Experimental problem solving: a plausible approach for conventional laboratory courses

R Khaparde
Homi Bhabha Centre for Science Education, Tata Institute of Fundamental Research
V. N. Purav Marg, Mankhurd, Mumbai 400088, India

rajeshkhaparde@gmail.com

Abstract. Almost every student is expected to work on a collection of experimental setups to get the desired ‘hands-on’ experience with physical systems during the conventional laboratory courses offered at colleges and universities the world over. In a number of conventional laboratory courses, the ‘minds on’ aspects and related cognitive abilities are not given their due importance, probably for a variety of valid reasons and constraints. This affects the overall learning and development of various capabilities that seems to be achievable through laboratory courses. As a plausible alternative to the traditional method of instruction, ‘experimental problem solving’ approach developed and implemented for the physics laboratory courses by the author is presented here. In this approach, students are given ‘experimental problems’ and encouraged to think and decide on several aspects and thereby perform self-guided experimental work with minimal help from the instructor. For this, each conventional experiment is presented as an experimental problem. The experimental problem solving approach thus integrates and fosters conceptual understanding, procedural understanding, experimental skills, cognitive processes, and overall problem solving ability. In this paper, the author presents details of the experimental problem solving approach and illustrates the approach with two sample experimental problems.

1. Introduction
Teaching and learning of physics at college and university level is often based on classroom-laboratory mode of interaction. In this mode, students attend classroom sessions where the teacher plays a central role in the ‘transfer’ and ‘learning’ of the subject content. In the case of laboratory sessions that complement classroom sessions, students’ individual experiences with physical setups, their observations, and analysis of evidence play an important role in development of several skills and capabilities. Colleges and universities offer significant ‘hands-on’ experience in experimental physics through well-prescribed conventional laboratory courses despite demanding a lot of effort, time and money. The most important objectives and goals of laboratory courses include fostering conceptual understanding, experimental (psycho-motor) skills, procedural understanding, cognitive processing, problem solving ability, affective and attitudinal abilities.

Several individuals and physics education research groups have identified the need for efforts [1] and worked towards developing novel approaches to improve the effectiveness of laboratory courses and thus elevate the quality of training in experimental physics. Several instructional approaches and related materials have been developed which include microcomputer-based laboratories [2,3], realtime physics [4,5], workshop physics [6], physics by inquiry [7,8], and ISLE laboratories [9–11]. ‘Active
learning’ approaches and interactive lecture demonstrations (ILDs) were developed [12–14] which evidently improve learning in introductory courses. Several important reports [15–21] have presented pertinent questions about the effectiveness of existing laboratory courses, compared the effectiveness of various methods, and described possible ways to improve the learning during introductory physics laboratories. Many of these approaches and methods have their own requirements and limitations which often restrict their implementation in large scale laboratory courses.

As a plausible alternative to the conventional method of instruction, the author proposes an ‘experimental problem solving’ approach which may significantly improve the overall ‘quality’ of conventional laboratory courses without involving significant additional funding.

2. What is Experimental Problem Solving?
During the past six decades, problem-solving approach has evolved as an effective method of teaching and learning science. Numerous reports [22–26] suggest that physics education must encourage active mental involvement and foster cognitive processing, creative thinking and problem solving abilities in students. In case of experimental physics, a simple analysis of cognitive tasks [27] indicates that designing and carrying out experimental work probably involves much more than that of theoretical problem solving. Experimental work essentially involves complex interplay of conceptual understanding, procedural understanding, experimental skills, and cognitive processes.

2.1 Conceptual understanding
Conceptual understanding is the knowledge and understanding of concepts, ideas and relationships, which are based on facts, laws and principles in physics. It is the understanding of ‘physics’ and ‘theoretical model’ which is involved in experimental physics. Conceptual understanding refers not merely to the understanding of individual concepts, but also to the understanding of their relations with each other and weaving them together leading to the understanding of the behaviour of a physical system as a whole.

2.2 Procedural understanding
Procedural understanding [28, 29] is the ‘thinking behind the doing’ or the decision-making that goes on while performing experimental activities. It is the understanding of a set of ideas related to the ‘knowing how’ of science needed to put science into practice. For example, if a student is asked to study the motion of a free-falling body with respect to its changing velocity, then planning the relevant experiment, deciding the measurements to be taken, the appropriate range of readings, the accuracy, the intervals at which the measurements need to be taken, and deriving meaningful outcome from the data, constitutes procedural understanding.

Procedural understanding plays an important role in experimental physics and helps in solving simple as well as complex real life experimental problems. The significance of procedural understanding is subsumed and therefore often lost under the rubric of ‘experimental skills’. It is a kind of cognitive understanding in its own right that hence should be emphasized.

2.3 Experimental skills
Experimental skills are those psychomotor abilities, which involve definite sequences of coordinated activities of the human sense organs and the limbs and are necessary in performing experiments, measurements as well as collecting and processing experimental data. It includes skill of handling wide range of laboratory components, tools, equipments and measuring instruments, setting up of an apparatus and carrying out actual experimental work with physical components/systems. It involves performing measurement, alignment, adjustment, control, recording, etc. Skills include activities such as 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 periodic time of a pendulum.
2.4 Cognitive processes
Cognitive processes are the means of obtaining and processing the information needed to tackle a problem and arrive at a solution. They include hypothesizing, predicting, observing, classifying, comparing, analyzing, interpreting, inferring, critical thinking, application, synthesising and evaluating.

2.5 Experimental problem solving
The terms ‘problem’ and ‘problem solving’ have several definitions that can convey their meaning as stated by different researchers and thinkers. A problem is often seen as a stimulus for which there is no ready response and the solution calls for either a novel action or a new integration of available actions.

A problem includes any activity that requires a student to apply his or her understanding in a new situation. For example, a student is asked to determine the acceleration of an object of mass \( m \) moving down on a frictionless inclined plane (with an angle of inclination \( \theta \)). This problem may be solved theoretically or may take the form of an experimental problem (if all the necessary apparatus including a frictionless plane are provided). Thus an ‘experimental problem’ as defined by the author [30] may be seen as an experimental situation in which one cannot see a direct solution and needs to perform operations involving a combination of conceptual understanding, procedural understanding, experimental skills and cognitive processes to arrive at the desired solution. The experimental problem solving is different from a pen and paper type cognitive problems as it is experimental in nature and involves use of apparatus, performing measurements, data collection and data analysis.

In an experimental problem solving approach students are encouraged to comprehend, think, apply, decide, evaluate and perform during independent experimental work with minimal help from the instructor. Students are expected to comprehend the problem and the given experimental situation, apply theoretical understanding and propose a model. They are expected to think, decide, prepare and evaluate (with enough trials) a detailed experimental plan, perform the experiment, carry out measurements, collect the data, analyse the data, derive conclusions and thus, obtain solution to the experimental problem with minimum help from the instructors. In this approach, the instructor may provide all the required help in using experimental setup and measuring instruments, however no help is offered with respect to procedural understanding, thinking and decision making. Sufficient reference material on all the above aspects is made available to students in advance.

In experimental problem solving, the emphasis is given on students’ autonomy in making decisions, planning the experimental stages and integration of knowledge, understanding and experimental skills to arrive at the desired solution. In this approach, the problem or the expected final stage of the solution can be clearly stated and explained as in the case of close ended tasks, however the detailed instructions that a student needs to follow to reach the desired state are not given. Instead, a few hints and instructions may be given to guide students towards the solution of the problem.

To illustrate the ‘experimental problem solving’ approach, two types of experimental problems are presented below. It is to be noted that the emphasis on each aspect of experimental problem solving is different in these two types of experimental problems. The first experimental problem is based on a three coil two loop magnetic circuit, in which students are shown a demonstration, expected to observe the effect and design an appropriate investigation to study the distribution of magnetic flux under different load conditions and thus explain the observations made during the demonstration. The second experimental problem involves designing and performing appropriate investigation for identification and characterization of optical components mounted inside an unknown optical black box.

3. Experimental Problem on Magnetic Circuit
Most physics students are familiar with electric circuits where, a voltage source \( V \) develops a current \( I \) in a closed conducting path of electrical resistance \( R \). The electric field inside a conductor causes the flow of electrons (current \( I \)), which is opposed by resistance of the conductor. Similarly, a magnetic circuit involves a source of magnetomotive force (mmf), which gives rise to a magnetic flux \( \phi \) in a magnetic path. This magnetic flux is opposed by the reluctance \( r \) of the magnetic path. Thus a magnetic circuit is a closed path containing magnetic flux. Parameters like magnetomotive force, magnetic flux,
reluctance and permeability of magnetic circuit are analogous to voltage, current, resistance and conductivity respectively in case of an electric circuit.

In this experimental problem, a two loop magnetic circuit as shown in Figure 1 has been used. The laminated iron transformer core, which is commonly used for the step-down transformers, presents an interesting example of a closed loop path for a simple magnetic circuit. In case of a transformer, the magnetic flux generated by the current in the coils is confined to the core due to its high magnetic permeability and absence of air gaps.

![Figure 1. Two loop magnetic circuit with three coils](image)

The experimental setup designed for this problem consists of a three coil transformer [Figure 2] made of E and I shaped iron strip laminations and mounted on a base board. Three coils of copper wire (19 SWG) each of 80 turns are wound on each leg of the core. The middle coil serves as the primary coil (P-P) and the two coils wound on the right and left legs serve as secondary coil 1 (S₁-S₁) and secondary coil 2 (S₂-S₂) respectively. Students are given the transformer board, several digital multimeters, set of fixed value resistors, an incandescent lamp with holder, connecting cords and an AC source (6V, 2A, 50 Hz, sine wave).

![Figure 2. Design of three coil transformer and photograph of the transformer board](image)

Students are expected to connect the incandescent lamp to the left secondary coil S₂ and keep the right secondary S₁ open. An alternating current is supplied to the primary coil P using the AC source. When the AC source is switched ON, students will not observe any glow in the lamp. The lamp does not develop enough power to glow when the right secondary is open. They are instructed to short the right secondary and to their surprise they observe that the lamp now glows bright [31]. The above observation implies that when the right secondary is shorted there is enough power delivered to the lamp. This happens even though the right secondary is not electrically connected with the lamp. Students are expected to design and perform the necessary investigation and study the flux distribution in the two loops under different load conditions and hence explain the above observation. They are expected to
plot appropriate graphs to represent the interdependence of various parameters involved in the given two loop magnetic circuit.

4. Experimental Problem on Optical Black Box

A typical optical black box described here is a sealed plastic cuboid shaped box inside which various optical components are mounted. This may be called a black box since students are not made aware of the contents of the black box. The black box as shown in Figure 3 is a cuboid with six faces marked as A, B, C, D, E and F and a horizontal reference plane marked with white lines. The box usually has six small circular holes (10 mm diameter) one on each face (at the centre) for the incoming and outgoing light. In this particular black box circular holes on faced marked C and E are blocked with thick white cardboard from inside. Thus, students have only four holes A, B, D and F for their study. Under different conditions of the inward light, careful observations and analysis of the light coming out from the small holes suggests possible optical components present in the path of the light inside the box.

Figure 3. Schematic diagram and photographs of a typical optical black box

Students are given an optical black box, a laser source of red light, appropriate stands and mounts, a white screen and a measuring tape. They are informed that in the given black box (say CODE No. R118) there are three different optical components mounted either parallel and near the faces or at the centre of the box along the marked reference axis. They could be of the following types, thin plane mirror, double convex lens (determine its focal length $f$), double concave lens, thin plane parallel glass plate, plane one-dimensional diffraction grating (determine the line spacing $d$ between the lines)

In this experimental problem, students are expected to apply their understanding of relevant optics and the distinctive characteristics of different optical components, design and perform appropriate experiments, record, analyze and interpret their observations and thus, identify the unknown optical components mounted inside the given black box. They have to identify the position and the orientation of these optical components and determine the values of various parameters, which characterize the optical component. Students are expected to note down their method and the observations and present the results and conclusions with justifying arguments and thus, solve the experimental problem on the optical black box.

5. Conclusion

It is believed that Physics education should be more than just transferring the knowledge and fostering the understanding of how various systems in nature behave under different conditions and how the laws of nature operate. Present day physics education should prepare students to ‘think and work like physicists’ and contribute to the new understanding and scientific developments. It is felt that the approach with which students work on the given set of experiments in a laboratory is the most important factor for the development of students’ abilities. A ‘minds-on’ or ‘experimental problem solving’ approach in combination with hands-on work should be emphasized in physics laboratory courses. The experimental problem solving approach has been successfully implemented by the author for the physics laboratory courses at the first and the second year of three and five year university degree programme.
The author suggests that colleges and universities could adapt the experimental problem solving approach which would significantly help to improve the quality of conventional laboratory courses. For this purpose, each existing laboratory experiment should be redesigned and presented as an ‘experimental problem’ for students to work on and ‘solve’. An experimental problem should not be presented as a single, monolithic unit, but instead presented as a sequence of interrelated simple tasks, each task being a small activity. Thus, students get to solve the experimental problem in smaller stages. Each task could have a different focus, involve a different type of experimental activities and aim at different learning outcomes. Each student may be given a carefully written student handout for each experimental problem in advance. The handout should provide basic introduction, theoretical background, details on apparatus and instructions on how to use them, and useful references. Appreciating the well-established benefits of peer instruction [32, 33] in problem solving and other aspects of learning, it is advisable to have two or three students work together on one experimental setup, collect and use the same data, but report their results and conclusions individually.

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