that are required when solving problems in science. It covers some 19 areas ranging from fundamental ideas of causation and association, through experimental design, data analysis and interpretation to validity and reliability as touchstones of evidence. Selected, important concepts of evidence associated with the four different stages of experimental work and their definitions are listed in Table 1.

Table 1 Selected concepts of evidence and their definitions

Concepts of evidence		Definition
Associated with the design	Variable identification	Understanding the idea of a variable and identifying the relevant variables to change (the independent variable), to measure, or assess if qualitative (the dependent variable), control variables and irrelevant variables.
	Fair test	Understanding of a fair test which is a systematic and valid task to draw inference about how the independent variable affects the dependent variable, while certain other variables are controlled.
	Sample size	Understanding the significance of an appropriate sample size.
	Variable types	Understanding the distinction between categorical, discrete, continuous and derived variables and how they link to different graph types.
Associated with the measurement	Relative scale	Understanding the need to choose sensible values for quantities to be measured.
	Range and Interval	Understanding the need to select a sensible range of values of the variables within the task so that the resulting line graph consists of values, which are spread sufficiently widely and reasonably spaced out so that the 'whole' pattern can be seen.
	Choice of instrument	Understanding the relationship between the choice of an instrument and the required scale, range of readings required, and their interval (spread) and accuracy.
	Repeatability	Understanding that the inherent variability in any physical measurement requires a consideration of the need for repetition if necessary, to give reliable data.
	Accuracy	Understanding the appropriate degree of accuracy that is required to provide reliable data, allowing meaningful interpretation.

Associated with the data handling	Tables	Understanding that tables not only present collected data, but also serve to organize and design the subsequent data collection and analysis.
	Graph type	Understanding that there is a close link between graphical representations and the type of variable they are to represent.
	Patterns	Understanding that patterns represent the behavior of variables and that they can be seen in tables and graphs.
	Multivariate data	Understanding the nature of multivariate data and how particular variables within those data can be held constant to discover the effect of one variable on another.
Associated with the evaluation of the complete task	Reliability	Understanding the implications of the measurement strategy for the reliability of the resulting data; can the data be believed?
	Validity	Understanding the implications of the design for the validity of the resulting data; an overall view of the task to check that it can answer the question.

The term variable has been used in Table 1 to refer to any observable quantity, which can be described by different values, e.g., temperature, length or time. Variables can be classified in terms of their roles and functions in the structure of the activity as independent, dependent or control variables. The values for the independent variable are chosen and manipulated. The value of the dependent variable is measured for each change in the value of the independent variable. Control variables are those, which must be kept constant while the independent variable is changed to make the test 'fair'.

It is essential to note that concepts of evidence associated with the measurement are concerned with decisions that have to be taken regarding the measurements, rather than the experimental skills required for performing the measurement itself. Concepts of evidence associated with data handling include understanding how to use a table as a method of organizing data rather than the drawing or construction of a table itself. A further aspect of data handling is the isolation of the required variable from the multivariate data to obtain the dependence between a set of variables.

The final evaluation stage subsumes all other concepts of evidence because reliability and validity can only be considered in the context of the strategy of the complete solution to the problem. In the above description an attempt has been made to restrict the definition of concepts of evidence to ideas that relate data to reality, which is a crucial distinction between mathematics and science.

It has been observed that conceptual understanding and experimental skills are the only aspects recognized in formulating the objectives of science laboratory training. What has mostly been overlooked is the essential component of procedural understanding. I believe that procedural understanding is, as said above, a cognitive understanding in its own right; it is different from conceptual understanding and it is therefore necessary to incorporate it explicitly in science laboratory training. Hence, during the practical training, we need to consciously emphasize the development of procedural understanding in addition to other aspects, namely, conceptual understanding, experimental skills, problem-solving ability and attitudinal and other affective factors/abilities.

Model of Science

The model of science, described below, was first developed by Gott and Mashiter (1991) and then adopted by Gott and Duggan (1995). Gott and Mashiter proposed that experimental problem solving in science requires an understanding of two sets of specific concepts: a conceptual/substantive understanding and a procedural understanding.

The ideas presented in the earlier pages have been woven in a model of science, with the focus on experimental science, by Gott and Duggan. This model views science and particularly experimental science as a problem solving activity. The cognitive inputs for solving the problems come from the interaction of two types of understanding; conceptual understanding, which is well known and well accepted, and procedural understanding, which is not so well known.

The model is based on the assumption that evidence is an important cornerstone in science. The degree of importance of evidence may vary from situation to situation. For example, given the universal law of gravitation, measuring acceleration due to gravity on the surface of the earth and relating it to the universal gravitational constant, the mass of the earth and the radius of the earth correspond to a situation where the evidence is of secondary importance. On the other hand, if the phenomenon of elasticity is considered, then Hooke's law can be used to explain stretching reasonably well, although the relationship varies with different materials and the law is only applicable within certain limits. In this example, sound evidence is crucial because data are required to make the law usable, a spring constant needs to be calculated for specific situations. In certain problems, one cannot even start without empirical evidence. However, this does not mean that substantive concepts do not guide the model.

For understanding the model and its implications, I first briefly describe the terms used in it.

Facts and Concepts

Williams and Haladyna (1982), define facts as 'associations between names, symbols, objects and locations', and concepts as 'classes of objects or events that are grouped together by virtue of sharing common defining attributes'.

In a situation, where an object is dropped freely under the influence of the earth's gravitational force, examples of 'facts', in this case, include statements such as (i) the object falls towards the ground, (ii) the object reaches the ground some time after its release, (iii) the object falls with changing velocity and (iv) the time the object takes to reach the ground depends on the height from which it is released. On the other hand velocity, acceleration, force, time of flight, uniformly accelerated motion are examples of concepts.

Conceptual Understanding

Conceptual understanding is the understanding of concepts and ideas in science, which are based on facts, laws and principles and are sometimes referred to as 'substantive' concepts. It is the understanding of the "physics" involved in an experimental problem. Conceptual understanding does not refer only to the understanding of individual concepts, but also to the understanding of their relationship with each other and weaving them together to understand the experimental problem as a whole.

If an object falls only under the influence of earth's gravitational force, which is constant near the surface of the earth, then the understanding that, neglecting the friction of air, the acceleration of the object will be constant, is an example of conceptual understanding.

Experimental Skills

Experimental skills are those psycho-motor abilities, which involve definite sequences of coordinated activities of the sense organs and the limbs, and are necessary in performing measurements as well as collecting and processing experimental data. Experimental skills refer to activities such as the adjustment and alignment of the experimental setup, use of measuring instruments and even drawing or construction of tables and graphs.

Adjusting the telescope of a spectrometer for parallel light, use of a thermometer for measuring temperature, use of a scale for measuring the length of a wire or use of a stopwatch to measure the time period of oscillations of a pendulum, are examples of experimental skills.

Procedural Understanding
As discussed earlier, procedural understanding is the understanding of a set of 'concepts of evidence', related to the 'knowing how' of science and needed to implement science in practice.

Cognitive Processes
Conceptual and procedural understanding cannot be independent of one another: some understanding of substantive concepts is necessary to carry out most procedural aspects of science. Similarly procedural understanding is necessary to put substantive concepts into practice. The cognitive processes refer to this interaction between conceptual understanding and procedural understanding involving the selection and application of facts and experimental skills. These cognitive processes are the means of obtaining and processing the information needed to solve a problem. They include hypothesizing, predicting, observing, classifying, interpreting, inferring. etc.

Solving Problems
A very broad definition of a 'problem' is adopted here. A problem includes any activity that requires a student to apply his or her understanding in a new situation. This will include explanation of phenomena, applied science problems, theoretical problems as well as experimental problems. The difference between these is with respect to the relative emphasis on conceptual and procedural understanding.

For example, suppose a student is asked to determine the acceleration of an object of mass m moving down a frictionless, inclined plane (with an angle of inclination q). This problem may be solved theoretically or may take the form of an experiment (if all the necessary apparatus including a nearly frictionless plane are provided).

The Model

The model of science is based on an assumption that solving problems is the main objective of science. In this model, both conceptual as well as procedural understanding have been given equal importance. To solve any scientific problem, we need both conceptual and procedural understanding related to the problem, which are then combined and processed to obtain the solution of the problem. The cognitive processing needed to solve the problem is seen as an interaction between 'conceptual' and 'procedural' understanding. The conceptual understanding will always be based on facts and the procedural understanding will always need experimental skills to observe the behavior and generate necessary data.

Gott and Duggan build up the notion of procedural understanding in a manner parallel to that of conceptual understanding. They draw attention to the fact that science is validated only by experimental evidence and that all laws and models in science are derived from observed behavior of various systems in nature. Collection of evidence requires experimental skills, which need to be guided and informed by decisions such as, what to look for, planning the necessary stages of design, experimentation and measurements, understanding the accuracy of measurements, range of data and knowledge of data processing.

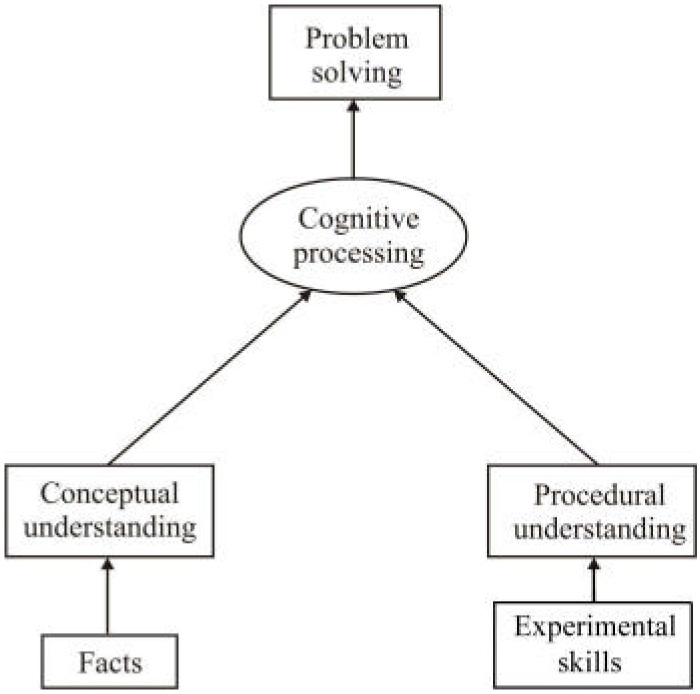

Figure 1 A model of science

An example will serve to illustrate how this model can be applied. Suppose the problem is to determine how the final speed of an object moving down an inclined plane is related to its mass. The student first needs to understand the concept of speed and know that it involves distance and time (conceptual understanding). He or she will need to have the experimental skills necessary to measure the distance, time and mass. The student must then decide how to construct a fair test and what distance and time to measure (procedural understanding). All this information has to be processed in designing the solution, examining the obtained data and drawing appropriate inferences.

It should be noted that the model does not imply that these two types of understanding are mutually exclusive, instead, the procedural and conceptual understandings are intertwined in a very complex manner. The importance of this model is to realize the fact that there is a 'content' to the procedural aspect of experimental physics, which can be well described and must be recognized while formulating the courses in experimental physics. We should follow this model of science and apply it with necessary modifications for the practical training. Further, one of the objectives of science education is to inculcate in the students the scientific culture, basic to which is the scientific experimental method. The problem-solving approach used in this model incorporates this objective in a natural way.

Classification of Experimental Activities

Experimental activities can be classified on the basis of their respective roles, learning outcomes or their methods of instruction. We have six types, with each type having a significant role to play in experimental physics. The boundaries between these types are not watertight. An experiment or activity can clearly include more than one type. For example, an inquiry type of experimental activity will not be without skills or data interpretation.

Inquiry

This type of activity allows students to discover, on their own a particular concept, law or principle, which has not been introduced to them earlier. Activities of this type have to be carefully planned and set up to enable all students to arrive at the same end point. Here, the guided discovery approach may be employed, in which questions may be posed to students and the necessary instructions may be given. Students will be required to organize facts, observations and results to derive meaningful generalizations and principles. The main objective of this type of experimental activity is to introduce concepts, laws or principles.

An example of this type would be a planned and guided activity in which students are asked to determine the volume of an irregular body made of a material of an unknown density, without any prior knowledge of Archimedes' principle.

Illustration
The objective of this type of activity is to illustrate/verify/consolidate a particular concept, law, principle, technique or process, which has already been introduced. Students are provided the opportunity to witness events and 'see' the concepts in action, so that they relate the theory more closely to reality. This builds students' confidence and belief in concepts, laws or principles. This activity may take the form of either a demonstration by the teacher or an experiment where students are given detailed instructions to follow. This type of activity may involve illustration of experimental techniques and processes, and use of instruments.

A typical activity of this type, performed either by a teacher or a student, is the study (with prior knowledge of Ohm's law) of the variation of current (passing through a resistor) with the applied voltage, for various resistors each having a different value of resistance.

Skill
In this type of activity students are given opportunities to acquire and practice psycho-motor and other analytical skills. These activities may involve setting up apparatus, use of instruments, and taking measurements or they might require students to learn and practice skills such as recording observations and data, and plotting graphs. The main objective of this type of activity is acquiring experimental skills necessary to carry out the experimental work.

An example of this type of experimental activity is a task in which the students are asked to determine the density of the material of various rectangular or square blocks by measuring their masses and dimensions.

Observation
This type of activity has often been described as 'theory-laden'. Students are asked to observe an event or phenomenon and are encouraged to apply previously learned principles to describe, explain or predict the event. The main objective of this type of activity is to develop an ability to apply conceptual understanding in a new situation or to reinforce major concepts, laws or principles.

An example of this type of activity is allowing a tiny, spherical, metal ball to fall through a highly viscous liquid, the students have to observe the motion of the ball with respect to its speed and explain the motion on the basis of previously learned principles of mechanics.

Investigation
This type of activity usually offers several alternative ways of reaching to a solution of the problem so that the design is much less controlled than the illustration or inquiry types of activities. In investigative activities students are supposed to use previously learned knowledge and understanding to solve a scientific problem or to study a phenomenon / an event. These activities provide students an opportunity to develop procedural understanding, while at the same time they allow students to use and refine their conceptual understanding. The main objective of this type of activity is to allow students to use or apply conceptual understanding, procedural understanding, cognitive processes and experimental skills in an integrated manner to solve an experimental problem.

An example of this type of activity would be an experiment in which the students are asked to investigate the relationship between electrical conductivity (of the material of a given block) and its temperature, without substantial guidance or procedural instructions.

Exploratory

In this type of activity students are given the necessary and possible apparatus and are encouraged to probe and build up new information through open-ended problems. Exploratory activities develop both conceptual and procedural understanding, but are different from investigations, in the sense that they are explorations of different questions and relationships in an unknown situation and do not have constraints of a definite design. In exploratory activities the end point is not fixed and hence the design is not at all controlled. No guidance is given, instead, students are allowed to choose the apparatus, procedures and methods to explore questions and relationships of interest. Exploratory activities foster creativity, interest and motivation towards the subject. The main objective of the exploratory activity is to develop an understanding of the methods and processes of science.

An example of this type would be an activity, where the students are given, along with other apparatus, a set of objects to be used for a simple pendulum having (i) the same mass and shape but different volumes, (ii) the same volume and shape but different masses and (iii) the same mass and volume but different shapes. Students are then expected to explore, on their own, the dependence of the time period of oscillations of a simple pendulum on different parameters like volume, mass, shape of the object and the length of the pendulum.

Each type of experimental activity has an important role to play in experimental physics. Hence the practical training essentially should have activities, experiments, problems, projects and demonstrations, which involve all six types of experimental activities. This will develop various abilities related to the experimental science and fulfill the objectives of the practical training.

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