10. Physics Education Research: Transforming Classrooms, Teaching and Student Learning at the Tertiary Level

Pratibha Jolly
Miranda House, New Delhi, India
pratibha.jolly@gmail.com

Introduction

Over the last two decades, systematic research in physics education has helped define a new agenda for teaching-learning environments the world over. Painstaking investigations have focused on the learning process and scientifically established the gaps that exist between what should be taught and what is taught; what is learnt and what is measured as having been learnt (McDermott, 1991). In-depth studies on student construction of meaning and difficulties with fundamental concepts have shown conclusively the difference between meaningful learning and passing examinations. Dismal performance of top ranking students on specially designed concept indicator tests, even in world renowned premier institutes, have triggered an introspective rethinking about the nature of teaching programs which were hitherto considered as quite successful (Mazur, 1992).

Teaching programs for the physics degree courses at the university level traditionally operate within the framework provided by the triad of lecture, laboratory and tutorial/ recitation. These are routinely designed to cover an impressive list of topics conceived to be of core importance in the learning of the subject. Rarely is an effort made to embed the curriculum in what may be perceived as good pedagogical practice and evolve effective methods of instruction. Although periodic changes in curriculum occur, these invariably focus on, one, a mandatory reshuffle of this list of content and two, in the name of modernization, addition of topics considered to be of contemporary interest. However, every teacher knows from personal experience that the efficacy of what goes on in a typical classroom or laboratory is highly doubtful (McKinnon & Renner, 1971). Many students are unable to grasp the basic concepts of physics. They resort to rote learning, plug-and-chug approach to solving problems and adopt cook-book procedures to carry out experiments. No wonder, students fail to reason qualitatively and transfer their classroom learning to unknown problems and real-world situations. Since the examinations accompanying traditional teaching evaluate success in algorithmic approach to learning and do not probe qualitative understanding of fundamental concepts or the scientific process, the deep-rooted problems of such systems remain largely unidentified and unresolved. However, these limitations have serious repercussions and perpetuate to lower the quality of both, education and research at all levels.

It is now exceedingly well recognized that the objectives of good science education can not be achieved merely by lecturing with greater clarity; including better laboratories; increasing the study hours; periodically revising the curriculum; altering the examination pattern; creating a better evaluation scheme or creating a completely new course structure. Of far greater significance are the methods adopted for instruction and the efficacy of the process of communication within the classroom.

Meaningful communication requires a bidirectional exchange between the teacher and the student. The key to this lies in comprehending the initial state of the student before developing appropriate instruction to transform that state. This entails the teacher listen to the students; elicit the beliefs students bring into the classroom; discover how students interpret concepts and construct new meanings; analyze the underlying patterns of students thinking process; and finally create experiences to alter those beliefs and learning so that these conform to the expected scientific norms.

Insight gained from such cognitive studies in the physics classrooms suggests that for instruction to be effective, the student must be made an active participant, rather than a passive recipient, in construction of his or her own knowledge (Redish, 1994). Consequently, the current thrust the world over is to develop active learning environments, instructional material and teaching strategies which are, both, hands-on and minds-on. Another major change in outlook is in setting criteria to evaluate successful learning, reflected through qualitative understanding, problem-solving and science process skills. Thus research based curricula devise new tools for assessment.

In this overview, we first briefly delineate salient directions along which physics education research is progressing and the emerging theoretical framework. Then we present illustrative examples of innovative teaching strategies and curriculum.

Research Questions in Physics Education and Theoretical Framework

Unlike physics research, physics education is rarely state-of-art. The mission of Physics Education Research is to provide an empirically tested theoretical framework to help build the science of teaching-learning of physics with rigor characteristic of research in pure sciences. It is moving along well-defined directions that address all aspects of the instructional problem. This paper dwells on three basic posers, as put forward succinctly by Fred Reif (1995):

- What is the initial state of the learner?
- What is the desired final state of the learner?
- What is the instructional process that can take the learner from the initial state to the desired final state?

Studies on Initial State of the Learner

Conceptual Understanding: Over the last twenty years, seminal research in students' conceptual understanding has shown that students bring to the formal classroom spontaneous reasoning based on naïve theories about the world (Driver, Guesne & Tiberghien, 1985; McDermott, 1984; Viennot, 1979). These beliefs and ways of interpreting physical phenomena are significantly different from those they are expected to learn. It has been found that these conceptions show a marked degree of universality. Diverse student populations, drawn from varying age, ability and cultural backgrounds, exhibit a striking similarity in their conceptions and learning difficulties. These alternate conceptions prevail even among teachers and experts and are also revealed by the history of science. Although fragmented, students' intuitive theories about the world have a degree of self consistency. Consequently, most common sense notions are fairly stable and resistant to change by traditional instruction. Research has shown that a great deal of mental effort is required to bring about a change in thinking and that it is important to address these conceptions explicitly during formal instruction.

Systematic attempts have been made to identify students' preconceptions and common learning difficulties through various levels of physics instruction in core areas such as mechanics, heat and thermodynamics, waves, sound, light and optics, electricity and magnetism, electromagnetism, modern physics, Galilean relativity, special relativity and so on (McDermott & Redish, 1999). Because of its importance in learning of physics, students' conceptions of mechanics have been most widely investigated. An indicative but not exhaustive inventory of some prevalent beliefs in elementary mechanics is included herein as Table 1. A glance at this table will suffice to illustrate the obvious challenge posed by students' conceptions to teaching of physics. Repeatedly, studies have shown that despite instruction, students often continue to hold simultaneously, both Newtonian and non-Newtonian views. The former are cued more often by the end-of-text problems while the latter surface when students are called upon to give spontaneous qualitative explanations of the phenomena under study.

The most convincing evidence for this mix-up of models and duality of beliefs is provided by students' performance on a diagnostic test in mechanics (Hestenes, Wells & Swackhammer, 1992) popularly referred to as the Force Concept Inventory (FCI). The FCI, a 29-item multiple-choice concept test specially designed and validated to measure how students' common sense notions about force and motion differ from the Newtonian concepts they are expected to master, has become a classic benchmark in physics education. It explores students understanding by decomposing the force concept along six conceptual dimensions categorized as kinematics; first law; second law;

Table 1: **A brief inventory of common conceptions held by students in mechanics.**

Research shows that despite instruction, a substantial number of students:
cannot differentiate between concepts of speed and position;
have difficulty distinguishing between position and velocity graphs;
do not associate a particular instantaneous velocity with a particular instant;
have difficulty with negative values of velocity;
think that velocity is an intrinsic property of an object independent of the frame of reference;
confuse concepts of velocity and acceleration;
confuse concepts of mass and weight;
believe that once the horizontal force is removed, the horizontal velocity ceases abruptly and the object falls vertically;
do not think that horizontal and vertical components of velocity are independent.
believe a force is needed in the direction of motion to keep something moving; i.e. 'motion implies force';
do not believe that a table exerts an upward force on a book resting on it;
think that a heavy body falls faster because it is heavier;
think that speed is roughly proportional to the gravitational force even for relatively massive objects falling through short distances;
given an Atwoods' machine, believe that 'lower (closer to earth) implies heavier.'

third law; superposition principle; and kinds of force. FCI discriminates between perceptions by including in each item carefully researched distracters that represent persistently recurring non-Newtonian beliefs (Halloun & Hestenes, 1985). While a high FCI score by itself may not indicate that the students have a coherent force concept, a low score is a fairly reliable indicator of the lack of it. However, validation through detailed interviews to check if a Newtonian response has been given for a non-Newtonian reason and a comparison with performance on other measures of understanding suggest that a high FCI score (>85%) is highly unlikely without substantial coherence in the force concept. The finding that students in traditional courses, irrespective of their exam scores and accreditation rating of their institute, average a pre-instruction score about 40% has firmly established the limitations of traditional instruction.

The FCI has been administered to student populations across the world and continues to be extensively used as a pre-instruction and post-instruction test by physics instructors to gauge the effectiveness of the introductory physics course (Hake, 1998). Rigorous analysis of data has established reliable measures of learning gain. The most compelling evidence of its' success as an assessment tool is provided by the experience of Mazur at Harvard. Mazur teaching a traditionally lecture-based introductory physics course was shocked to discover that his generally high scoring class rated dismally low on FCI. This motivated him to radically alter the format of his lectures. His pioneering instructional strategy, Peer Instruction, (1996) is described in some detail in a later section.

Problem Solving: Ability to solve problems is considered to be of key importance in learning of science (Reif, 1981). Several researchers have tried to arrive at a cognitive understanding of patterns of students thinking by tracing how students employ their knowledge of formal physics for problem-solving. The data is usually collected by setting up an individual problem-solving session and asking the student to think aloud as she develops a solution to the problem. Such clinical interviews attempt to ascertain what reasoning and procedures students evoke – and equally importantly, do not evoke. Important clues for interpreting this data are collected by asking experts to solve the same problems and comparing-contrasting the performance of novice students with that of experts.

These investigations show that novice students are bad problem solvers. They tend to plunge towards a solution with little or no thought on strategy, rarely undertaking a qualitative or diagrammatic analysis of the problem and grasping haphazardly at individual equations in their repertoire. The general tendency is to work backwards from unknowns to givens, selecting equations that allow them to determine the requisite variables by a simple plug-and-chug. Once a result is obtained, students do not deem it necessary to check or validate the answer they get even if it is off by orders of magnitude.

At the root of poor strategy lies a fragmented knowledge of the facts of physics (Eylon & Reif, 1984). Equations are seen merely as small functional units for calculating quantities and are usually not viewed as connected to other pieces of information as ordained by governing principles or concepts. In the absence of such linkages, the knowledge structure is poorly organized and much effort and time is required in recalling and retrieving the necessary information just when they need it.

The lack of perspective results in poor grasp of the semantic nature of a problem and its schematic representation. Research shows that students have difficulty in describing qualitatively the meaning of a problem and identifying which concepts underlie the given task. When asked to find semblance between two different problems, they are most likely to categorize problems on the basis of surface similarities such as the physical characteristics of the objects involved (Chi, Feltovich & Glaser, 1981). Thus problem situations involving springs, pulleys, inclined planes etc. are likely to be classified in disparate categories under those object heads even if they can all be solved using the same principle, say conservation of energy. Not surprising then that a projectile launched by a spring gun can prompt students to start with the spring-force equation for determining its trajectory. This preoccupation with surface features results in naïve representations of problems to the detriment of conceptual knowledge.

The research summarized here has helped place the data on students' conceptual understanding in a theoretical perspective by analyzing students reasoning, looking for patterns in errors, suggesting plausible reasons for the observed learning difficulties and determining prerequisite conditions for conceptual growth.

For a summary, interpretation deficiencies can frequently be attributed to the fact that students

i. remember knowledge in isolated fragments which are often incorrect;

ii. even when they invoke a definition of a concept, are unable to interpret it correctly;

iii. have limited facility with technical vocabulary and frequently use terms colloquially;

iv. have limited math capability;

v. do not have a coherent picture of the knowledge they are learning;

vi. are unable to connect between multiple representations of the same reality in terms of the physical event, its qualitative description, the physical model, related mathematical model, corresponding equations, diagrammatic and graphical representations, and formal principles or concept definitions;

vii. are unable to distinguish between evidence and inference; and

viii. rarely ponder on consistency of the conclusions they arrive at.

Attitudes and Beliefs about Learning: The human mind is a complex entity – the attitude with which any activity is approached also has a strong bearing on how it is interpreted and how it is implemented. Researchers have found that among other factors, students' background, personality traits, motivation, interest level and images of science, scientists and the process of science, all affect learning. There is a deep connection between students' epistemological beliefs and how students process and interpret the information they are presented with.

In the context of making sense of physics concepts and problems, some of these investigations (Hammer, 1995) have focused on the cognitive aspects of students expectations from the courses they study, asking questions such as

- how the students view the structure of the knowledge they are learning;
- what approach students adopt to attain that knowledge and develop appropriate skills; and
- what perception students have of the physics they are learning and it's connection to the real world.

Case-studies tracking students' expectations, as they progress along a course of study, have helped identify important facets of student cognition. The findings have been used by researchers to construct multiple-choice questionnaires for use with large student populations. One such instrument developed at the University of Maryland (Maryland Physics Expectations; MPEX) probes student expectations along six dimensions (Redish, Saul & Steinberg, 1998). These are listed below together with what a typical student is likely to believe:

1. *Independence:* This deals with beliefs about learning. To be good in physics, a student needs to be actively engaged in the process of making sense of the concepts presented in the class. This entails questioning, assessing, evaluating and transforming information continuously. However, many students have a passive view of learning and accept whatever is written in the text or presented by the teacher as self-evident truth.

2. *Coherence*: This deals with beliefs about the structure of physics knowledge. To be good in physics, a student needs to realize how empirical evidence, natural laws, physical models and theoretical formulations are interconnected; that these are diverse facets of a single coherent scheme for understanding all natural phenomena. However, many students view each piece of information in isolation and see no coherent connection between diverse physical systems.

3. *Concepts*: This deals with beliefs about the content of physics knowledge. To be good in physics, a student needs to understand concepts that underlie each theoretical formulation.

However, many students view physics merely as a collection of formulae which need to be applied algorithmically to produce a right answer.

4. *Reality Link*: This deals with beliefs about the connection between physics and reality. To be good in physics, a student needs to understand the deep connection between classroom formulations derived on the basis of simple idealized models and the real world phenomena. However, many students think of physics as a collection of abstract theories with little connection to the real world.

5. *Math Link*: This deals with beliefs about the role of mathematics in learning physics. To be good in physics, a student needs to understand that formulae and equations, in addition to providing a concise symbolic representation, offer a powerful way of encoding qualitative information about the real world phenomena. However, many students view mathematical formulations merely as means of calculating numbers for specific problems.

6. *Effort*: This deals with beliefs about the activities necessary for meaningful learning. To be good in physics, a student needs to invest a great deal of personal effort in enriching her learning environment and constructing her own understanding from the available resource material. However, for many students formal classroom lectures are the be all and end all of instruction.

MPEX includes five to six questions in each of the six categories in the form of definitive statements. The students are required to rate each statement on a *Likert* five point scale ranging from *strongly agree* to *strongly disagree*. Then the student response is compared against the corresponding expert opinion on each item to decide whether it represents a favorable or unfavorable attitude. The survey, administered to 1500 students in introductory calculus-based physics in six colleges and universities of USA, showed that students harbor novice beliefs far from those expressed by experts (Saul, 1998). Further, analysis of the pre-instruction and post-instruction data showed that in general, students expectations tend to deteriorate significantly along most of the cognitive dimensions as a result of instruction. Working with a smaller group of students in an Indian classroom (Jolly & Rangaswamy, 1998) we found similar results (Table 2).

***Table 2:* Percentage of students giving favorable/unfavorable responses on MPEX survey.**

B.Sc	Independence	Coherence	Concept	Reality Link	Math Link	Effort	Overall
I	40/37	45/40	48/34	68/20	63/21	72/13	56/28
II	43/43	39/39	54/36	61/19	68/20	75/19	57/29
III	35/48	41/44	43/42	60/19	52/29	59/26	48/35

At a gross level, this data shows that the overall attitude is far from the characteristics desirable for a good physics student. A greater number of students respond favorably to the reality, math and effort clusters in comparison to the independence, coherence and concept clusters. Surprisingly, in each of the clusters, the first year students start with significantly better attitudes. With progression in learning, by the third year, there is a noticeable deterioration in attitudes conducive to good learning along all the six dimensions. Thus it would appear, the activities in the three year traditional physics course do little to enthuse students.

All these results point to the failure of traditional lecture-driven education and the critical need for redesigning instruction that can lead the novice student closer to the expert ways of doing science.

Desired Final State of the Student

Amongst the most frequently cited goals of physics instruction are, one, to teach the fundamental principles of physics, and two, to impart qualitative and quantitative problem-solving skills. A measure of success along these directions is the capability of the student to display concepts to and then the capacity to generate optimum problem-solving procedures in new situations. However, research shows students fall far short of such expectations.

Investigations on experts performance at a variety of problem-solving tasks helps define the desired final state and target of instruction. Several control studies contrasting the difference between novice and expert problem-solving techniques (Larkin, McDermott, Simon & Simon, 1980; Reif & Heller, 1982) have led to the conclusions that experts tend to:

- describe a problem qualitatively before attempting to solve it;
- begin a task by cueing the deep structure of a problem;
- try to determine what information, concepts or principles can be applied
- develop a strategy before they embark on a solution;
- place the problem in a larger perspective;
- use multiple approaches involving a judicious mix of qualitative thinking, mathematical, diagrammatic and graphical tools; and
- invariably check that the conclusions are consistent within the conceptual framework.

At the back of this way of thinking about the physics is a well organized knowledge structure. Experts tend to:

- gather and store information in clusters related by underlying concept or principle;
- have a hierarchical arrangement of concepts that facilitates recall and application;
- associate key features with each chunk of information;
- build interrelations between different chunks of information;
- evoke ‘compiled’ knowledge to quickly solve a familiar problem without working out all the steps; and
- depend on very few basic principles or chunks of information to solve any problem.

Then the quintessential question is how instruction can inculcate the desirable expert-like traits in students and transform them from novice to expert.

Implications for Instruction

Ongoing research establishes that the process of achieving disciplinary expertise can be equally challenging for just about everyone. In many situations, even experts display novice-like behavior. Cognitive studies draw parallels between students learning and the growth of new ideas and theories in history of science. These often involve major shifts in outlook. To be successful, each student must undergo a process of re-conceptualization similar to a paradigm shift. Seminal advances in theories of learning provide the requisite new perspectives on the conditions necessary for such conceptual growth (Kuhn, 1970).

Enhancing Learning through Active Mental Engagement: Research shows that to engender conceptual change (Posner, Strike, Hewson & Gertzog, 1982; Scott, Asoko & Driver, 1992), it is necessary to explicitly confront the student with situations that help him perceive the inconsistency or contradiction between his naïve theory and the evidence generated by the phenomena. The resulting disequilibrium can provide the crucial intrinsic motivation for active learning. However, to be accommodated, the new idea has to be:

1. *Intelligible*; the student must be able to grasp how it can be applied to the situation;
2. *Plausible*; the student must perceive its capacity for resolving the conflicts generated by its predecessor; and
3. *Fruitful*; the student has to foresee its potential for solving an extended range of problems and opening new areas of inquiry.

These three conditions appear to be conducive for conceptual change and ultimate reorganization of the knowledge structure in conformity with the disciplinary aims.

The above tenets have an important bearing on design of instruction: the bottom line is that the student must be actively engaged in first recognizing her own existing beliefs and then, in constructing a new understanding. This suggests a student-centered learning environment where the primary onus is on the student and the teacher assumes the role of a facilitator who challenges and resolves conceptual conflicts using appropriate activities and Socratic dialogues.

Several models of research-based instruction have been designed. As an example, Karplus's *Learning Cycle Model*, anchored in Piaget's theory of learning, explicitly aims to develop student-centered learning environment conducive for conceptual understanding (Karplus, 1975). It has three major segments:

1. *The exploration phase* wherein after a brief general introduction, the students are engaged in a series of activities that allow them to experimentally explore the underlying concept and relate it to their prior experiences.
2. *The concept introduction phase* wherein the teacher formally introduces a model, a concept or a principle to explain the observations, usually through an exposition.
3. *The application phase* wherein students are engaged in a new set of hands-on activities, explore related phenomena or solve problems using the newly acquired conceptual knowledge.

This model has been used quite successfully with diverse student populations at a variety of levels including the tertiary. There are several variants of this method. Possible adaptations differ from each other in the relative time spent on each of the phases, the specific choice of learning tasks, mediating technologies and the relative emphasis on the quantitative versus the qualitative. The crucial point in all these is that the students are actively engaged in the process of concept invention and integration.

Enhancing Learning through Social Interactions: Vygotsky's theory of social development (Vygotsky, 1978) has a strong influence on the design of active learning environments. According to him, social interactions in the community play a fundamental role in the development of cognition and the process of "making meaning." Higher mental processes in the individual have their origin in the social processes and can be understood only in the social and cultural context in which they are embedded. Thus social influences impact cognitive development (Figure 1).

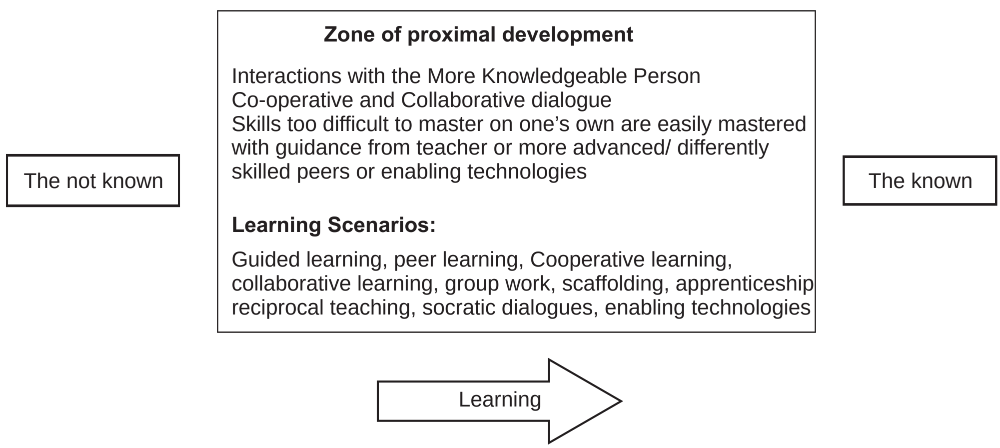


Figure 1: **Guided learning process loop based on Vygotsky's theory of social learning.**

Important learning takes place through social interactions with a skillful instructor who may model behavior, or provide instructions though what Vygotsky terms as co-operative or collaborative dialogue. This information is internalized by the learner who uses it to guide her own performance. This 'More Knowledgeable Other' (MKO) plays a crucial role in cognitive development. The MKO could also be a peer with greater ability in a particular task, concept or process. In contemporary renderings, technology with carefully designed 'Knowledgeable and Interactive' human-machine interface can sometimes play the same role.

Research-based Instruction: Examples of Praxis

Over the last two decades, a large number of Physics Education Research Groups (PERG) based in departments of physics in renowned universities and colleges in the US have given immense impetus to curricular and pedagogic reform driven by research findings. The initial focus on physics courses for pre-service teachers soon shifted to Introductory Physics Courses offered to large groups of students in engineering courses. These covered the usual topics in mechanics, electricity and magnetism, heat and thermodynamics, optics, waves and oscillations and so on. In a cascade effect, student learning in a wider spectrum of courses including those for physics majors has been/is being investigated. The demonstrated potential for extrapolation at all levels has led to recognition of effort, advocacy, policy support and consolidation. All this has changed the landscape of discourse and praxis in physics education the world over.

Development of research-based curricular practice across the board is rooted in phenomenological studies and Action Research in the classroom. It follows a cyclical or iterative process succinctly represented by a learning wheel (Figure 2).

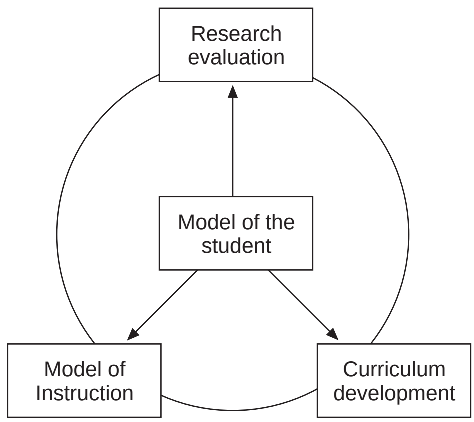


Figure 2: **Model of research-based curriculum development.**

At the focus is a model of student as a learner; it drives the cogs of research, curriculum development and instruction. The research also provides the tools for evaluation to further drive the wheel, creating a helix of continual improvement. The efficacy of the curricular materials and instruction is often determined by investigating the learning gains on diagnostic concept tests such as FCI, FMCE (Force Motion Concept Evaluation), etc. administered pre- and post-instruction. These tests have by now acquired significant credibility as reliable and valid measures of student learning by virtue of having been administered to large populations in a variety of educational settings and control environments.

The examples of research-based instruction summarized below are continually evolving. These instructional models have been adopted and adapted in various measures beyond the point of origin by diverse institutions some of which began as participants in control experiments or field trials. It is common now for one model to integrate well-tested tools and strategies developed in other research-based models of instruction. Of generic importance and amenable to integration in a variety of scenarios (Redish, 2003), these include specially designed categories of concept questions and concept enhancing tasks; computer-based data-acquisition systems employing a wide range of sensors for real-time measurement of physical quantities; graphing, data analysis and mathematical modeling software; simulations; animations; video-based data capture and analysis software with libraries of video clips, etc.

The following section does not follow the development chronology but a categorization by the predominant mode of teaching.

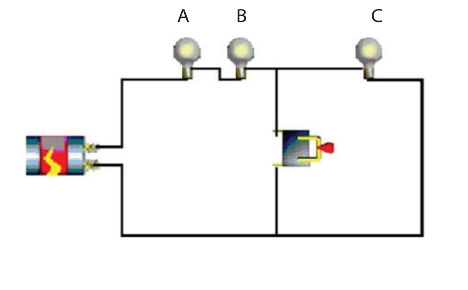
Enhancing Lectures with Research-based Strategies

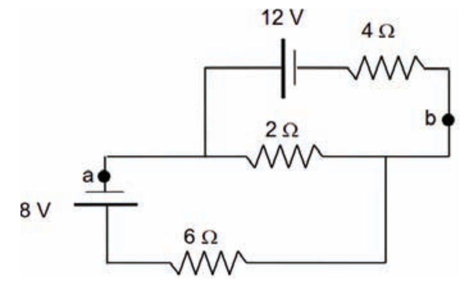
Considering that the lecture mode of instruction is strongly entrenched in most institutions of higher learning, a major thrust has been to incorporate into it research based activities to enhance the quality of student learning. A few example of praxis are summarized below.

Peer Instruction: Developed at Harvard by Eric Mazur, *Peer Instruction* has been widely acclaimed as a game changer in physics education for the credibility it has given to the research findings (Mazur, 1996). Mazur's personal transformation is worth recounting here for its motivational value. An acclaimed and much awarded teacher of introductory courses, until 1990 Mazur evaluated his conventional lectures stimulated by classroom demonstrations as generally successful as his students scored well on what he considered as difficult problems. When he first encountered the research finding on the FCI, he viewed the data on poor performance of students with skepticism. He found it difficult to believe that most students when asked to compare forces in a collision between a heavy truck and a car think that the truck exerts a larger force – even after instruction. His first reaction was "Not my students …!" To check things over, he administered FCI only to discover that not just students in his introductory physics class, but also physics majors at Harvard, fared no better than projected by the research on other student populations in diverse institutions.

To validate this eye-opening experience, Mazur decided to pair simple qualitative questions with relatively difficult quantitative problems with the same underpinning concept. Figure 3 reproduces his oft quoted example of paired questions on dc circuits. Physicists would rate the qualitative question as trivial and quantitative question that entails setting up simultaneous equations using Kirchhoff's Laws as harder.

The results reverse the expectation on student performance. Students fare poorly on the qualitative question. A common misconception is that closing the switch has no affect on the current; that it splits and recombines at the top and bottom junctions, respectively. However, despite poor conceptual understanding, many students are better able to numerically churn the answer for the second problem. The correlation between the score on the paired problems is poor. This data forced Mazur to conclude that even his students were mastering the plug-and-chug approach and not concepts. Practice on more problems merely added more recipes on the platter without building capacity for transferring skills for solving unfamiliar problems. The insight motivated Mazur to revisit the generic goals of instruction and critically review the lecture mode. He questioned how to focus on conceptual understanding without sacrificing quantitative problem solving. He concluded that time could be made available within the lecture by precluding step-by-step derivation of equations and teaching verbatim from notes/ texts that are easily accessible to students for reference and guidance. He also recognized that students learn best through discussions with each other.





A series circuit consists of three identical light bulbs connected to a battery as shown. When the switch S is closed, do the following increase, decrease or stay the same? 1. The intensities of the bulbs A and B 2. The intensity of the bulb C 3. The current drawn from the battery 4. The voltage drop across each bulb 5. The power dissipated in the circuit	For the circuit shown, calculate 1. The current in the 2 ohm resistor 2. The potential difference between points *a* and *b*.

Figure 3: **Paired problems to evaluate qualitative and quantitative understanding of concepts.**

Peer Instruction redefines both, the goals and the structure of the lecture. The basic strategy is to encourage student interaction in the class and continually refocus their attention on the concepts underpinning the theme of the lecture. Students are given reading assignments from the prescribed text before the class. They are quizzed to check if they have read but not graded on the emergent understanding. The lecture aims to elaborate the readings, explicitly address perceived difficulties, generate deeper conceptual understanding and reinforce this through additional examples or application to other contexts. The lecture itself is broken into short modules where the lecturer presents the salient aspects of the material being covered. Each of these segments is followed by a multiple-choice conceptual question, the *ConcepTest*, incorporating carefully chosen distracters. This is projected to the class on a transparency or using the computer. The students are given time to ponder over and record their individual responses. Then they discuss their answer with other members of their group and debate the validity of their understanding. This impels the students to actively process and justify their own thinking. It also provides the teacher with a mechanism for determining how well a concept has been assimilated during the lecture. With the help of low-tech flash cards, or where possible, a dedicated computer-based data collection system such as *Class Talk*™ or *Personal Response System*™ wherein students key in their answers using hand-held devices or clickers, the feedback is available to the lecturer instantaneously as a histogram of responses. This information allows the teacher to assess the pace at which he can cover the material and where reinforcement is required. Figure 4 shows the flow of the instruction.

This format of instruction has several inherent advantages. It provides a rich archive of common student difficulties for further development work. Careful evaluation shows phenomenal gains in the FCI scores as well as improved performance on traditional problems. It ensures that teaching does not outperform learning. Last but not the least, it breaks the monotony of the lecture and the unavoidable fading of student interest.

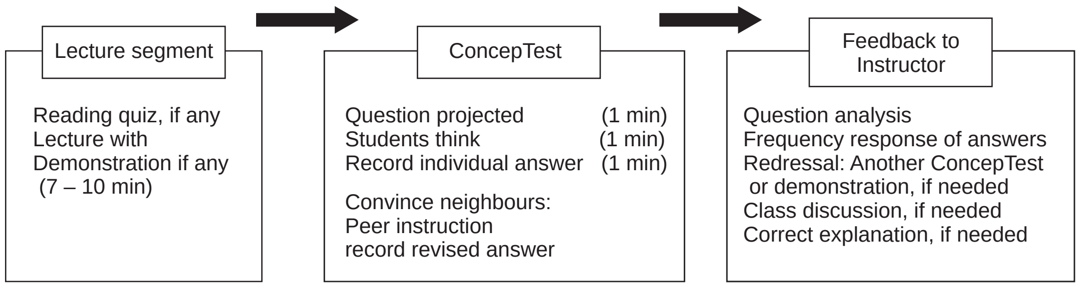
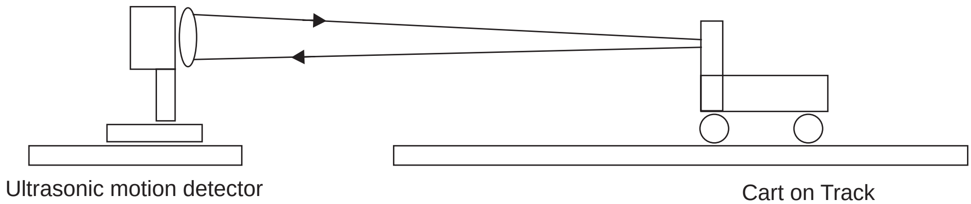


Figure 4: **Format of peer instruction detailing how ConcepTest is administered in a typical lecture segment.**

Interactive Lecture Demonstrations (ILDs): Developed by Thornton at Tufts University and Sokoloff at University of Oregon, this is an attempt to transform the traditional lecture into an active learning environment using Microcomputer-Based Laboratory (MBL) demonstrations (Sokoloff & Thornton, 1997). Primarily developed for teaching of kinematics and dynamics to non-calculus students, the demonstrations use a motion detector to generate real-time graphs of position, velocity and acceleration with respect to time and a force probe to record the force in a variety of situations. In the lecture format, the experiments are suitably integrated into a carefully structured interactive format. The instructor describes an experiment or a demonstration and performs it for the class first without using the MBL. Figure 5 gives an example of questions on a demonstration sequence.

The students are asked to individually predict the result and record it on a handout prediction sheet. Then the class is asked to engage in small group discussion with the nearest neighbours and decide on a group prediction. Each student records a final prediction on the handout sheet which is collected at the end of the class. If there is no group agreement, the students are free to record their individual predictions. Subsequently, the instructor carries out the demonstration on the MBL linked to display unit appropriate for a large classroom. Few students are asked to describe what is observed qualitatively. The students then describe the results and discuss the results, recording them on a results sheet which they are allowed to keep.

To help students consolidate their understanding, a comprehensive series of ILDs are employed. These closely follow the learning sequence with stress on the hierarchical understanding of motion and force concepts. An attempt is made to compare and discuss analogous physical situations based on the same concept but having different surface features. An example is provided by coin toss problems and the analogous motion of a car moving up or down a ramp. The ILD protocol encourages reflection, active engagement and peer learning. The students are made to realize that there are no ‘wrong’ predictions and learning progresses by resolving conflicts in thinking by observing and evaluating new evidence. For mechanics, the FMCE is used for assessing learn gain. The group reports a significant jump from 20% correct predictions to as much as 70% to 90% post instruction.



A motion detector records the motion of a cart in the following demonstrated conditions. Predict both the velocity and acceleration graphs in each case.

Demo 1: Cart moves away from the motion detector at constant velocity.
Demo 2: The cart is pushed towards the motion detector at a constant velocity.
Demo 3: Cart moves away from the motion detector speeding up at a steady rate.
Demo 4: Cart moves away from the motion detector slowing down at a steady rate.
Demo 5: Cart moves towards the motion detector slowing down at a steady rate.

Figure 5: **Typical interactive lecture demonstration sequence.**

There exists now a large repertoire of well tested ILDs for other core physics areas. ILDs have proved to be of great value also in calculus-based courses. ILDs for teaching of electric circuits and optics use low-cost equipment. It is the protocol for student engagement that determines success of the strategy.

Just-in-Time Teaching (JiTT): Developed by Greogor Novak and Andy Garvin at Indiana University-Purdue Indianapolis, Evelyn Patterson at the U S Air Force Academy, with Physlets contributed by Wolfgang Christian at Davidson College, JiTT blends active learning with web technology which is used to not just deliver multimedia curricular materials but also establish a powerful electronic communication system between the students and the faculty (Novak, Patterson, Gravin & Christian, 1999).

The World Wide Web is leveraged to:

- keep the students intellectually engaged with the course work through sustained communication with instructors and peers; and
- provide the instructors a mechanism for tracking what individual students know and think.

Through a well-defined process, before each lecture, students are assigned ‘warm-up’ questions on the web. These pertain to a topic to be addressed in the upcoming lecture and are due hours before the class. The students are expected to read the topic before the lecture and provide the best answer to the questions posed. Inasmuch as the material has not been taught yet, the web-assignments are graded for effort and not for correctness. The instructor analyzes the student responses before the lecture to fine tune instruction ‘just in time.’ The insight is used to launch class discussion or activities to explicitly address preconceptions and possible learning difficulties. Often, student responses are displayed electronically or on transparencies. A follow-up *puzzle* is web-assigned after instruction, this time to gauge learning. Web is also used to deliver enrichment extra-credit exercises and on-line homework, often with Physlets.

Conceptualized far before social networking sites became the norm for linking groups, JiTT exemplifies best practice for building a sense of scientific community. Technology is used not to substitute the teacher but to 'humanize' the classroom by creating a learning environment that reinforces personal interaction, feedback loop and a rapid response system. Students find the personalized attention from the faculty and greater bonding with peers – within and beyond the classroom – immensely motivating. The course website includes a bulletin board that further strengthens information and communication. It augments professional networking, cooperative learning and collaborative work that hone scientific writing and communications skills. Some of the JiTT techniques have been adopted by Peer Instruction.

Active Learning Problem Sheets (ALPS): Developed at Ohio State University by Alan Van Heuvelen, the ALPS implement a comprehensive new way of teaching called *Overview Case Study Physics* (Heuvelen, 1991). This is a spiral form of instruction in introductory physics wherein the course is divided into distinct conceptual modules. Each module follows a three step implementation:

i. *Overview*: This impels the students to construct a qualitative understanding of the material using diagrams and graphs;

ii. *Exposition*: The students learn how a problem may be formally represented using multiple tools like qualitative description, sketches, diagrams, graphs and mathematical equations and are familiarized with how multiple representations are used to describe the same concept;

iii. *Case study*: The students apply this knowledge to solve case study problems that require them to evoke multiple representations and integrate these to build a complete solution.

For most part, students work in small collaborative groups and are actively engaged in problem solving using multiple approaches. Diagnostic tests show the Overview Case Study approach leads to significantly higher gains in learning in comparison to traditional lectures. Significantly, trials at various institutions show this to be independent of instructor style or rating.

Enhancing Tutorials/Recitation with Research-based Strategies

Interactive Tutorials: Pioneered at University of Washington (UW) by Lillian McDermott originally for introductory physics, interactive tutorials supplement traditional lectures by replacing usual problem-solving sessions by carefully sequenced worksheets designed to develop fundamental physical concepts and qualitative reasoning (McDermott, Shaffer & the Physics Education Group at the University of Washington, 1998). The strategy is to engender conceptual change using a three step process that *elicits*, *confronts* and *resolves*. As a first step, the students are posed a problem or shown a demonstration and asked to predict the outcome. The situation is contrived to be counter intuitive so as to elicit a response that reflects what earlier research has shown to be a common learning difficulty or error. Further questions follow the Socratic approach to confront the student with the contradictions in thinking and resolve these to fit into a coherent framework of understanding.

Each Interactive Tutorial worksheet is accompanied by a pre- and a post-test answered individually. Students work through the worksheets in small collaborative groups prodded by questions from teaching assistants. This approach takes into account the need to explicitly address common misconceptions during instruction. More importantly, the tutorials help the student to build a conceptual understanding and transfer this to explain real-world situations.

The University of Washington (UW) tutorials are easy to implement as the activities are not technology intensive. They are strongly rooted in rigorous research. The rationale and result findings are extensively published and detail significant gains in conceptual understanding.

Activity Based Physics Tutorials: Developed at University of Maryland by Edward Redish and group (Wittmann, Steinberg & Redish 2004, 2005), these largely follow the UW format. However, in addition to developing conceptual understanding, the focus is on relating conceptual and mathematical representations and on building qualitative to quantitative links. The underpinning motivation is the research finding that students tend to form independent schemas for qualitative and quantitative problem solving and there is need to explicitly reinforce how to transfer qualitative ideas for solving problems quantitatively. To this end, technology is leveraged by integrating activities developed using computer-based data simulations and video clips of experiments and phenomena. For example, students can develop the mathematical model for propagation of transverse waves in a long spring by analyzing the diagrammatic reproduction of time frame shots available on actual video clip. The motion of a cart bouncing off springy walls leads students to explore motion in potential wells. The explorations of classical ideas on the boundary of quantum mechanics neatly dovetail tutorials on Modern Physics.

Cooperative Problem-solving: Developed at University of Minnesota (Heller, Keith & Anderson, 1992) the focus of this approach is on learning physics through solving problems (Heller & Hollabaugh, 1992). However, the lecture, the problem solving strategies and the typical end-of-text problems find innovative replacements. The aim is to explicitly teach a problem-solving heuristic and expert behavior. Additionally, carefully choosing appropriate problems with a story line provides the conceptual framework wherein students' preconceptions can also be addressed explicitly. Figure 6 gives an illustrative pair of problems to differentiate between a traditional end-of-text problem and context rich problem. The latter makes a direct connection with real world, places cognitive demands on the student who has to make sense of the storyline, distinguish information which is redundant, evoke appropriate concepts and representation before setting up the numerical solution.

The classroom protocol is based on a *Cognitive Apprenticeship Model* which involves the following steps:

1. *Modeling*: The lectures consist of expositions which introduce the concepts and a story line from which context-rich problems arise naturally. An attempt is made to also model the thinking processes physicists use to construct knowledge.

2. *Coaching and Scaffolding*: Initially extensive coaching and scaffolding is provided by explaining the conceptual and procedural aspects of problem solving through several examples in multiple contexts.

3. *Fading*: The cognitive support is withdrawn gradually and the students are expected to apply their learning to develop independent solutions to progressively more complex problems.

A. Typical textbook style problem A 5.0 kg block slides 0.5 m up an inclined plane to a stop. The plane is inclined at an angle of 20° to the horizontal, and the coefficient of kinetic friction between the block and the plane is 0.60. What is the initial velocity of the block?
B. Context-rich problem While visiting a friend in San Francisco, you decide to drive around the city. You turn a corner and find yourself going up a steep hill. Suddenly a small boy runs out on the street chasing a ball. You slam on the brakes and skid to stop, leaving a skid mark 50 ft long on the street. The boy calmly walks away, but the policeman watching from the sidewalk comes over and gives you a ticket for speeding. You are still shaking from the experience when he points out the speed limit on this street is 25 MPH. After you recover your wits, you examine the situation more closely. You determine that the street makes an angle of 20° and that the coefficient of static friction between your tires and the street is 0.80. You also find that the coefficient of kinetic friction between your tires and the street is 0.60. Your car's information book tells you that the mass of your car is 1570 kg. You weigh 60 kg and a witness tells you that the boy had a weight of about 18 kg and took 3.0 s to cross the 15-ft wide street. Will you fight the ticket in court?

***Figure 6*: Illustrative example of a traditional end-of-text problem and a context rich problem.**

The problem solving takes place in a laboratory with students working in cooperative groups. With careful monitoring of individual roles and group dynamics, this program has registered not just significant learning gains but also provided an exemplar for group based instruction.

Unified Learning Environments

Workshop Physics: Developed by Priscilla Laws at Dickinson College for small introductory calculus based physics classes, Workshop Physics is undoubtedly the most effective approach to teaching-learning (Laws, 1991, 2004; Laws, Teese, Willis & Cooney, 2009; Sokoloff, Thornton & Laws, 1998, 2004). It does away with the triad of standalone lecture, laboratory and tutorial/ recitation, replacing it instead with an integrated inquiry-based learning environment suitably designed for emphasizing the processes of scientific investigation and development of investigative skills. The class meets for two hour periods thrice a week. Students work in pairs (and sometimes groups of three or four) at a computer workstation equipped with required laboratory equipment, a range of sensors for data-logging in real-time using powerful data-acquisition software enhanced with graphing, spreadsheets, data analysis and mathematical modeling tools. Also available are simulations and tools for video capture, video data analysis and mathematical modeling of video data. The physical design of the classroom space is also special. The room has a central space for common use and demonstrations. The work stations are arranged along the four walls. There is ample space for lab equipment such as 1.5 m long dynamic tracks for studying motion. The hexagonal shape of the extension tables is a result of much research and encourages students to turn towards each other for discussions and collaborative work. In our own context, we routinely use this model effectively for project-based learning and capacity building programs (Figure 7).

(a)

(b)

(c)

(d)

Figure 7: **(a) The Workshop Physics at Dickinson College (b) A typical MBL setup to explore real-time motion of a cart (c) The low friction circular surface in the center is used for kinesthetic carts, large rolling objects, and rotational motion experiments (d) Project-Based Learning Lab inspired by Workshop Physics at Miranda House.**

Workshop Physics reverses the traditional sequence of lecture based learning wherein students are presented with definitions and abstract theoretical principles, are required to apply badly assimilated knowledge to the solution of text book problems and sometimes work in labs to verify the equations or relationships between parameters. It is based on the precept that to learn physics, students must understand the subtle interplay between observations, experiments, definitions, mathematical descriptions and the construction of theories. They need to get concrete hands-on experience of the phenomena to make sense of the abstract mathematical derivations and theories. Moving from the concrete to the abstract, students begin by making predictions. They then make observations, undertake guided derivations and develop mathematical models of the phenomena under investigation. While computer interfaced measurements and data modeling predominate, the instructor often throws in need-based segments of a lecture or demonstrations or discussions for the entire class.

Workshop Physics is not a curriculum but a way of teaching. However, it makes use of specially designed Activity Guide Book that interweaves text material with activities that include prediction, qualitative observation, explanation, equation derivation, mathematical model building, quantitative experiment and problem solving. Suggested textbook readings, home assignments, additional explorations and project work further extend and enhance the learning experience. Learning is facilitated through interactions and intense discussions with peers and instructors. Students learn to work independently and also to collaborate. They learn the art of argumentation and communication as they are frequently required to make presentations.

The touchstone of Workshop Physics is that students are actively engaged in construction of knowledge at each stage. Rather than rote learn a huge amount of text material, they experience the physics they are learning and explore indepth the topics presented. This empowers them to master strategies for independently learning physics in other contexts. The actual learning sequence and tasks are motivated by the results of PER and in addition to traditional end-of-chapter problems, include real-world problems and context rich problems.

Workshop Physics Adaptations for Large Classes: The PER community views the Workshop Physics as an optimal model for teaching-learning of physics. Its success has led to several variants and adaptations for large introductory classes with as many as hundred students. Typically, classrooms are replaced by large halls, and desks with tables around which a group of students can learn collaboratively. The table shape and arrangement follow a variety of topologies. Each student group has access to at least one networked computer or laptop, internet, facilities for multimedia projection, even hand held devices such as clickers or tablets for greater interaction and feedback. Screens and white boards are strategically located so that the display is visible to all students. Characteristically, all variants reduce the time allotted to the formal lecture, create technology enhanced environment, and sustain a high level of interaction. Within the constructivist framework, they adopt physics education research based curricular materials, active learning protocols for peer and group learning and assessment tools described earlier. The success of the teaching-learning process hinges on the quality of the Socratic dialogue and the facilitation provided by the instructors. In addition to the anchoring faculty, teaching assistants are required to provide one-to-one interaction with the large number of student groups. In addition to the knowledge of the discipline, all tutors must have pedagogic knowledge emanating from research. All this requires special training.

Some of the better known unified models are described below.

Studio Physics: This was originally implemented in 1994 by Jack Wilson at the Rensselaer Polytechnic as a *Comprehensive Unified Physics Learning Environment* (CUPLE) (Wilson, 1994). The class meets twice a week for two-hour sessions. Approximately one hour is spent on lecture and homework discussion. This is immediately followed by an activity where students solve paper-and-pencil problems, investigate computer simulations, or conduct hands-on experiments. The approach eliminates the time gap between the information provided by the lecture and its application.

Scale-up Physics: Student-Centered Active Learning Environment for Undergraduate Programs (SCALE-UP) was developed at the North Carolina State University to cater to large enrollment physics courses with hundred or more students such as in the engineering stream (Beichner et al., 2006). Students work in three groups of three on large round tables arranged in banquet style. Teachers and teaching assistants circulate to interact with students, engaging them in Socratic dialogues. This social interaction is the key element in the success of the pedagogic approach. Students work on hands-on activities, simulations or interesting questions and problems classified as:

- *tangibles* which are ‘hands-on’: these are quick labs that require students to decide what can be determined by observation and measurement. Examples include determining the thickness of a single sheet of paper for practice with significant figures and estimation or finding the force needed to roll a racquet ball along a circular arc.
- *ponderables* which are ‘minds-on’: these problems are not well-defined and require making estimations or locating information from other sources, including the web. An illustrative example is determining how far a bowling ball skids before its motion is only rolling; or how many candy bars worth of energy it takes to push a shopping cart past the snack aisle; or how many steps are needed to cross the country.

Many of these problems can be solved in more than one way, so students have to determine the approach that works best for them. There are also some hypothesis-driven labs involving advanced work where students have to also write detailed reports.

Curricular materials have been created to ease the pressure on the teaching faculty. The group claims that one faculty member, one graduate student and one undergraduate student are enough to successfully monitor the work of 99 students. The pedagogic approach and the class management techniques have been successful adopted by more than 50 colleges and universities.

TEAL: The SCALE-UP approach adopted by MIT is called Technology Enhanced Active Learning (Figure 8). This is being used in introductory courses with as many as 500 students.

One such course is *Visualizing Electricity and Magnetism*. It uses extensive course notes with links to multimedia visualizations, available on the laptops and the web. The instructor delivers 20-minute lectures interspersed with discussion questions, visualizations, and pencil-and-paper exercises. Students learn collaboratively in groups of three, discussing electromagnetic phenomena. Desktop experiments are combined with java simulations, 3D illustrations/animations and shockwave visualizations to ‘make the unseen seen’ and concretize learning of abstract concepts. Students use handheld devices and an electronic polling system to record answers to concept questions. Assessment shows that the learning gains are higher by a factor of two than in traditional instruction.

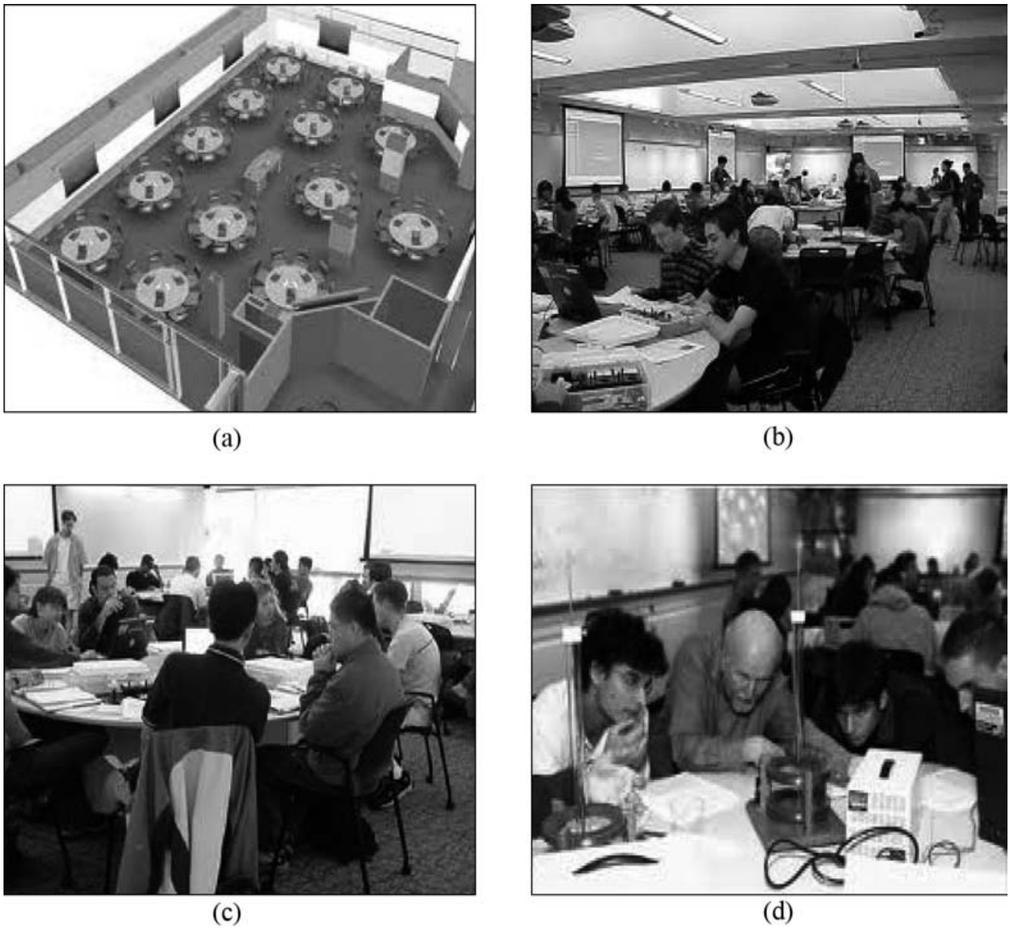


Figure 8: **Rendering of TEAL Classroom and students at work. Each table has three groups of three students.**

Summary: Learning Studio is the Future of the Classroom

Research in physics education conclusively shows that the lecture paradigm is no longer the only possibility. Credible alternative paths replace the lecture format with *learning environments* and the proverbial lecture hall with a learning *workshop* or a *studio.* These completely redesign the course structure to take into account both the research on student learning and the social theories of learning. The lecture, laboratory and tutorial or recitation are all combined seamlessly to create an integrated learning experience, with the instructor switching freely and frequently from one mode of instruction to another; evoking intensive individual mental engagement as well as team work and discussion. In these environments, the low-tech and the hi-tech computer-based tools such as microcomputer-based data acquisition systems, graphing and data manipulation tools, simulations, dynamic models, databases of text and video play an integral role. Technology plays a personalized and deeply humanizing role by providing efficient communication systems to network the community of learners and their instructors. The new generation has a high capacity to take charge of its own learning and is often far ahead on the learning curve than the instructors in abilities for collaborating, social networking and leveraging technology. The success of these programs suggests that the not too distant future certainly belongs to the new paradigm of *comprehensive unified learning environments.* Then this is the quantum leap required as we move on the knowledge network and scale up education for greater access to our masses.

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DISCUSSION

Chair- B. N. Meera, Bangalore University, Bengaluru, India

COMMENT: I would like to share an insight from our work with mathematics teachers in government school system. As you said, it is very difficult to change the beliefs of teachers regarding teaching and learning. It has been recognized in literature that it is a very tough job. So for some teachers what works is that they adopt new and innovative practices in the classrooms, see the evidence of student learning happening in the classroom and then it might help them in changing their beliefs. For some other teachers it might happen that change in beliefs happen first through reflection. So it is difficult to generalize what changes first, beliefs or practice. What we found was, there was a lot of support needed for teachers to change their beliefs and practices inside the classroom. This support can be in the form of workshops or from within the classrooms with the help of a mentor present to guide their teaching-learning process. The support also can be in the form of looking at the curriculum critically and developing it towards student learning, taking student's conceptions into cognizance.

Q1: I am from a teacher education system. I think you have given the real picture about physics education in India. The problem is related not only to physics but other basic sciences also. In the beginning of your presentation, you have pointed that the flow of students towards the basic sciences is much reduced. Do you think that this is because of overemphasis of parents and students on job opportunities?

PJ: I do think there are many factors. This is one of the factors.

Q2: I am from a technical background and I teach physics. My point is that if we take physics to be a game, a kind of play that you want students to enjoy, then there are rules of the game. You just can't play a game without certain rules. There are certain underlying assumptions as well which are based on some logical conclusions. What would you recommend regarding how we explain the rules of the game? Is there some discussion going around for explaining the rules, or rules could be explained just like a lecture. For example, like the Newton's laws of motion. Similarly Einstein's relativity, Coulomb's law. How do I communicate these rules to my students?

PJ: We are not saying that every student will sit under an apple tree and an apple will fall on their head or will collect astronomical data over their lifetime. But there is a guided discovery approach, active learning and active engagement methodology which is preferred and is research based and seems to work rather than talking in a monologue and through a lecture. My entire talk was devoted in saying that 'that' does not work. Research shows that at the end of the lecture, they can pass an examination but they cannot answer a concept test and you must try some of those things so that you can assimilate what is being said. You have to try it in your classroom. It may not be possible every time to put your child to get that 'aha' moment and or serendipity of a discovery or how laws have come to be known. Even in the instructional mode, you can create experiences that generate better understanding of physics otherwise it will just be a lot of keywords or jargon. Somebody did say and that was your comment "one size does not fit all". Many students will work and be very good, despite the system. Many professors who are particularly driven and are extremely good, will think that every single person in the classroom is just like them. I feel sorry to say that education is not about just those. So I don't think that you are talking about the rules of teaching. I am sorry to say that I don't share that vocabulary.

Q3: You talked about the work in the emerging economies, countries or developing world. But even the developed countries have exactly the same problem. So the way in which you share your problem in developing countries, we also share them in developed countries because even we are facing exactly the same problems.

PJ: We have data from our classrooms. We have data from Harvard and other countries as well. UK has some extremely good programs. Jayashree Ramadas has worked with Rosalind Driver and her own work is so good. I was very fortunate to have an inside view. I started working on my interfacing work, first from the BBC microcomputer. But let me say that having been a leader, I feel that some of those pedagogies are not as well shared as the US work gets shared.

But you have an immense amount of resources and we need to take a lot from these countries and integrate it. But I know that problems are common and universal.

Q4: You nicely explored the current scenario of physics teaching. I just want to know how to reinforce these concepts through problem solving method or laboratory method? Secondly, how should students retain the correct concept? We have seen that sometimes students have alternative conception and the teachers try to rectify them but students carry these misconceptions for years. After two years they may make the same mistakes, even the teachers. So how can one help them retain the correct concepts, correct knowledge?

PJ: As I said there are no shortcuts and scale up is difficult. Lateral studies will show that retention is not going to be that much. When you ask students a question what happens when you drop two objects, the student asks how should I answer this? Should I answer it the way you taught in the class or what I think actually happens? This dichotomy is going to return again and again. I find it happens to me as well. I don't think that we need to talk down to the students and say we know it all. History of science shows that the same ideas resurface. So, how do you change the understanding? There are no shortcuts. You have to keep doing it again and again. But if it happens in one class say an experimental class, then it's going to change nothing. Perhaps we will have a time when there will be no lecture room, there will be those studios where the student-teacher ratio will be better, optimum and where they will be an enlightened person facilitating that classroom and enlightened because she was taught differently or she was groomed to be someone different in the mass which is traditional. Our workshops are aiming to get regional people. Once exposed then they will go and there will be a cascade. That is one goal: to educate the educators.

COMMENT: I agree with you in everything that you presented about physics theory and physics instruction theory and actual practical application of this work in physics teaching. I want to add to the earlier discussion about rules. Just the way a physicist has certain rules, similarly even students and those who may know more physics than us actually have pre-existing rules in their minds. As a physicist, I may not hear about the students' rules, but as a physics teacher it is my responsibility to understand their rules, before I impose my rules on them. That is our aim. We want them to understand and comprehend those rules. Sometimes students are experiencing dilemma regarding what they want to know and what the teachers want to communicate to them and there is a conflict. It is our responsibility as teachers to understand what students are thinking before we impose our rules on them and vice versa.