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Contents

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ASEJ publishes scholarly work and strictly follows the "blind review" procedures and many other editorial policies described in the *Publication Manual of the American Psychological Association* (Washington, D.C.: American Psychological Association, 1983). Thus *ASEJ* is a refereed journal similar to most other scholarly periodicals published in Canada and the United States.

From the Editor

The articles in this special *Alberta Science Education Journal* issue on physics education argue for changes in physics teaching and curriculum.

In "The Unpopularity of Physics," **Wytze Brouwer** argues that major changes are needed to make physics more interesting and to entice more students to pursue physics formally or informally, in postsecondary study or as part of lifelong learning. He focuses on the recent trend of organizing physics curricula around interesting themes or storylines.

Don Metz and **Arthur Stinner,** in "A New Perspective for Teaching Physics in the 21st Century," review physics curriculum emphases and teaching methods throughout the past few centuries and make sound suggestions for future directions.

George Guoqiang Zhou, in "Disadvantages of Traditional Physics Teaching and a New Way to Teach Problem Solving for Conceptual Understanding," argues for a much greater emphasis on conceptual understanding in physics and reports on studies on enhancing conceptual understanding using computer-based simulations and applets.

In "Engagement Enhances Interest in Physics," **Harcharan Pardhan** of the Aga Khan University Institute for Educational Development (AKU-IED) in Karachi, Pakistan, shows how using many examples of interest to students can engage students in physics and change the attitudes of students and prospective teachers. Pardhan's distinction between a teacher's content knowledge and a teacher's pedagogical content knowledge will help teachers teach in more relevant and interesting ways.

In "Is Conceptual Change in Science Possible?" **Mark Hirschkorn** reviews the history of conceptual-change teaching and learning and provides evidence of the rather limited success of teaching for conceptual change. He also reviews promising methods for inducing conceptual change using computer-based learning materials.

Samson Madera Nashon and **David Anderson,** in "Obsession with *g:* A Metacognitive Reflection on a Laboratory Episode," show how informed interaction between the instructor and the students can lead to greater student reflection and understanding of the physical concept being investigated.

In "How to Make the Teaching of Heat Transfer More Effective," the first of three articles focusing on conceptual learning in science in Pakistan, **Muhammad Nabi Khan** and **Amos Ngugi** show how students' conceptual learning can be enhanced through the use of predict–observe–explain (POE) activities, which, when properly carried out, can also greatly increase students' interest in learning science.

Mir Zaman Shah, **Mahmood Ghaznavi** and **Mohammad Ibrahim Khan,** in "Reflection on Learning About Forces," report on using POE activities to aid students' conceptual understanding and to wean Pakistani students away from the overly textbook-oriented national curriculum. They further emphasize the increase in student interest in science when science teaching becomes more interactive and activity based.

Muhammad Riaz, in "Helping Students Understand the Particulate Nature of Matter," suggests using interactive strategies and activities to help children understand the particulate nature of solids, liquids and gases.

—Wytze Brouwer

The Unpopularity of Physics

Wytze Brouwer, *Department of Physics, University of Alberta*

A physics professor at Poly
Wrote a text in a manner quite jolly.
His book found the key
To the kid's apathy
And continues to rake in the lolly.

—Anonymous

A senior administrator sent the following note to a physics department chair:

> It has come to my attention that physics courses were rated among the lowest of all subjects taught. The effectiveness of physics teachers also was ranked among the lowest. Do something about this.

The chair asked the department's teaching specialist—me—for advice.

Before deciding what to do about the problem, I looked at the research on course value and teaching effectiveness to determine if this problem was peculiar to that school district or widespread. Researchers such as Cashin (1990) and Civian and Brennan (1996) have carried out studies in this area.

Cashin's (1990) study involved thousands of students at major universities in the U.S. As Table 1 shows, students ranked physics courses in the lowest category with chemistry, computing science, engineering, and mathematics and statistics, well below subjects such as fine arts, education, biological sciences and military sciences.

In terms of instructor effectiveness, Cashin (1990) found a similar story. As shown in Table 2, students ranked physics instructors in the lowest category. Instructors in the fine arts, military sciences and other humanities were rated well above instructors in the more quantitative subjects, such as chemistry, mathematics and physics.

Clearly, student dissatisfaction with physics courses and instructors is widespread.

Table 1
Student Ratings of Courses at Major U.S. Universities

High	Medium-high	Medium	Medium-low	Low
Fine and applied arts Music	Education Foreign languages Arts	Biological sciences Military sciences Psychology	Accounting English language History Social sciences Law	Chemistry Computing science Engineering Mathematics and statistics Physics

Table 2
Student Ratings of Instructors (by Subject) at Major U.S. Universities

High	Medium-high	Medium	Medium-low	Low
Fine and applied arts Military sciences Music	English language Arts and humanities	Nursing Education	Biological sciences Chemistry Math and statistics Philosophy	Business and management Computing science Engineering Physics

A coffee-break discussion among educators will generate many possible reasons for the dissatisfaction expressed in student evaluations:

- Physics is difficult, and students do not like to think or work hard.
- Student evaluation of instructors is nothing more than a popularity contest.
- Students should be asked to rate their courses and instructors after they have been out of school for several years and have developed a more mature outlook.
- Student evaluations are unreliable and not useful for improving instruction.

Civian and Brennan (1996) and Aleamoni (1987) summarize the available research on these hypotheses, and it appears that most of them are not supported by evidence. For example, they found that most students, contrary to popular opinion, value difficult but worthwhile courses more highly than easy courses.

A number of studies show that students do distinguish between an instructor's personality, sense of humour and classroom manner and that instructor's effectiveness as a teacher (Aleamoni 1987, 27). Thus, an instructor's personality does not strongly affect the students' evaluations of the instructor's teaching skills.

Drucker and Remmers (1950) asked students who had been out of school for five or more years to rate their former instructors. These ratings correlated strongly with those of the instructors' current students. We have all met students who have fond memories of past teachers whom they did not appreciate until much later, but the research suggests that such reappraisals are the exception, not the rule.

The reliability of student evaluations, which are widely used at universities, is easily established by the robustness of the ratings over the years. Measurements of reliability are often over 0.9 if the evaluation questionnaire has been constructed with care.

Many years ago, an Alberta high school physics teacher asked me for a consultation about his physics teaching. His classes had achieved the top rating on the provincial achievement exams in physics for three consecutive years, but not one of his students had elected to take physics in university, except as a compulsory subject for another program. The teacher felt that his approach was effective in teaching students the physics skills and knowledge necessary for passing exams. But, he suspected, in focusing on achievement, his students had developed a strong dislike of physics. In contrast, an Alberta physics teacher whose students regularly went on to honours physics programs was forced into early retirement by a school administration that did not appreciate the fact that his classes achieved only the provincial average on the achievement exams. These two examples raise the question of what the primary goals of our teaching should be.

After doing my research, I asked my class of future physics teachers about their perception of the value of the physics courses they had taken and the effectiveness of their physics instructors. I had expected these students to be appreciative and understanding of physics courses and instructors. I was in for a great surprise! Some of their responses follow:

- Physics courses at university seem to be designed to weed out students for professional faculties.
- There appears to be little attempt to apply physics to everyday life or to provide a modern perspective on physics.
- Instructors seem to be obsessed with covering content rather than increasing students' appreciation of physics.

- Physics instructors at university show little evidence of pedagogy in their planning of lessons.
- There seems to be much more emphasis on high grades than on understanding.
- Physics lecturers show little enthusiasm for teaching introductory physics.
- Physics courses tend to focus on mathematical problem solving rather than conceptual understanding.

These criticisms were directed at university physics, not high school physics. But the obsession with covering content, competitiveness, the lack of interesting applications and so on probably also apply to high school physics. In fact, Ford and Wilde (1999, 222) report that in the U.K. enrolment in A-level physics (the highest level in secondary education) fell from 46,000 in 1988 to 33,000 in 1996, with the most frequent reasons given being “Physics is too difficult” and “Physics is boring.”

My physics education students expressed surprise and dismay that many physics instructors show little enjoyment of or enthusiasm for physics in their lectures. It is indeed surprising that people who have chosen physics as a career do not seem enthusiastic about the subject that plays such an important role in their lives. A possible reason for this is that many physicists, and perhaps also physics teachers, are quite introverted and reserved in showing how much they love physics. Another possible reason is that most physicists and physics teachers, lacking a background in the history of physics, do not really appreciate the intellectual beauty of introductory physics. Developing a more historical perspective on classical physics helps to keep one’s enthusiasm going, even when teaching introductory physics. Enthusiasm is a lot more infectious than knowledge, and enthusiasm can last a lifetime.

A further criticism, commonly raised in the literature and by my students, is that physics courses focus too much on mathematics and not enough on physics. My education students asserted that being good at problem solving is not the same as understanding physics. In fact, the research literature emphasizes that conceptual understanding of physics does not automatically accompany problem-solving facility. For a review of the research and recommendations for teaching, see Brouwer (1995).

Recommendations

Tobias (1990) notes that a common complaint about physics instruction, from those who do not continue studying physics, is that it is almost impossible to obtain an overall view of physics, or even of the area of physics covered by a particular course. Treating the theories of physics as human inventions helps to make physics more dynamic, and helps instructors and students to look for evidence to support the theory and for shortcomings with which we may now, at the beginning of a new millennium, be well acquainted.

Strategies for improving physics instruction suggested by Tobias (1990), the American Association for the Advancement of Science (AAAS) Project 2061 and others include the following:

- Become more familiar with the history and philosophy of physics.
- Include the perspective of modern physics in every course, especially introductory physics courses for general students.
- Organize physics curriculum topics around a storyline or theme.
- Focus on conceptual understanding as well as mathematical problem solving.

Know the History and Philosophy of Physics

Knowledge of the history and philosophy of physics can enrich your teaching immensely by providing a perspective that appeals to many students. Read, for example, the reflections on physics of great physicists such as Einstein, Heisenberg, Schrödinger and Feynman. These can be read as interesting literature and need not take time away from preparation or other interests. A corollary of this recommendation follows.

Incorporate Modern Physics

Include the perspective of modern physics in every course you teach, especially introductory courses for general students who will likely not pursue physics. Of course, including modern physics means that you will cover less of the classical material. But if this strategy leaves students with a better overview of physics as a science, a better attitude toward physics and perhaps a desire to take more physics courses, then the decreased material covered is a small price to pay.

Use a Storyline or Theme

Organizing physics curriculum topics around a theme designed to engage students' interest gives them a continual explicit overview of the course and an understanding of how each piece of their learning fits into the whole course. A theme also allows curriculum developers to restrict the course content by including only topics that contribute to the development of the theme.

Themes suitable for introductory physics include the following:

- Physics as an experimental science
- Physics concepts as being developed throughout history
- The physics of everyday events
- Introductory physics and our solar system
- Household electricity
- Conservation laws in physics
- Physics in the medical and biological sciences

Any of these themes would serve to unify and create interest in a variety of units in high school and even university physics. We need no longer have over 90 per cent of our students stating that they are taking physics only to fulfill requirements.

Aubrecht, Holbrow and Rigden (Wilson 1997, 259–64) report the interesting conclusion reached by participants in a miniconference on physics curriculum: "And here there was considerable agreement: an introductory physics course must have a story line." They express surprise that this idea of using a storyline to connect physics to students' experiences or interests was strongly urged by many conference participants. A possible storyline suggested is the experimental evidence for quantization in nature.

Holcomb (1994), director of the U.S.-based Introductory University Physics Project, promotes three physics curriculum emphases:

- The physics course should display a theme or themes that convey to students a coherent structure of the course.
- Contemporary physics should be a prominent and integrated component of the course.
- The number of topics treated should be reduced in comparison with the traditional introductory physics course, and the topics should be relevant to the theme(s) selected.

Amato and colleagues (Wilson 1997, 153–58) report on their revitalization of the introductory physics course at Colgate University in Hamilton, New York. They aimed to increase student interest in physics and to entice students to continue studying physics and astronomy. For their introductory course they chose the central theme "Why do we believe in atoms?" and for the second course they chose the themes "Where in the universe are we?" and "How do we know where we are?"

Hobson (Wilson 1997, 285–90) has developed a physics course aimed primarily at liberal arts students at the University of Arkansas. The course is based on the principle that less is more, and it emphasizes modern physics, the philosophical and cultural implications of physics, and qualitative as well as quantitative methods. Four themes unite the course:

- How do we know what we know in science?
- What is the relationship between Newtonian physics and modern physics?
- What is the current social context of physics?
- Energy as a unifying concept in physics.

The idea of using a strong unifying theme for introductory physics courses at universities and high schools is gaining widespread acceptance across North America, and the time is appropriate for Alberta curriculum reform to lead the way in Canada.

Focus on Conceptual Understanding

Another shortcoming of traditional physics instruction has been uncovered by physics educators including McDermott (1984) and Posner et al. (1982), who have shown that most high school graduates and many university graduates still hold misconceptions in physics. The traditional idea that you do not really understand physics unless you can solve problems should give way to the idea that you do not necessarily understand physics if you are adept at solving problems. The research shows that physics educators have neglected to promote conceptual understanding of physics.

At least 30 per cent of the questions in my assignments and on my exams are conceptual questions. My students soon realize that I am serious about encouraging conceptual understanding, and they begin to seek this understanding in their study and review.

Conclusion

I have always been proud that, on evaluations of my courses, students answer the question "As a result of this course, I would like to take more physics" (or, on the latest questionnaire, "I would like to know more about these topics") with a resounding "Yes." With such a response, I feel that these students will appreciate physics for the rest of their lives. I recommend that curriculum projects be organized more explicitly around the goal of creating deeper, longer-lasting interest in physics.

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A New Perspective for Teaching Physics in the 21st Century

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The study of physics allows us to pursue fundamental questions of nature as we grapple to learn more about the world in which we live and our relationship with it. As we come to understand nature by way of the concepts of science, we develop a better understanding of ourselves.

Few dispute the claim that physics is the heart and soul of science. In physics, we lay the foundation for organizing interactions across an inconceivably vast space and the Lilliputian dimensions of the atomic world. Physics provides the means and tools for studying geological and biological processes, and it connects the book of nature to the book of mathematics.

Why, then, are students not beating down our doors to study physics? Why does physics seem reserved for a special few? What have we accomplished in physics education if 99 per cent of students never go beyond high school physics and conveniently forget all the physics they have been taught the instant they lay down their pencils after the final exam? Should we not want these students to see physics in the world they will inherit, in the context of their intellectual and empirical understandings, and in the decisions they will make for themselves and their communities?

Recent reforms in physics curriculum are guiding us into a new century of physics education. How will these reforms change physics education? Are we heading into a new era of instructional enlightenment, or can we expect more of the same? In this article, we briefly examine the historical development of physics curriculum and instruction, look at the significant factors influencing curriculum and instruction, and suggest opportunities to forge a more enlightened view of physics and physics instruction today.

Brief History of Physics Curriculum and Instruction

Historians of science generally argue that physics education began with the Greek schools of natural philosophy. However, in terms of widespread public education in North America, physics education as we know it today has its roots in the preparatory (prep) schools that began to emerge in the 18th and 19th centuries. By the middle of the 19th century, dozens of academies in New England were preparing students for university entrance. Only the elite pursued higher education, and instruction was dominated by the teacher and the textbook. Rosen (1954, 194) quotes Elbridge Smith, the first headmaster of the English High School in Cambridge, Massachusetts, who commented on the science instruction of 1847:[1]

> In science the instruction was wholly by catechism. There were illustrative diagrams in the textbook which might, or might not, be explained and might, or might not, be transferred to the blackboard . . . . Not a single particle of apparatus or a book of reference except the Bible and possibly a dictionary.

National and provincial curricula did not exist, and textbooks written by those deemed experts in the field became the curriculum.

Although instruction centred on the textbook, some professors began to advocate the use of demonstrations to improve learning. In 1847, the Boston School Committee listed an expenditure of $260 for scientific apparatus such as pulleys, levers, capstans, pumps and even an eyeball for dissection. By 1899, most high school textbooks and laboratory manuals included quantitative measurement as a major component (Kapuscinski 1981).

By the second half of the 19th century, several factors worked to encourage the inclusion of laboratory science in schools. Applied physics, such as pneumatics, began to play an important role in everyday life and in industrialization. Moreover, graduate students who had studied at foreign universities returned to North America influenced by the European attitude toward science—an attitude reflected in the popularity of scientists such as Pasteur and Lord Kelvin and in the inclusion of physics as a mandatory subject in the German Realschule and the French École Polytechnique.

Riding the wave of economic and population expansion, and fostered by the 1862 U.S. federal government land grants, new universities began to emerge throughout North America. Admission requirements began to change, and curriculum reform witnessed old subjects such as Latin and Greek being dropped in favour of the sciences. During this time, the world became smaller as new technologies, such as steam power and the telegraph, began to improve communication and fuel the development of transportation and the expansion of competition.

The curricula at most prep schools reflected varying degrees of emphasis on the sciences, but the instructional approach remained strictly didactic. Rosen (1954) notes that in 1880 only 4 out of 176 school systems offered a course in laboratory physics. However, universities motivated prep schools to include laboratory instruction by changing their entrance requirements. Rosen (1954, 200) quotes Harvard University's 1887 admission requirements, which now included "a course of experiments in the subjects of mechanics, sound, light, heat, and electricity, not less than forty in number, actually performed by the pupil." Harvard now required candidates to write an entrance examination that tested their ability to perform experiments and use apparatus correctly. This challenge from the university for high schools to include science instruction uncovered shortcomings in the preparation of teachers. In response, Harvard produced the Harvard List, which contained standard experiments and procedures.

The introduction of laboratory methods was instantly contentious. Critics protested that the cost was prohibitive and the methods suspect. Even more problematic, schools had trained few teachers in laboratory science, and the courses relied too much on quantitative methods and abstract mathematics. Rosen (1954, 202) quotes Professor Payne, of the University of Michigan, who in 1887 wrote in the journal *The Academy* that the laboratory method "assumes all knowledge can be presented in such a manner, and that a student is to be a specialist, a scientist and that the only proper mode of teaching is by inductive, experimental research."

Rosen (1954, 197) also quotes C. R. Mann, a physicist who claimed that, according to his analysis of the state of physics teaching in 1910, "laboratories have not solved the problems of science teaching . . . . We do not know how to use laboratories effectively." Mann cited three major problems: poor teachers and textbooks, a focus on passing examinations, and no connections to the daily life and problems of the student.

In response to this criticism, Harvard modified its list in 1897 to include 50 per cent instruction in laboratory experiments (today reduced to 35 per cent) and 50 per cent instruction from the textbook. By the early 20th century, E. H. Hall's (1904) lab manual for the Harvard List was the standard textbook for laboratory science. This model of physics instruction spread rapidly throughout North America, and the number of schools multiplied rapidly because all states had compulsory education by 1918. The Harvard models of mechanics, sound, light, heat and electricity had established the core of all physics textbooks published for years to come. As the curriculum became cast in stone, using alternative instructional techniques was the only means to improve physics education.

In the post–World War II period, Weaver and Webb (1951) boldly stated that the country with the best scientists wins the wars.[2] In the U.S., the desire to maintain technological supremacy led to a curriculum based on a new instructional methodology—inquiry-based, or discovery, learning. Inquiry-based learning methods promote the observation of phenomena and an inductive progression from facts to theory. Students behave like little scientists and discover the laws of nature through their investigations. Many popular textbooks of the time, such as the Physical Science Study Committee's (PSSC 1961) *PSSC Physics* and the Biological Sciences Curriculum Study (BSCS) biology textbooks, were adopted throughout the world.

The curricular reforms of the 1960s were heralded as a significant break from the past. Shymansky, Kyle and Alport (1983) mark a clear delineation between traditional curricula and the new inquiry-based paradigms of instruction. They define the new curricula as those that

- were developed (with public or private funds) after 1955;
- emphasize the nature, structure and processes of science;
- integrate laboratory activities into the core of the instruction; and
- emphasize higher cognitive skills and an appreciation of science.

They define traditional curricula as those that

- were developed before 1955, or patterned after a program developed before 1955;
- emphasize knowledge of scientific facts, laws, theories and applications; and
- use laboratory activities as verification exercises or lesson supplements.

Although the intended curriculum emphasized higher cognitive skills, the implemented curriculum involved mostly the same old traditional approach to physics instruction. From a quick read of any modern laboratory manual in physics, higher-order cognitive thinking is not apparent.

What Does Educational Research in Physics Tell Us?

Early reflections on the state of physics teaching and learning primarily took the form of informed criticisms such as those found in the writings of John Dewey. Dewey was an educational philosopher who had been exposed to the natural sciences in his undergraduate studies. He had experience teaching high school and a keen interest in education. Dewey reasoned that the psychological processes of learning should guide instructional techniques. He espoused the benefits of facilitating individual experiences by actively engaging the learner with his or her environment. For Dewey, it was not enough to fill students through "information hoppers" with an abundance of scientific facts. Individual experiences were the raw materials the learner used to formulate meanings.

Dewey (1910) criticized the educational practices of the time that treated science as subject matter, which were "breaking down because of its sheer mass." However, his rationale for engaging students in practical work went beyond the common notion that the lecture and textbook are not enough: "Many a student has acquired dexterity and skill in laboratory methods without it ever occurring to him that they have anything to do with constructing beliefs that are alone worthy of the title of knowledge" (p. 124).

Dewey's philosophy and teachings perhaps led to a more humane and flexible school system, but his ideas relating learning theory and practical work were not embraced in instruction until many years later. However, his emphases on the experience and engagement of the learner and on the learning process would resurface in later curriculum reforms.

The decades following the curriculum reforms of the 1960s witnessed increased activity in educational research. Many periodicals began to publish research studies on the effectiveness of the reforms. Whereas some studies (Novak 1988) questioned the effectiveness of the laboratory experience, others (Harris and Taylor 1983; Millar and Driver 1987; Hodson 1992) turned their interest to philosophical review of inquiry-based methods.

Inquiry-based learning focuses on science process skills and emphasizes hands-on activities favouring observation, classification, measurement, and controlled experimentation using independent and dependent variables. Harris and Taylor (1983) claim that inquiry-based learning favours abstraction and the confirmation of theories. Abstraction implies the view that meaning is embedded in, and can be drawn out of, objects, and verification of existing theories is dogmatic and leaves no room for alternative explanations. Further, they assert that curriculum that uses inductive methods extensively, such as PSSC physics, describes the world as governed by universal, fixed laws. Programs like these suggest that the scientist's job is to uncover nature's laws. This naive view of science implies that a specifiable scientific method can be taught as a series of steps in the form of hypothesis, observation, measurement and generalization.

The problems of inquiry-based learning led educators to critically reappraise its principles and practices. They found that students were never challenged to employ, by developing and evaluating their own ideas, any skills they had learned. Further, students rarely put forward their own ideas about the physical world, and there was never enough time to pursue individual interests. In other words, the practical implementation of the reforms was merely traditional instruction disguised as inquiry. After many years, educational researchers began to concentrate their efforts on cognitive issues, and analysis of the cognitive domain emerged in the 1980s as the dominant type of research in science education (Yager 1992).

The 1980s ushered in a period when new ideas about conceptual developmental models describing how students learn science were widely published and discussed. The work of New Zealand physics educator Roger Osborne is especially relevant to our discussion. Osborne (1984) found that young students understand motion (dynamics) around them using a sequence of mini-theories that he labelled "gut dynamics," "lay dynamics" and "physicist's dynamics."

Gut dynamics is intuitive, spontaneous and largely nonverbal, and it allows children to cope with common occurrences around them. Examples of gut dynamics are the ideas that heavy things fall faster and that things need a push to get them going.

Lay dynamics is based on the form and content of the language the children grow up speaking and the images conveyed by those with whom they are in contact and by the media and the books they consume. Examples of lay dynamics are the ideas that astronauts are weightless in the space shuttle and that if there is no force, there is no motion.

Physicist's dynamics is the counterintuitive world of physics texts, experiments and problems students solve in class. Osborne (1984) found that students could learn physicist's dynamics that enabled them to operate in the idealized world of the physics laboratory and the physics exam. Unfortunately, many did not develop an integrated and coherent view of dynamics and retained a mixture of gut and lay physics. As Osborne puts it, "Gut dynamics enables one to play hockey, lay dynamics one to talk about *Star Wars,* while physicist's dynamics enables one to do physics assignments. There is no problem!" (p. 506). What worries physics educators is that a high percentage of students, even though they can solve fairly sophisticated physics problems, still operate with gut and lay physics ideas in everyday life.

A plethora of informative, well-argued articles on the topic of dynamics (McCloskey 1983; Terry and Jones 1986; Reif 1987; Sadanand and Kess 1990; Finegold and Gorsky 1991; Gunstone and Watts 1994) began to appear in science and physics education journals. A comprehensive article by Hestenes, Wells and Swackhamer (1992) summarizes the researchers' main findings:

- Common-sense beliefs about motion and force are generally incompatible with Newtonian concepts.
- Conventional physics instruction produces little change in these beliefs.
- This result is independent of the instructor and the mode of instruction.

The most surprising finding was that misconceptions seem to spontaneously disappear for physics majors. Especially interesting is "the paradoxical fact that few physicists can recall having believed, let alone having overcome, any of the misconceptions" (p. 151). The authors insist, however, that research has established unequivocally that everyone has such misconceptions before learning physics—even the great physicists. Physics teachers, too, forget the conceptual struggle they underwent in achieving an expert understanding of the notion of force in Newtonian physics. They teach lessons that to them are of exemplary clarity and believe that the lessons will also be clear to the students. The influence of this "force concept inventory" on physics education cannot be overestimated, even though many criticisms have been levelled against this research.

As a result of this extensive research, the international science education community seems to have concluded that the findings have serious implications for the teaching of physics:

- Students' common-sense beliefs should be regarded not as misconceptions but, rather, as reasonable hypotheses grounded in everyday life.
- Students should be encouraged to articulate these hypotheses, which are generally based on personal kinesthetic memory.
- Physics teachers should make it a priority to identify these hypotheses. This act should be regarded as a necessary but not sufficient prerequisite to successful physics teaching.
- Physics teachers should try to overcome students' misconceptions by presenting the coherent conceptual system of Newtonian physics in new and interesting ways.

How do we accomplish this task? In the past, we relied on textbooks to guide our instruction. Can we realistically rely on textbooks to evaluate and integrate what research in physics education tells us? If not, what then?

The Role of the Physics Textbook

A little over 20 years ago, noted physicist and physics educator A. P. French (1981) wrote an article called "Fifty Years of Physics Teaching" in which he argued that two ambitious programs had transformed the teaching of physics in high schools. The first was the PSSC, which was formed in 1956, a year before the launching of *Sputnik.* The program's goal was to "develop a course that would present physics not as a catalogue of facts and formulas to be learned, but as an intellectual adventure concerned with exploring and understanding the real world" (French 1981).

It is generally believed that the launching of *Sputnik* precipitated national paranoia in the U.S. about the inadequacy of science education in general and physics in particular. To be sure, *Sputnik* gave the new program a much-needed impetus. For the next four or five years, a monumental effort was mounted to produce a radically new course, with a textbook, teachers guides, tests, laboratory experiments, films and supplementary monographs. The PSSC approach captured a substantial portion of the high school population. By the early 1970s, it had replaced a significant percentage of traditional high school physics courses. According to French (1981), this influence reached much farther because various features of the approach were incorporated in other widely used textbooks. We both started our physics teaching careers using this approach in Canada—Arthur Stinner in the late 1960s and Don Metz 10 years later.

In a later article on physics education, French (1988) puts his finger on the inadequacy of textbook-centred teaching:

> This tends, among other things, to give the impression that science is a closed and completed body of knowledge and, furthermore, that one need not look beyond the textbook to acquire it. . . . Therefore, I regard the development of radically different types of textbooks as almost inseparable from the development of more enlightened and more effective physics courses.

The Harvard Physics Project (HPP) was a history-based approach developed by Gerald Holton and others in the late 1960s. The HPP promoted a more enlightened treatment of physics with a more humanistic view grounded in history. Initially successful, the historical approach diminished as its supporting system of teacher development was gradually removed. Holton and Brush (2001) have reintroduced the historical approach in their recent book *Physics, the Human Adventure: From Copernicus to Einstein and Beyond.*

In science, teaching by the textbook plays a dominant role and dictates both what is taught and how it is taught. Noted science educator Robert Yager (1992), after examining science textbooks in the U.S., ironically states that the most significant decision a science educator makes is the choice of a textbook. He goes on to suggest that textbooks imprison science teachers in the belief that the instructional sequence of assign, recite and test produces knowledge. He asserts that science courses almost never offer direct experience, and laboratory work, if it occurs at all, is of the deductive–verification type. Relying on textbooks does not seem to produce scientifically and technologically literate people, he concludes.

In the textbook-oriented mode of instruction, students are indoctrinated into a nonskeptical acceptance of an inductivist–empiricist picture of science. Moreover, learning is seen as a slow accumulation of knowledge through practice, where the learner is assumed to be, in the John Locke tradition, a tabula rasa. Science teachers have learned their science from textbooks, and they teach from textbooks that largely emphasize memorization of scientific facts and recitation of algorithms in an ongoing rhetoric of information.

Thomas Kuhn (1962, 166) clearly and without apology acknowledges the dogmatic nature of textbook-centred science education: "Though scientific development is particularly productive of consequential novelties, scientific education remains a relatively dogmatic initiation into a pre-established problem-solving tradition that the student is neither invited nor equipped to evaluate."

According to Kuhn (1962), what distinguishes science teaching from teaching in the humanities is its almost exclusive reliance on textbooks. Kuhn argues that textbooks are the pedagogic vehicles for the perpetuation of "normal science." Textbooks excel in demonstrating exemplars—that is, model solutions of what scientists consider to be an important class of problems. Kuhn believes that exemplars are at the heart of the education of both the student of elementary physics and the mature scientist working within the confines of "normal science."

Though it is generally true that different science textbooks in a given science display different subject matter, Kuhn (1962) believes that they do not differ significantly in substance and conceptual structure. In the humanities and many social sciences, on the other hand, textbooks differ fundamentally in the way they "exemplify different approaches to a single problem field." It is interesting to note that, in the mature sciences, "there is no apparent function for the equivalent of an art museum or a library of classics. Scientists know when books, and even journals, are out of date" (p. 256). When science changes, textbooks are rewritten to accommodate the change. However, these changes are made mostly to the content, not the approach; textbooks have clearly not adapted to what research tells us about students' conceptual understandings, their view of the nature of science, and active and meaningful engagement.

Conclusion

Although textbooks guide curriculum and instruction in physics today, they have failed to evolve beyond being compendiums of exemplars. Senior students should go further to develop a deeper understanding and the ability to generalize across diverse connections. The unrealistic expectation of textbook developers is that students will be able to extend their understanding of exemplars to the world in which they live. It is our position that physics instruction must become more contextual so that students can find more personal relevance in learning physics. In this way, physics becomes more a way of thinking about the world in which we live and less an encyclopedia of laws and theories.

A general problem emerges whenever teachers try to escape from textbook-centred teaching. To motivate students to acquire content knowledge, teachers use contexts that attract them. However, students often cannot deal with the questions and problems that the context generates unless they already have some content knowledge. To combat this problem, there are many excellent approaches that use active-learning strategies that blend well with a contextual and/or historical approach.

Such innovations in science teaching today are all based on recent research in physics education and all seem to rest on one basic premise: actively engaging the student results in a better learning experience. These innovations can be placed in the following broad categories:

- Microcomputer-based laboratories
- Active engagement in lectures
- Collaborative learning
- Structured problem solving

Good examples of microcomputer-based laboratories are Workshop Physics, a pedagogical method created by Priscilla Laws and her group at Dickinson College in Carlisle, Pennsylvania, to replace the standard calculus-based physics course, and the Web-based virtual physics experimental site Physics 2000 (www.colorado.edu/physics/2000/index.pl). Harvard physics professor Eric Mazur (1997) and the physics education research group at the University of Minnesota (http://groups.physics.umn.edu/physed/) have developed context-rich problems for collaborative learning. Structured problem solving is used by the University of Washington Physics Education Group (www.phys.washington.edu/groups/peg/), which has developed a series of exercises to help students with conceptual difficulties. Finally, we would like to mention the work in improving physics education done by our colleague Wytze Brouwer at the University of Alberta. His collaborative approach, which replaces the conventional lecture-centred teaching of large classes in first-year physics, is well described in Brouwer (1995).

In textbooks, we are seeing a shift toward recognizing the importance of embedding teaching in rich contexts, as well as paying serious attention to science educators' research in conceptual development. We recommend that textbooks also incorporate the history and nature of science in more effective ways than merely placing entertaining vignettes in the text.

Cutting the umbilical cord to conventional textbook-centred teaching will be successful only when textbook writers and physics teachers have a deeper understanding of the qualitative and quantitative requirements of good physics teaching and how students learn physics concepts. This is a necessary but not sufficient requirement for good science teaching. Teachers and textbook writers must also have more than a cursory acquaintance with the history and nature of science. In developing a new perspective on instruction in this century, we hope that all the fine attempts mentioned rise above the conventional textbook-centred, lecture-centred teaching of physics to foreshadow a new kind of physics teaching for the future.

Notes

1. At this time, instruction in the sciences was more integrated and was referred to as natural philosophy. The physics topics as we know them—kinematics, dynamics, electricity, waves, atomic theory—were predominant in this curriculum.

2. This claim reverberates today on our television screens as they show laser-guided missiles obliterating their targets with uncanny accuracy.

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Disadvantages of Traditional Physics Teaching and a New Way to Teach Problem Solving for Conceptual Understanding

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Many studies of students' ratings of university courses and instructors, such as Cashin's (1990) study, have revealed that most students rank physics courses in the lowest category with subjects such as engineering, computing sciences, mathematics and statistics, well below subjects such as fine arts, home economics, music and education. In terms of effectiveness, physics instructors were also ranked in the lowest category. Some physicists interested in physics education reflected on these results and offered general suggestions about how to make physics more appealing to students (Brouwer, Austen and Martin 1999). However, as far as I know, no study has aimed to find out how the negative attitude toward physics developed.

We can explore the unpopularity of physics courses and instructors from different angles, looking at the physics curriculum, the teaching approach and the subject itself; however, the teaching approach is the fundamental factor. To understand how teachers are teaching physics and students are learning physics, I conducted a classroom-based research project in the winter and fall terms of 2000. In this article, I report my findings on the negative consequences of traditional teaching methods and suggest ways to improve physics teaching, particularly a new way to teach problem solving for conceptual understanding.

Methods

The study was conducted over two terms and involved more than 700 university students. The 552 participating students in the winter term came from the six sections of an algebra-based first-year physics course, and the 160 students in the fall term came from the two sections of a calculus-based first-year physics course. The two courses covered the same topics, including kinematics, dynamics and heat, but the calculus-based course was more challenging.

This study employed multiple methods, including tests, surveys, observations, interviews and consultations. I administered a conceptual test to all the students at the end of each course. The test instrument, FCI-Plus, was a combination of the Force Concept Inventory (FCI) (Mazur 1997) and three conceptual questions taken from the literature (Berg and Brouwer 1991; Whitaker 1983). The FCI contains 30 conceptual questions and has been widely used for testing the effectiveness of physics courses (Hake 1998; Redish, Saul and Steinberg 1997; Redish and Steinberg 1999). I also surveyed all the students at the beginning and the end of each course to collect information about their attitudes toward physics and physics instruction. The survey included Likert-scale questions asking students to respond to statements with *very true*, *true*, *uncertain*, *not true* or *not at all true*. I also regularly observed the classes and reviewed students' assignments (interviewing students if necessary to clarify what they had written). I also set up a physics clinic, welcoming students to come for help with questions. I kept observation journals for each class and recorded most of my interviews and consultations with students.

Negative Consequences of Traditional Physics Teaching

Brouwer (1995a) discusses the common shortcomings of traditional physics lectures, including the lack of connections between classical physics and the frontiers of physics, too many examples of problem solving, too many topics at the expense of quality, little encouragement of and opportunity for students' intellectual involvement, and little interaction between the instructor and the students.

In the classes I studied, I found all these shortcomings, particularly too many examples of problem solving. A great part of the lectures focused on providing examples; worse, the examples took similar formats and were too detailed in derivation. Students were kept busy copying what was on the board and, consequently, had limited time for thinking. Mazur (1996, 13) vividly describes this kind of teaching:

> We require the students to buy textbooks of encyclopedic dimensions, and then we use lecture time to present what is printed in the text. We write the material on the blackboard, and students copy it into their notebooks. If we are lucky they can follow the first 15 minutes of the lecture. If they lose the thread somewhere—and this is bound to happen sooner rather than later—note taking becomes completely blind: "I'll think about it later." Unfortunately, the thinking is not always happening, and many students resort to memorization of the equations and algorithms copied in their notebooks.

As Mazur (1996, 13) writes, "Many bad study habits are a direct result of the lecture system." In this article, I focus on three negative outcomes of problem-solving–oriented teaching:

- Students' declining attitudes toward physics
- Students' poor performance in conceptual understanding
- Students' difficulties in problem solving

Students' Declining Attitudes Toward Physics

Table 1 shows that the students in my study were less likely to perceive physics as being interesting and science as being a major force for social development at the end of the course than at the beginning of the course. They also were more likely to perceive physics as being hard to learn at the end of the course than at the beginning.

These results are consistent with the findings of Redish and Steinberg (1999), who, based on survey results from more than 1,500 students from six colleges and universities, concluded that "the percentage of students with favorable attitudes tends to deteriorate as a result of traditional instruction." These results are also consistent with the studies revealing the unpopularity of physics courses and instructors.

Why did more students think physics was uninteresting and hard to learn at the end of the course? The reason is problem-solving–oriented teaching. Students spent most of the class copying what the instructor wrote on the blackboard and, consequently, had little time to think and to ask questions. They were not

Table 1
Attitude Survey Results

	Winter term (n = 552)		Fall term (n = 160)	
	Pre-test	Post-test	Pre-test	Post-test
Students who viewed physics as interesting (%)	67	63	94	87
Students who viewed physics as hard to learn (%)	42	44	35	44
Students who viewed science as a major force for social development (%)	91	85	97	88

given the opportunity and not encouraged to make sense of physics and enjoy its beauty. Quantitative examples followed every formula introduced in the lecture, and the exams asked students to solve similar questions. This led students to think that learning physics was nothing more than learning to use the formulas.

Brouwer (1995a) tried a new way of teaching—letting students suggest a method for problem solving and then applying that method. If the method led to an incorrect solution, the students and the instructor then analyzed together where they had gone wrong. Some students were puzzled by this approach and commented, "Dr. Brouwer, why don't you just do the problem the right way? We don't have to learn how not to do it" (p. 291).

When half of the university students who took three semesters of traditional physics instruction stated, "All I learn from a derivation or proof of a formula is that the formula obtained is valid and that it is OK to use it in problems" (Redish and Steinberg 1999), the students were not to blame. In the frame of traditional teaching, it is unlikely that students will take as the goal "an understanding of the limitation of those formulas or the relation of the formula to fundamental principles and concepts" (Redish and Steinberg 1999).

Students tend to focus on "recipes" for standard problem solving. Unfortunately, no single strategy works for all questions; thus, students must have a deep conceptual and qualitative understanding of physics processes and concepts. A student in my study pointed to the board and told me, "I can understand what is on here, but I have problems with assignments and exams. I did poorly on the midterm." I knew what she meant by the word *understand:* she could follow the derivations of the sample question the instructor had written on the board, but she did not in fact understand the question. She did not know much about the following questions: What is the nature of the phenomenon in the question? How many steps does the whole process involve? How could the process be represented qualitatively in physics language? When students remember and place their faith in a recipe and then it does not work at a critical moment (such as during an exam), how do they feel? Frustrated! How boring physics must be when it is portrayed as a set of recipes that do not even work all the time! What an unfair treatment of the colourful aspects of physics! No wonder students come to class with an interest in and a thirst for physics but leave with a feeling of annoyance.

Students' Poor Performance in Conceptual Understanding

Studies have long documented the importance of conceptual understanding. In the 1980s, a number of studies revealed that students could memorize the facts they learned in class but were often not able to use those facts to build arguments, make predictions, explain observed phenomena, solve real-world problems, and read and think critically (Carey 1986; Champagne, Gunstone and Klopfer 1985). As a result of these studies, many educators supported a shift from an emphasis on facts and results to a new emphasis on teaching for conceptual understanding (Anderson and Smith 1987; Hiebert 1986). However, in the 1990s, ignorance of conceptual teaching still existed. Many scholars continually called for a focus and strategic change to physics teaching (Brouwer 1995a, 1995b).

During my study, I found that most instructors did not pay enough attention to conceptual teaching and learning and probably did not recognize its importance. After one class, I had the following discussion with the instructor:

> INSTRUCTOR: Is it boring? It is old stuff for you.
>
> RESEARCHER: No. You know, I am not learning physics now. I am learning how students learn and how teachers teach, especially about concepts.
>
> INSTRUCTOR: Unfortunately, not much is on concepts for this course; lots on problem solving.

This informal talk revealed the instructor's perspective on conceptual teaching and learning. His comment was far removed from the cognitive studies that tell us that students have great difficulty learning mechanical or heat concepts (Zhou 2002). The instructor likely did not emphasize conceptual teaching, as the intensive studies recommend.

A direct negative consequence of traditional physics teaching is students' poor performance in conceptual understanding. Table 2 shows the results of the FCI-Plus test of students' conceptual understanding. All the class means are below the pass line (80 per cent) set up by the FCI developers.

Students' Difficulties in Problem Solving

Based on class observations and clinical consultations, I concluded that the students' troubles in problem solving resulted from several disadvantages.

First, the students did not have the necessary skills for physics problem solving. They did not know where they should start. "So many variables. How can I know which variable I need to find out from which process?" a student complained when she came to my clinic for help. For a question involving two masses hanging from a fixed pulley, the students did not know how to set up a coordinate system. "Do we need to know which mass is bigger to decide if the acceleration is upward or downward?" one student asked in the class when the instructor set the coordinate upward. The student did not know that the set-up of a coordinate system is not absolute but, rather, determined by convenience.

Second, unfamiliarity with physics language was an obstacle for some students. They had difficulty understanding what the question was asking. They often failed to notice the known variables hidden in the text. For example, the students were given a question involving a boy who climbs onto a board sitting on two supports and then walks to one end. The question asked the students to find out how far the boy is from the end when the board starts to tip. Some students did not know that *starts to tip* means that the normal force exerted by one support is equal to 0.

Third, the students had problems with math, especially in the extremum (extreme value) questions. They did not know how to find the maximum or minimum value from an equation.

The fourth and most important disadvantage is that the students often attempted a mathematical solution without conceptually understanding the process in the question. Research on problem solving suggests that students should be able to describe a situation conceptually and present the problem qualitatively before attempting a solution (Driver and Warrington 1985). I quantitatively investigated the correlation between conceptual-learning achievement (measured by FCI-Plus scores) and problem-solving achievement (measured by a combination of the scores from the midterm and final exams) in three classes. The correlation coefficients were 0.481, 0.564 and 0.539, respectively. All three numbers were significant ($p < 0.01$). This indicates that success in problem solving positively correlates with conceptual understanding.

The students' assignments clearly demonstrated the difficulties they experienced in problem solving as a result of poor conceptual understanding. They began with numbers instead of qualitative analysis. They changed to a different equation when they discovered that their original equation did not work. I could see where they had crossed out lines and started again.

When I asked one student what she did when she had a question to solve, she replied,

> I start with numbers. Substitute the numbers into the equation. If it works, I am glad, but quite often it does not work. I get frustrated. When I get frustrated, I cannot concentrate on the question. Although I try a second time, it is often no use. I get even more frustrated. Finally I have to give it up.

I knew that by *numbers,* she meant *variables,* and I said, "Your strategy may work when the question has only one or two numbers. If the question has more than two numbers, it very likely does not work."

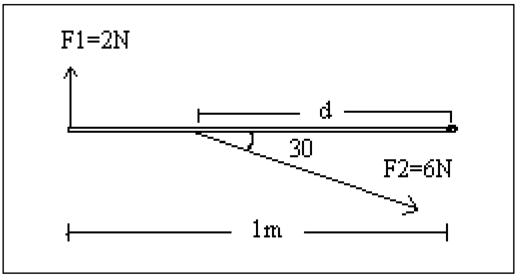
The student replied, "Exactly. I can solve the simple questions in the book, but I always have trouble with the complex questions, such as questions in assignments."

Table 2

Class Means on a Conceptual-Understanding Test

	Winter term						Fall term	
	Section 1 (n = 81)	Section 2 (n = 76)	Section 3 (n = 99)	Section 4 (n = 105)	Section 5 (n = 88)	Section 6 (n = 103)	Section 1 (n = 89)	Section 2 (n = 71)
Mean	18.3	17.6	16.6	18.1	18.4	18.0	20.5	23.0
Mean (%)	55.5	53.3	50.3	54.8	55.7	54.5	62.1	69.7

Figure 1
A Lever in Equilibrium with Two Forces Acting on It



For the simple situation illustrated in Figure 1, students are asked to find the distance *d* for which the lever is in equilibration. The following equation is often the first line of a student's solution:

$$2 \times 1 - 6 \times d \sin 30° = 0.$$

Students often skip the step of

$$F_1 l_1 - F_2 l_2 = 0,$$

an equation that represents qualitative understanding.

One day a student came to my clinic for help with the following question:

> A moving car plows into a stationary car, and then the two cars move together as a unit. What is their common velocity just after the collision?

I said, "Tell me what you did for this question, please." This was a routine in my clinic. Whatever questions the students had, I always encouraged them to express their thoughts first so that I could find out where they had gone wrong. Also, this thinking aloud helped students recognize their own errors.

The student said, "I know I need to use the conservation law of momentum." Then she wrote the equation $p_1 = p_2$ on a piece of paper and told me how she had found the answer:

> RESEARCHER: Great!
> STUDENT: But it does not make sense to me.
> RESEARCHER: What do you mean?
> STUDENT: Do you think the momentum conserves in a completely inelastic collision? I believe it conserves in an elastic collision. Two balls collide and separate.

I then did the deduction of the conservation of momentum similar to how the instructor had done in the class, and I reminded the student that I did not assume anything about the collision (whether the balls stick together or separate) when I did the deduction. She nodded, but I could see that she was still struggling to understand:

> STUDENT: When a ball hits another ball like this [she drew a picture of a moving pendulum hitting an initially static pendulum], if the balls exert equal forces on each other, the net force is 0. How can the balls move?
> RESEARCHER: Can you say that again?
> STUDENT: I think the first ball will exert a bigger force on the second ball. The net force keeps them moving forward.

Aha! Here was the problem! She distrusted Newton's third law and thought that force was necessary to keep the pendulum moving after the collision:

> RESEARCHER: Do you think we have to have a force for motion?
> STUDENT: Don't we? I apply a force on the pen. If the force is bigger than the friction, the pen moves.

I could not even count how many times students had done this kind of demonstration to present an argument. Similarly, I used a demonstration to convince her. I pushed the pen hard:

> RESEARCHER: Even though I stop pushing, it keeps moving for a while.
> STUDENT: Because you give it an initial velocity.
> RESEARCHER: Yes, the initial kinetic energy keeps it moving. It finally stops because of the friction.
> STUDENT: OK.
> RESEARCHER: In the case of the ball collision, the system has initial kinetic energy. During the collision, the system loses some of its kinetic energy, but not all of it. The remaining kinetic energy keeps the two balls moving forward together.
> STUDENT: I see.
> RESEARCHER: The two balls exert equal forces on each other. That is Newton's third law. Over 60 per cent of students incorrectly think that the first ball exerts a bigger force on the second ball.
> STUDENT: I am glad to hear that.

It is clear that the standard problem-solving assignment might be useless for some students, even if they get the right answer. The students did the assignment by modelling the examples the instructor had provided in the lecture, but they had little understanding. They picked up the equation they learned in the class because they knew that it was supposed to be used in the follow-up assignment.

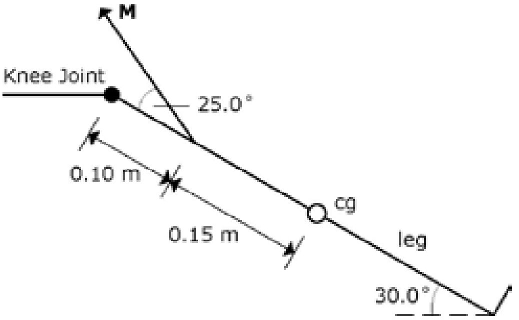
Here is another typical example. After he taught students about the centre of gravity, an instructor assigned the following question:

> As shown in Figure 2, a person is sitting with one leg outstretched so that it makes an angle of 30° with the horizontal. The weight of the leg below the knee is 45 N with the centre of gravity located below the knee joint. The leg is being held in this position because of the force *M* applied by the quadriceps muscle, which is attached 0.10 m below the knee joint. Obtain the magnitude of *M.*

A student came to the clinic for help with this problem. He wanted me to clarify the concept of the centre of gravity for him, but his real question was, “How can I use this equation [the definition of the centre of gravity] to solve this problem?” I was fooled for a while by his question. A possible explanation for his question is that he did not understand the concept of the centre of gravity at all. Because he saw the phrase *centre of gravity* in the problem, his first inclination was to figure out how to use the equation.

Figure 2

A Schematic of a Person Sitting with One Leg Outstretched



A Conceptual Way to Teach Problem Solving

Of the three negative consequences of traditional physics teaching, poor performance in conceptual understanding is the most critical. If students do not conceptually understand what they have learned and have no big picture of physics, we can hardly expect them to love physics. Moreover, students cannot become good problem solvers without having a good qualitative understanding. Physics instructors can improve their physics lectures in this regard through the following strategies.

Respect Students’ Conceptions

Studies show that students come to the classroom with their own understandings of the world. Instructors should pay attention to students’ conceptions rather than focusing only on delivering scientific concepts (Zhou 2002). The rewards of doing so are manifold.

Become Familiar with the History of Physics

Teaching physics in a nonhistorical context gives students the sense that physics is an absolute truth. Referring to the history of physics can bring life to the subject and make students realize its human aspects (Martin, Kass and Brouwer 1990). Also, historical materials can help students understand the origins and definitions of physics concepts (Zhou 2000).

Learn to Teach More Conceptually

Students have more difficulties in solving conceptual questions than standard problems. Instructors could discuss some qualitative questions during the lecture, assign conceptual questions for homework and include conceptual questions on exams. Eventually, the students will pay attention to the conceptual aspects of physics (Brouwer 1995b).

Get Students Involved

With about 100 students in the classroom, a passive lecture cannot get students actively involved in the learning process. Some physics instructors have successfully developed and applied techniques that engage students—learning teams, peer instruction and so on (Powell 2003).

Use Information Technology

The use of computers can free up time for discussion. Many instructors now combine lecture notes, texts, graphics, animations and links to more information into one hypertext. There are many computer-based simulations that can be used to help students learn physics (Zhou et al., forthcoming).

When I state the importance of conceptual understanding, I do not imply that problem solving is not important. Problem solving is undoubtedly an important tool in teaching physics. What I want to suggest is that we use an alternative approach to teaching problem solving that integrates conceptual understanding and problem-solving skills. In other words, we should teach problem solving for conceptual understanding.

Problem solving is not only essential for allowing students to practise what they have learned but also valuable in teaching for understanding. Historically, scientists have developed theories while solving a variety of problems, be they theoretical or practical. Problem solving, therefore, has two dimensions: applying knowledge and creating understanding. A popular strategy in science education—the project approach—is on the right track in terms of the second dimension. In traditional teaching, however, problem solving is most often employed only for knowledge application. After almost every equation, the teacher gives students detailed problem-solving examples. The teacher writes all the steps of derivation on the blackboard, and students are kept busy copying the steps in their notebooks. These examples function as models for the students when they are working on their assignments. In one class I observed, the instructor gave students a “recipe” (the instructor’s word) for solving dynamics problems, including free-body diagrams, equations and calculations.

To teach problem solving for deeper understanding calls for a different form of instruction, a more conceptual way of teaching. Compared with teaching problem solving by modelling, the conceptual method focuses not on the recipe for problem solving but, rather, on understanding the problem. It starts not with a free-body diagram but with the conceptual description and qualitative understanding of the process. It is open to students’ questions and ideas, instead of hurrying to cover more examples. It extends the problem into a big context instead of constraining it within a standard textbook style. Table 3 shows the differences between the two approaches to teaching problem solving.

The following are examples of effective and ineffective teaching strategies, in terms of teaching for deeper understanding, that I observed during my study. One instance of ineffective teaching happened in a class on circular motion. The instructor swung a ball and asked the students what force the ball exerted. Among other answers, one was “Weight.” The instructor replied, “We do not consider weight now, but we will discuss it later,” and continued. But the instructor never returned to this topic.

Another instance of ineffective teaching happened in a class on rotational motion. The instructor was demonstrating the solution to a problem that described a ball rolling down an

Table 3
Two Methods of Teaching Problem Solving

	Modelling	Conceptual
Focus of teaching	Recipe for problem solving	Understanding the problem
Function of teacher	Supply a model of problem solving	Teach for understanding
Process of teaching	No interruption so that more examples can be covered	Open to students’ questions or ideas
Format of teaching	Highly formatted	Flexible
Role of students	Copy in their notebooks what the teacher writes on the blackboard	Actively participate in the process of problem solving
Problem solver	The teacher only	The teacher and the students
Context of problem	Standard textbook format	Link to real-life context
Number of problems	Many	A few

incline without slip. The problem was to find the velocity of the ball when it reached the bottom of the incline. “Because there is no friction, we can apply the conservation of energy,” the instructor said. He wrote the equation on the blackboard and started to substitute values into the equation. A student asked, “If there is no friction, how can the ball roll down without slip?” The instructor replied, “The friction is small. It is negligible.” He then continued doing the calculation.

The moment a student asks a question is the moment he or she is thinking. Teaching students at this moment can be much more effective than passive lecturing. These two examples demonstrate missed opportunities for teaching. In the first, the instructor missed an opportunity to explain a fundamental principle of physics—simplifying real-life phenomena to physics problems: What factors can we ignore in what situations and for what purposes? In the second example, the student was correct. The instructor missed an opportunity to correct his own mistake. Disappointed, I wrote in my notebook after the class, “Why can’t the teaching be more driven by the students?”

An instance of effective teaching happened in another instructor’s class on circular motion. The instructor discussed a problem involving driving a car on a banked road. Instead of writing the question on the blackboard to start, the instructor asked, “How many of you have driven on Fox Drive?” Many students raised their hands. Then the instructor reminded them of the transitional section (banked and curved) from Whitemud Drive to Fox Drive and qualitatively discussed with them why the road is banked and why there are speed limits on the banked sections. Finally, the instructor brought some numbers into the problem and calculated the speed limit.

Another instance of effective teaching happened in a class about collision. The instructor gave students a problem involving a golf ball bouncing down a flight of steel stairs. The question asked students to find the height the ball can bounce from the bottom of the stairs, assuming that all the collisions with the stairs are elastic. The answer was found to be that the height of the bounce is the same as the vertical height of the staircase. However, the instructor did not stop here. He reminded students of the difference between this answer and their experiences. Students had never seen a case in real life that supported this solution. A discussion of the assumptions in the question followed.

In these examples of effective teaching, problem solving was not constrained within the standard format but, rather, was posited in a real-life context. In the first case, the instructor successfully encouraged students to think through a qualitative analysis to mathematical calculation. He not only drew physics closer to the students’ lives but also clarified the meanings of each component of the equation. If the teacher had written the question in a standard textbook format on the blackboard, the instruction would not have been as successful because it would have encouraged students to immediately follow, with little thinking, fixed steps they had learned from other examples; in other words, students would have first tried an equation rather than thinking qualitatively. In the second case, the problem solving was extended into evaluation of the solution. Through evaluation, students get to know how physics works and what its limitations are. It is hoped that this strategy can reduce the number of students who distrust physics or think it a mystery.

Concluding Remarks

In my physics clinic, I applied the conceptual method of teaching problem solving. I took the following steps to help students in their problem solving:

1. I asked the students to tell me what the question was about.
2. I encouraged the students to express how they had tried to solve the question.
3. I detected where the students had gone wrong.
4. I challenged the students’ wrong ideas.
5. I guided the students with step-by-step questions.
6. I reviewed the process with the students.

If the students had no clue how to solve a problem, I never simply told them how to do it. I believe that students should be the problem solvers and the instructor a facilitator. I always challenged students to think questions through step by step. Students often got excited when they solved a question by themselves with my help.

I told students that effective problem solving generally includes the following steps:

1. Read the question carefully.
2. Picture the process.

3. Conceptually or qualitatively analyze the process.
4. Set up equations.
5. Do the calculations.
6. Evaluate the result.

I made sure that students started their problem solving with a qualitative understanding of the process. When teaching dynamics, teachers too often persuade students to start with a free-body diagram. However, if the students do not understand the physical process, they have trouble drawing the diagram. Even if they can draw the diagram, they may not know how to deal with questions involving maximum or minimum values.

My experiences in the physics clinic confirmed for me that the conceptual method of teaching problem solving is an effective alternative to the standard modelling method. It emphasizes the conceptual or qualitative aspect of problem solving, which does not receive enough attention in traditional teaching, without sacrificing the mathematical aspect. The students' appreciation of what I did in the clinic encouraged me to promote this new teaching emphasis on qualitative understanding.

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Engagement Enhances Interest in Physics

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"Physics is not an easy subject; it requires a high degree of dedication" (Jordan 1994). This is a common belief about physics. As a student and teacher of science, I have many memories of friends, students and colleagues sharing their feelings about physics: "Physics is boring." "Physics is difficult." "Physics is for boys." "Physics is only for intelligent students." "Physics is irrelevant, not like biology, which can be related to my body." "Physics is strange, and only crazy people like Newton do it." In today's technological and information society, "more money and jobs can be found in other fields" (Jordan 1994) that do not call for as much rigour as physics. Moreover, as Jordan notes, there is an "increasing lack of importance attached to science . . . in the curriculum" in the U.S. All of these factors would appear to be the cause of the decline in student interest in physics. In Pakistan, even though science is emphasized from elementary school through university, the attitude that physics is boring and difficult still prevails, particularly among female students. This attitude, I have come to believe, is the result of the problematic teaching of science in general and physics in particular.

From my own experiences in teaching and working with inservice science teachers for about a decade in Karachi, Pakistan, at the Aga Khan University Institute for Educational Development (AKU-IED),[1] I know that many teachers have become interested in the basic concepts and questions that physics addresses. Teachers have realized that, although the language of physics may be abstract and mathematical, physics topics can be appreciated in the teaching and learning of other subjects, such as biology. Also, even without our knowing formulas or Newton's laws, force, motion and gravity affect us all. In this article, I share reflections from my inservice graduate teachers at AKU-IED. These teachers graduated in 1998 from the one-year Advanced Diploma Subject Specialist Teacher (SST) Programme in science. It was during this field-based program that I first interacted with them in my capacity as a coordinator and facilitator of the program. One teacher (I will call her Nina) later participated in my research study toward my Ed.D. from 1999 to 2002 (Pardhan 2002).

The Change in Nina's Teaching

At the beginning of the second stage of my collaborative action research, Nina shared the following thoughts about her teaching of biology:

> Particulate nature of matter and it is applied in biology! When we did the PSTS packages[2] . . . I thought it is physics. But now when I come across it in biology I realize it is not only physics and I ask you [the researcher] questions about this just like my students ask me questions. (Pardhan 2002, 121)

Nina's words suggest that her perception of physics has changed. At the beginning of the SST program some years ago, Nina's view of physics was as follows:

> I never liked physics at school. . . . The teacher taught straight from the textbook [and used the] lecture method. . . . Once I remember my physics teacher was teaching us reflection of light. She showed us a

> candle reflected in a mirror and gave an oral textbook explanation of the image. This I never understood and that is the reason I never liked physics because most of the terms were not well understood by me.

This vignette reveals that Nina's science teachers were good at textbook theory but never engaged the students in practical experiences. Consequently, Nina pursued a B.Sc. honours degree with a subject combination in biological sciences only. She then taught predominantly high school biology for about 20 years before enrolling in the SST program in 1997. Nina describes her teaching strategies prior to the SST program as primarily providing explanations and notes—"rote learning rather than conceptual learning"—because that is the way she had been taught. Louden (1991, vi) writes, "Teachers teach in the way they do not just because of the skills they have not learnt. The ways they teach are also grounded in their backgrounds, their biographies, in the kinds of teachers they have become."

Nina's time in the SST program influenced her practice. By the end of the program, Nina had enhanced her pedagogical skills and pedagogical content knowledge:[3]

> The change that I feel in me is in the making of lesson plans, using different strategies, looking for new and innovative activities such that my students benefit from them by understanding and applying the science knowledge gained in their everyday life and future career. . . . I have become more eager to make science learning interesting and effective for my students.

When asked what science she was referring to, Nina responded,

> It is biology I am teaching, but now I am also using physics particulate nature to explain ideas like diffusion and osmosis. . . . While teaching biology, when it comes to any math concepts . . . I find it difficult. . . . I have no one to help [me]. . . . I nowadays collect books [and] read and try out exercises [to] try to understand the math behind and the given explanation for the question, Why are cells [meaning human] small in size? . . . After doing the activities myself I get a better understanding and feel comfortable helping students understand the *why* of the questions.

Nina moved from teaching for memorization to teaching for understanding. She also wants to enhance her own conceptual understanding of biological concepts using an interdisciplinary approach. Mathematics and "its science counterpart" (Brotherton n.d.)—physics—were Nina's least liked subjects before her SST experiences. She now recognizes the importance of applying these two subjects in her own field of interest. As a result, she is motivated to go beyond the content of the biology textbook to enhance her own and, in turn, her students' conceptual understanding. In a departure from the way she learned science, she is modelling the interconnectedness of biology, chemistry, physics and mathematics in the hopes that students will then also take an interest in math and physics.

What Led to This Change in Nina's Teaching?

> Right from the beginning I have been weak in this subject [physics]. I never got a proper coaching in it, and my interest was never in it. I had learnt so many words, but I could never relate to them until I saw you [the researcher] during the Subject Specialist Teacher Programme . . . giving [a variety of relevant] practical examples in physics for reflection of light and virtual image formation . . . and then we discussed image formation. . . . I still remember it, though it was done only once. Another example [is] when you gave a demo for the movement of the gas particles [and showed] ammonia gas and hydrochloric acid in a glass tube moving from opposite ends of the tube and making a white cloud. . . . If I had learnt it in that way then I would have been interested in physics. (Pardhan 2002, 81)

Nina's teaching was influenced by the way she was taught in the SST program. This strengthens my belief that interest in physics is related to how learners are taught. I was fortunate to have had a teacher who used experiments, models, visuals (such as charts) and explanations to help students understand physics and math concepts. This teaching, along with other factors (such as my interest, dedication and parents' support), led me to pursue a career as a teacher educator specializing in physics. I taught my students (other teachers) in the way

I had learned, and they seemed to enjoy the lessons and did well on the exams. However, during my initial teaching encounters and experiences at AKU-IED with visiting faculty from the University of Oxford in the areas of science and mathematics, I realized that my teaching—even though I used demos, models and class discussions—was not challenging, constructive, interactive and reflective. This realization was triggered by my exposure to a new perspective on how people learn—the constructivist perspective.

Theoretical Perspective

After studying the writings of such pioneers in constructivism as Cobb and Steffe (1983), Driver (1989) and Scott (1987), I realized that central to teachers' pedagogical content knowledge (Shulman 1986) is knowledge of how learners construct scientific and mathematical concepts:

> Learning outcomes depend not only on the learning environment but on what the learner already knows: Students' conceptions, purposes and motivations influence the way they interact with learning materials in various ways. (Driver and Bell 1986, 444)

Thus, students' lack of interest in physics is not the result of just the "lack of importance attached" (Jordan 1994) to the subject; how physics is delivered in the classroom plays a more important role (Shulman 1986; Driver and Bell 1986).

I recognized the importance of considering the psychological and experiential dimensions of learning rather than just the content. The shift must be from teaching for memorization to teaching for conceptual understanding. Thus, teachers must have knowledge about the most meaningful and powerful ways to represent subject matter and understanding (Shulman 1986). Reflecting on my own teaching practice, I came to understand that, even though I used demos, discussions and models, I did more talking and doing; in the process, I did not engage my students in their own knowledge construction and reconstruction. From Shulman's work, I learned that for a teacher to teach conceptually, the teacher must have conceptual understanding of the content.

With these insights, I designed my SST science program through a focused and interactive approach involving basic concepts in science, particularly physical science. The steps followed a cyclic pattern: pre-test (eliciting teachers' prior ideas), constructing knowledge, adapting knowledge, post-test (assessing change) and reflection.

Program Framework

The program's four major themes allowed the teachers to explore the basic concepts of science for Grades 1–8 as per Pakistan's national curriculum:

- "Understanding Materials and Why They Change"
- "Understanding Energy"
- "Understanding Forces"
- "Understanding Living Things and the Gases They Exchange"

An individual Primary School Teachers and Science (PSTS) package was devoted to each theme. I adopted and adapted these PSTS resource materials from a University of Oxford project for the following reasons:

- The content covered most of the basic concepts in Pakistan's national curriculum.
- The packages were easily accessible.
- The teachers were competent in the language of instruction (English).
- The packages were based on research into the alternative conceptions of teachers and students.
- The packages required the use of low- or no-cost materials that were easy to access or improvise.
- The packages used a variety of strategies—analogies, mind maps, models, thought experiments and investigations.
- The packages were based on the constructivist approach.
- The hands-on activities did not require a laboratory. They could be done in the regular classroom or even at home.
- The packages used a sequential approach to help students move from intuitive ideas to scientific ideas.
- Most important, the format of the packages modelled the pedagogical-content-knowledge approach.

The program used the constructivist approach to increase the teachers' knowledge of the basic concepts of matter, energy, forces and living things. It involved five phases: three face-to-face phases at AKU-IED alternating with two field-based phases of about three months, when the teachers returned to their classrooms. During the field-based phases, the teachers adapted and implemented contextually relevant materials from the packages and other sources. They then reflected on and re-planned or redesigned their action plans and moved to higher levels of comprehension of content, pedagogy and pedagogical content knowledge. This curriculum-revision process took the form of the four-step conceptual-change model detailed in the following section.

The Four-Step Model for Conceptual Change

Step 1: Pre-Test

The pre-test for each theme consisted of 20 items adapted from the PSTS package. The items were designed to measure teachers' initial content knowledge. For example, the items on the pre-test for the theme "Understanding Materials and Why They Change" explored teachers' understanding of basic concepts such as states and physical properties of matter (dissolving, melting/freezing, boiling, phase change, temperature change) and chemical properties using simple familiar reactions (rusting, burning, respiration) in terms of the particulate nature of matter. In each of the first 17 items, the participants had to identify the correct statement(s) about the specified concept. For example, item 6 read as follows:

a. During change of state the effect of the attractive forces between particles is always weaker.
b. During change of state the volume of the substance always changes.
c. During change of state the temperature of the substance goes up during melting and boiling and down during solidifying and condensing.
d. During change of state the distance between particles remains the same.
e. During change of state the number of particles involved remains the same.

Items 18–20 were semistructured, requiring written responses. For example, item 19 read as follows:

> Read the paragraph carefully and then complete the table.
>
> A piece of tissue paper was placed flat on a table. Half a teaspoon of water was poured into the centre of the tissue paper. The tissue paper was then left on the table for one hour.

Observation	Possible reason
Initial (just after pouring the water):	
After one hour:	

Step 2: Constructing Knowledge

In this step, teachers' active participation with peers and facilitators through interaction with the structured materials was facilitated. The teachers were encouraged and given opportunities to challenge their understanding of the concepts through application to new situations and daily-life encounters. Here, the teachers were actively constructing, deconstructing and reconstructing their knowledge.

Step 3: Adapting Knowledge

Following the enhancement of their content knowledge, the teachers were required to adapt—or, in Shulman's (1986) words, "to transform"—their personal science content knowledge to various grade levels and to make connections between science disciplines or topics. This critical and challenging step tested teachers' "ways of representing and formulating the subject that make it comprehensible to others" (Shulman 1986, 9). The teachers prepared unit plans on selected topics to be taught during the field-based phase, which they subsequently implemented and reflected upon.

Step 4: Post-Test

The post-test, the final step, was intended to indicate teachers' learning of the concepts. The post-test had the same format and number of items as the pre-test, but to minimize the influence of recall, items 1–17 and statements within each item were shuffled. Furthermore, some of the statements were modified to convert correct statements to incorrect statements and vice versa. For example, item 6 of the pre-test became item 9 of the post-test and read as follows:

> a. During change of state the number of particles involved remains the same.
> b. During change of state the temperature of the substance goes up during melting and boiling and down during solidifying and condensing.
> c. During change of state the effect of the attractive forces between particles is always stronger.
> d. During change of state the volume of the substance always changes.
> e. During change of state the distance between particles changes.

The semistructured items were also modified. For example, item 19 read as follows:

> When you enter a cold room immediately after a hot bath or shower
> a. How would you feel?
> b. Why?

Salient Features and Considerations

To facilitate the conceptual-change process in light of the contextual needs of the teachers, other salient features of the program needed modification and consideration. Considerations were as follows:

- Using an interactive and provocative approach employing central constructivist principles
- Engaging in advance and ongoing planning; preparation; and identification, acquisition and distribution of appropriate materials (packages, equipment, relevant readings, handouts, instructions)
- Formulating guidelines (instructions, expectations, supplementary readings, activities) to facilitate teachers' work
- Building in relevant and appropriate tools for assessment (formative and summative), including pre- and post-tests with special consideration to conceptual equivalency between the two

All of the program's 14 teachers—13 females (including Nina) and 1 male—showed significant improvement in content knowledge as measured by the pre- and post-tests. The teachers attributed this to the way in which they were taught. One teacher wrote the following reflection:

> The discussions [we have] to engage and clarify our ideas [and] our views about the content knowledge [are] helping a lot. . . . I really have to think very hard to engage my [students] in activities which are interesting as well as challenging. I am collecting and writing the things so that I can implement [them] . . . to allow [my students] to think and work in a better way for understanding.

The teachers acknowledged that the structured program had made a difference in their conceptual understanding, and they were determined to apply what they had learned in their own classrooms. Though the program was structured, its format allowed the teachers to share and clarify their own thinking, as this teacher noted:

> The use of the science packages was a big challenge. At first by looking at the activities it seemed like child's play, but when we started doing those activities and started to think about the various aspects I realized that it was not an easy job. Compressing the solid, liquid and gas (air) with the plunger in a syringe gave a hands-on experience. I also realized how important it is to do the experiments before introducing [them] in the class [and] how important it is to have a clear understanding of our own concepts. Another very important concept which was mixed up in my mind was clarified. . . . I realized how important these sessions are which make us think and clarify [our] concepts by asking, sharing the views with colleagues as well as our facilitators.

Conclusion

Nina represents many teachers, especially female teachers, with whom I have interacted at the AKU-IED who frowned when the words *physics topic* or *physics concept* were mentioned before formal instruction and engagement in an active-learning process. Many of these teachers have now "developed a comfort level for the subject" (Brotherton n.d.) through the conceptual-change model. Many female teachers have told me, in happy and enthusiastic voices, "Had I learnt it this way then, I would have been interested in physics. I would have been teaching physics. I would have had a better understanding of things around me." As Brotherton emphasizes, "It is possible to encourage the . . . female student to believe in herself and her ability in physics."

Nina and several of the other teachers entered the program with science anxiety, particularly with regard to physics and chemistry. They also held predominantly traditional beliefs about teaching and learning. Their realization that their own understanding of basic science concepts, especially in physics, is crucial to enabling their students' conceptual understanding provided a necessary condition for a change in their beliefs and attitudes. The program design and delivery allowed the teachers to strive for greater conceptual understanding of concepts such as energy, force, properties of matter and particulate nature of matter, and motivated them to be more responsible for their own learning.

Notes

1. AKU-IED was established in 1994 with a vision to be instrumental in education reform and improvement in Pakistan. To this effect, it offers a two-year M.Ed. program in teacher education and shorter certificate and advanced-diploma programs. The short-term programs are offered in five areas: social studies, science, math, English and primary education. For more details, visit www.aku.edu/ied/index.htm.

2. Resource materials from a U.K. project called Primary School Teachers and Science (PSTS) (out of the University of Oxford) were adapted for the SST program.

3. Shulman (1986, 9–10) writes, "Within the category of pedagogical content knowledge I include for the most regularly taught topics in one's subject area the most useful forms of representations of those ideas, the most important analogues, illustrations, examples, explanations and demonstrations—in a word, ways of representing and formulating the subject that make it comprehensible to others. Pedagogical Content Knowledge also includes an understanding of what makes the learning of specific topics easy or difficult; the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons."

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Is Conceptual Change in Science Possible?

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> Be very, very careful what you put into that head, because you will never, ever get it out.
>
> —Thomas Cardinal Wolsey (1471–1530)

Historical Origins of Conceptual-Change Research

The 1970s were the beginning of the study of conceptual change. Piaget's cognitive-stage theory (Piaget and Inhelder 1969), which detailed how students construct their knowledge through a process of assimilation and accommodation, was being quite widely accepted and applied in education. Kuhn's (1970) *Structure of Scientific Revolutions*, in addition to observing how science evolves, voiced the pedagogic observations of many teachers, who saw their students' cognitive development as being heavily influenced by social context and constructions. Driver and Easley (1978), after reviewing the literature, stated that more attention should be given to students' personal/private conceptions of science content. These were the foundations for the study of both constructivism and conceptual change, which have been dominant in educational circles for the past 30 years.

Context

As a beginning teacher of high school science in Alberta in the early 1990s, I was strongly motivated to learn the rules of the game I was about to play. I felt that I owed my students the ability to anticipate what they would find interesting and useful and to present the material in such a manner that they would be motivated to participate in the class and not just act as recipients of the information. However, the fact that the diploma exam would account for 50 per cent of their final grade also motivated me to try to anticipate and focus on the topics emphasized on the exam, to increase my students' chances of doing well.

I had some success in both these areas; however, I was continually frustrated, as were many of my colleagues, that some of the students could not make connections between the contexts used in class to illustrate concepts and the contexts used on the diploma exam. In an attempt to broach this problem with other teachers, I got involved in constructing and marking the Physics 30 and Biology 30 diploma exams. Through discussion, I learned that my peers categorized the inability of students to transfer knowledge from the classroom to the test as a conceptual-ability problem. They hypothesized that not all students could shift from their own (private) alternative conceptions to the (public) scientific conceptions that they needed to succeed on the exam. A similar problem existed in all the sciences, but it seemed more prevalent in physics.

Through teaching, I began to discover the areas of the physics curriculum with which students had the most difficulty, and I began to explore ways to help them make connections between class discussions and their own experiences. Without realizing it, I was engaging in a process receiving much focus in educational circles in the 1980s and 1990s, a process that sought to answer the question, How do we promote conceptual change from the students' common-sense or alternative conceptions to the scientific conceptions they require to do well in science? As diSessa and Sherin (1998) rather bluntly ask, "What changes in conceptual change and how do I facilitate that process?"

Beeth and Hennessey (1996, 4) write,

> Teaching and learning science have become increasingly complicated tasks. It seems that everyone connected with science education wants students to understand science content at some deeper, unspecified, level.

Considerable literature has been written on the topic of creating conceptual change in students. A decade ago, Duit (1993) reported that more than 3,000 empirical studies on various aspects of students' conceptions had been published over 25 years. Much research on conceptual change has since been done, but there have been few new conclusions, other than that conceptual change remains a problem for both teachers and students. In a recent extensive literature review, Martínez, Solano and Gómez (2001) concluded that, from 1975 to 2000, little changed in conceptual-change theory.

Getting students to change their intuitive, practical alternative conceptions of the world to more scientifically applicable conceptions continues to be a problem for teachers and a focus for research. This continuing concern prompts me to ask, Is it reasonable for teachers to expect all students to undergo significant, permanent conceptual growth in science?

What Is Conceptual Change?

In order to understand the conclusions of researchers and appreciate the concerns of teachers, it is necessary to define what is meant by *concept, conceptual change, alternative conceptions* and *scientific conceptions.*

What should we consider a concept? Labelling something does not indicate how different people perceive that concept and apply it to their own lives. For example, young children will initially apply the concept of dog to any four-legged, furry creature—a cat, a sheep and so on. Through making mistakes and encountering new labels and creatures, children will narrow their concept of dog until they can differentiate between concept differences as subtle as dog and wolf. The contexts we experience and the explanations we receive as we progress through life focus our understanding of different concepts. When teachers attempt to apply different explanations for concepts that students have already filed under "Understood," students tend to resist by relying on their own experiences with these concepts. It is, thus, difficult to provide a definition of *concept* that is accepted by all researchers. In fact, many articles focus exclusively on defining what a concept is (diSessa and Sherin 1998). For this article, I will use Zhou's (2002) definition: a concept is a class of objects, symbols and events grouped together in some fashion by shared characteristics that find their meaning within a theoretical context.

Thus, *conceptual change* is defined as a change in the cognitive structure or schema (as well as the networks that connect these cognitive structures) into which students build their concepts. At a practical level, this translates into students fitting new and relearned concepts into a framework that more closely resembles the scientific, publicly promoted understanding proposed by their teachers.

In order to establish where conceptual change starts and stops, it is necessary to establish what concepts students have before being taught (their alternative conceptions) and what concepts the teacher wants them to learn (the scientific conceptions). Again, the literature provides many different labels for students' previous conceptions, including *preconceptions, alternative conceptions, personal/private knowledge, misconceptions, naive science, children's scientific intuitions, children's science, common-sense concepts* and even *spontaneous knowledge* (see Eryilmaz [2002] for a review of the origins of the terms). I agree with Dykstra, Boyle and Monarch (1992) that *alternative conceptions* best describes the conceptions that students have upon entering the science classroom, because the students' conceptions are alternative to those the teacher teaches. The conceptions are not wrong, as *misconceptions* suggests; they have served the students well in their everyday lives. Nor do the conceptions exist only before classroom instruction, as *preconceptions* suggests: students continue to carry these conceptions with them through and after classroom instruction.

Students' learning of the scientific conception is a goal of science instruction. Students are encouraged to reach levels of comprehension that will allow them to apply their unique understanding of science to natural and technological phenomena that are not explained by their alternative conceptions. Zhou (2002, 2) writes,

> When we say we conceptually understand something, we mean that we know what is going on, that we have ideas about why it goes a certain way, and that we know its history, current state, and can even make predictions as to its future situation. Therefore, conceptual understanding stands above the sum of various knowledge facts and reflects our high-level knowing at a holistic view.

In 1982, Posner et al. proposed a conceptual-change model (CCM), which has become a common starting point for subsequent research. They listed four necessary conditions for conceptual change (p. 214):

1. Dissatisfaction with the existing conception(s)
2. A new conception that is intelligible
3. A new conception that appears initially plausible
4. A new conception that suggests the possibility of a fruitful research program

These four conditions bear a striking similarity to Kuhn's (1970) description of how science progresses through scientific revolution. Posner et al. (1982) quite openly supported Kuhn, referring to him many times as the source of their beliefs: "A major source of hypothesis concerning this issue [conceptual change] is contemporary philosophy of science" (p. 211). Kuhn detailed the appearance of anomalies that lead to scientists' dissatisfaction with the old paradigm (similar to step 1 of the CCM); the appearance of a new paradigm that offers scientists a choice (similar to step 2); and the merits of the new paradigm allowing more accurate predictions, more problem solving and more compatibility with the subject matter (similar to steps 3 and 4).

The similar origins of constructivism and conceptual-change theory have resulted in parallels between much of the work done in the two areas. Conceptual change in science education is fundamentally, or at least usefully, homologous to the dynamic of change in professional science communities (Duschl, Hamilton and Grandy 1992). Thus, having a working knowledge of how and why science communities have changed provides insight into how conceptual change occurs.

The CCM was considered a seminal work in the field of conceptual change because it was the first model to propose a mechanism by which teachers could attempt to create conceptual change in their students. It has since been criticized (most notably as being a purely cognitive model that ignores social and contextual factors), but it still serves as a foundation for much work on conceptual change.

Since the publication of the CCM, other models have emerged that use the CCM as a beginning but modify it to include social-constructivist leanings. For instance, Driver and Easley (1978, 68) specify the type of teaching required to promote conceptual change in students:

- Providing opportunities for students to make explicit their own conceptions about a topic so that the conceptions can be inspected
- Presenting empirical counterexamples
- Presenting and reviewing alternative conceptions
- Providing opportunities to use scientific conceptions

In the literature detailing mechanisms to promote conceptual change, the most common instructional strategy recommended is introducing conceptual conflict by confronting students with discrepant events that contradict their existing conceptions (Tao and Gunstone 1999). In this strategy, the teacher places the students into a situation that reveals the inadequacy of the students' alternative conceptions in explaining or predicting a scientific phenomenon. Essentially, the students' existing schemas of the world are pressed for their adequacy, consistency and explanatory power. Then, the teacher introduces the scientific conception and shows that it provides a more defensible, acceptable prediction or explanation (Macbeth 2000).

Dykstra, Boyle and Monarch (1992) propose a conceptual-change process with more steps, progressing from differentiation to class extension to reconceptualization. Niedderer and Goldberg (1994) similarly suggest that there is an intermediate step between the students' alternative conceptions and the scientific conceptions promoted by the teacher. More recently, while studying students' conceptual changes in evolution, Demastes, Good and Peebles (1996) identified four patterns of conceptual change:

- Cascade of changes—one conceptual change sets off a sequence of changes, like dominoes falling

- Complete change—the scientific conception abruptly replaces the alternative conception
- Incremental change—change takes place in a slow progression from alternative conception to intermediate conception to scientific conception
- Dual constructions—students maintain two distinct logical conceptions applied in different contexts

Variation can also be seen in students' reactions to the conflict between their alternative conceptions and the discrepant events presented to them. Tao and Gunstone (1999), summarizing the work of a number of researchers, report the following reactions from students:

- Bright, enthusiastic students welcomed conceptual conflict, whereas unsuccessful students ignored or tried to avoid it.
- Some students failed to recognize that a conceptual conflict existed.
- Some students recognized the conflict but chose to avoid it by passively relying on others in the class.
- Some students resolved the conflict only partially.
- Some students resolved the conflict by stubbornly continuing to use their alternative conceptions.

Variation in responses to any initiative designed to address an issue in the classroom is commonplace. Thus, that students respond differently to attempts to use conceptual conflict to promote conceptual understanding will surprise few teachers. But does this mixed response suggest a larger problem? Is there some fundamental barrier that science students must overcome before they can undergo conceptual change? The rest of this article reviews evidence suggesting that the goal of promoting conceptual change in science has inherent problems and that, perhaps, teachers must be realistic when they set out to modify their students' conceptions.

Alternatives to Conceptual Change

How susceptible to change are students' alternative conceptions? Searle and Gunstone (1990) performed a longitudinal study of seven students to determine how well the scientific conceptions taught to them before university carried over to an introductory university physics course. Despite the small sample, the results suggest the long-term implications of students' difficulty with conceptual change. Of the seven students studied, only one showed significant maintenance of the scientific conceptions learned before university; the rest had reverted to levels of understanding more characterized by the application of alternative conceptions. The researchers concluded that students' alternative conceptions resist change or replacement through instruction and that the degree to which students enjoy a physics course does not correlate with conceptual ability. Similarly, Zhou (2002) asserts that it is difficult to permanently change students' alternative conceptions to scientific conceptions. He cites a study in which 93 per cent of the students in a high school physics class held a conception of motion considered naive and unacceptable prior to taking physics and 80 per cent held the same conception even after successfully completing the course. Zhou also refers to work showing that students often take high school physics because they feel they have to and not because they want to. Zhou goes on to show that externally motivated students tend to employ superficial cognitive strategies focused on passing exams and getting the marks they need to move on to what they really want to do. Motivating these students to develop a deeper conceptual understanding is difficult.

Tao and Gunstone (1999) studied 12 students in Grade 10 science to determine the efficacy of conceptual conflict in fostering conceptual change and, then, how this conceptual change is realized. They concluded that conceptual conflict does not always produce conceptual change and that conceptual conflict is more effective when paired with the provision of opportunities for students to reflect on and reconstruct their conceptions. Even more striking is the researchers' assertion that "students vacillated between alternative and scientific conceptions from one context to another during instruction. Their conceptual change was context dependent and unstable" (p. 872). As a physics teacher, I often observed students who could apply scientific conceptions in the context of the classroom and topic studied but who would, even through switching to another room, often become confused about how to apply the conceptions they had learned. Their scientific conceptual ability seemed somehow tied to what they spatially and mentally associated with what they had learned. Removing those associations diminished the students' ability to use their newly learned scientific conceptions, and they would then revert to their alternative conceptions. Tao and Gunstone (1999, 876) write,

> Conceptual change . . . is a slow process during which students achieve contextually based change in a range of contexts, and based on these conceptions they may reorganize and systematize their cognitive structure and acquire conceptual change across the contexts. Context-independent conceptual change is exceedingly difficult, and students may fail at any intermediate stage during the process.

Macbeth (2000) offers a simple explanation for why students have so much difficulty permanently switching from their alternative conceptions to scientific conceptions. Students begin science instruction with a wealth of life experience that has served them well in navigating and anticipating what the world presents. Students do not need to know Newton's laws of motion to operate their bicycles or to anticipate what will happen if they hit a wall while on their bicycles. Students' Aristotelian perspectives serve them as well as they served the people before Newton and his laws of motion. Physics may be unique in how students' conceptions can actually hinder their learning of the subject. Macbeth writes,

> What must be taught cannot easily be found elsewhere, and worse, what is found elsewhere inveighs against the aims of science instruction. The resistance to change that science educators find in their students' naïve and incommensurable ways of seeing and thinking about the natural world is thus both an obstacle and distinguishing mark for science education. (p. 234)

Students often use their life experience as a foundation for such activities as writing a poem in English or evaluating a social effect in social studies, and although science teachers seek to make similar connections to students' lives, this strategy often serves to maintain the very alternative conceptions the teachers seek to change. "Diverse facts can cause difficulty for students in learning physics. The abstract feature of physics is one fundamental reason that many view physics as an unattractive course" (Zhou 2002, 43).

Dykstra, Boyle and Monarch (1992) have a similar perspective to that of Macbeth, but they take a decidedly constructivist approach to the problem. They argue that presenting students with Newtonian arguments will do little to develop scientific conceptual understanding, because the arguments make little sense in the context of students' own beliefs. The authors believe that physics should focus not on the scientific concepts the teacher wants to give to the students but, rather, on "students' beliefs about the world, which means that such beliefs have to be identified" (p. 619). They go on to stipulate how students can get by with, and even be successful through, memorizing formulas and problem solutions (with no awareness of the underlying situation-independent conceptions) because they are being evaluated not on their conceptual understanding but, rather, on their performance.

Adams and Chiappetta (1998) studied former junior high honour students entering their first high school physics class to evaluate the effect of students' beliefs about the nature of science (and their attitudes toward physics class) on their conceptual development. The researchers came to three conclusions. First, the physics students in general did not find the study of physics relevant to their everyday experiences and, therefore, were reluctant to try to tie the scientific conceptions they learned in class to their experiences outside of class. Second, the students who demonstrated high conceptual change were more likely to have a logical view of the world and a view of the nature of science that closely resembled that of the teacher. Third, the students who demonstrated high conceptual change were able to develop an internally consistent understanding of the content. Interestingly, they often constructed that content as isolated knowledge that operated separately from their alternative conceptions in their everyday lives. In other words, the students had constructed two worlds—a physics world in which they had a good scientific conceptual ability, and a real world in which they used their alternative conceptions.

Most of the research on conceptual change in students agrees that changing students' alternative conceptions to more scientifically acceptable conceptions is a difficult process and that making that change permanent is even more difficult. Conceptual change is affected by context, student ability and motivation, teacher ability and belief, and many other factors. Yet, none of the studies suggest ceasing research into how to best facilitate conceptual change. The literature not only emphasizes the difficulties of creating permanent conceptual change but also offers possible solutions to the issues raised. Often the solutions are the focus of the studies—pointing out the problems serves to introduce the rationale for why teachers should consider using the proposed solutions.

Solutions

In any discussion of ways to foster lasting conceptual ability in students, it must be noted that none of the suggestions work in all circumstances for all students. Teachers (themselves a diverse group) work with amazingly diverse groups of students, and they often instinctively use different techniques with different students—based on their perception of how receptive a particular student will be to a particular strategy and on their experiences with that student. However, being aware of the reportedly successful strategies gives teachers more tools for increasing their students' conceptual understanding.

Linder (1993, 295) asserts,

> The educational problem brought to the fore by the alternative conceptions literature is not, I argue, that students have alternative conceptions or strong highly-resistant-to-change preconceptions; the problem is that many students do not develop new meaningful relationships with the new contexts that they are introduced to within the educational environment.

Based on the observation that students use different conceptions for different contexts, Martínez, Solano and Gómez (2001) and Linder (1993) suggest that teachers should explain to students the appropriate context of a new concept. Further, they should relate this context to other contexts to which the concept can be applied. "Students achieved context-independent and stable conceptual change by perceiving the commonalities and accepting the generality of scientific conceptions across context" (Tao and Gunstone 1999, 872). If students associate a scientific conception only with the examples used to explain it, they will not be able to recognize its other contexts on tests or, more important, in everyday life. Constructivist theory suggests beginning with the personal contexts that students bring to class and then finding the science that allows the students to explain a concept to themselves. This lets students construct their scientific conceptions in a context that is meaningful and real to them and that goes beyond the classroom.

Eryilmaz (2002) suggests promoting cross-contextual relationships by engaging students in "conceptual discussions" with their peers and the teacher. Asking students to explain the reasoning behind their conceptions to other students (who have their own schema) forces them to expand the contexts in which the concepts could be applied. In Eryilmaz's study, this strategy decreased the number of alternative conceptions the students maintained.

Macbeth (2000) suggests that many of students' alternative conceptions can be attributed to explanations obtained inductively from their own experiences. He suggests that inductive reasoning can also be used to show students that their alternative conceptions do not hold up in scientific contexts. By contriving situations in which students are asked to interpret their observations, teachers can create hypothetical-inductive conflict by having the students create scientific conceptions that refute their own alternative conceptions. This is really just a specific technique for creating conceptual conflict, but it is intriguing to see how teachers can replace alternative conceptions with more scientific ones by using the same mechanisms students used in creating those alternative conceptions. Effectively, Macbeth (2000) is attempting to get students to construct new scientific paradigms using a technique already familiar to them.

Researchers have proposed other solutions that have been shown in certain circumstances to affect students' conceptual ability. Winer and Vazquez-Abad (1995) borrow from personal construct psychology in recommending the use of more visual techniques, such as the repertory grid, to identify problems and then suggest interventions to aid students' conceptual change. DiSessa and Sherin (1998) suggest that the answer lies in more precisely defining *conception*, and they propose a coordination model to facilitate the process of conceptual change. Metacognition has also received some attention because it is believed that if students become more aware of their own conceptual growth, they will take steps to make the changes more personal and permanent (Zhou 2002).

In short, there are many ways to address the problem of getting students to undergo a permanent change from alternative conceptions to scientific conceptions. The best or most applicable way is largely determined by personal bias, experience and the classroom dynamic. However, Dykstra, Boyle and Monarch (1992, 642) nicely summarize the approach to promoting conceptual change most commonly held by researchers:

> The general treatment strategy for reconceptualization seems to be
>
> 1. find some phenomenon which is easy to produce, not part of normal everyday experience, but close enough that students will feel confident predicting its outcome, *and* whose outcome differs in some significant way with their predictions;
> 2. have the students predict the outcome and discuss their justifications for those predictions;
> 3. have them test their predictions against the actual outcome;
> 4. establish a "town meeting," a facilitating environment which supports the student community in a discussion to develop and test new ideas in order to resolve perceived discrepancies between the predictions and their justifications and the actual outcome of the experiment.

Conclusion

Adams and Chiappetta (1998) found that students showing high conceptual change differ from those showing low conceptual change in the way they approach science classes. The techniques that were most effective with one group were not well received by the other. However, they found that the students who ultimately displayed the greatest degree of conceptual change were those who responded well to a logical–sequential model of instruction. This suggests that there is a fundamental difference between students in how they learn and, subsequently, how much conceptual change they undergo. It is not reasonable to expect a single technique or even a series of techniques to meet the needs of all science students. Perhaps the historical belief in science that a grand unifying theory underlies any question motivates teachers' efforts to seek out that one best practice for promoting conceptual change. Is it reasonable for teachers to expect all students to undergo significant and permanent conceptual change in science? No. The diversity in learning style, the inherent difficulties of the process of conceptual change and varying teacher–student relationships all serve to allow students to slip through the class without significantly changing their alternative conceptions. Based on this conclusion, should researchers stop trying to find ways to facilitate conceptual change? Again, no. With every student who is reached who would not have been reached before, conceptual-change research is a success.

What is the future of conceptual-change research? Research into how computers may increase students' ability to learn new concepts is beginning to emerge. Dykstra, Boyle and Monarch (1992), Tao and Gunstone (1999) and Zhou (2002) all suggest that computers are excellent tools for exposing students to a variety of contexts and conceptual conflicts. Then, after a specific conceptual change has been suggested, computers can offer immediate practice and remediation in the new concept. Whatever the future holds for conceptual-change research, this area will continue to frustrate successive generations of teachers and students and to receive ongoing attention from researchers.

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Obsession with *g*: A Metacognitive Reflection on a Laboratory Episode

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Background

Physics-methods students in the Teacher Education Program (TEP) at the University of British Columbia (UBC) go through a series of laboratory activities to get a feel for what their future physics students will experience when doing similar activities. Also, such activities help the preservice teachers reflect on what they did (or did not do) when they were high school students.

But physics-methods instructors have their own agendas when designing such activities—including making preservice teachers aware of the subtle misconceptions their future physics students might hold. These misconceptions are subtle in the sense that detecting them is not easy; however, if they go undetected and unchallenged, they can manifest themselves as serious flaws in students' thinking and reasoning and even foster elaborate canonically incorrect conceptions in physics (Anderson et al. 2000). Moreover, such misconceptions could exist among teachers, including preservice teachers, regardless of their level of expertise or experience.

Our instructional styles are influenced by constructivist epistemology, which views knowledge as being constructed (Ausubel 1968; Driver 1983; Driver and Erickson 1983; Gunstone 1994; Hodson 1998; Kelly 1955). This epistemology, together with the Piagetian and Ausubelian theories of learning (which are also constructivist in nature), influences our desire to discover preservice teachers' prior knowledge of whatever topic we plan to teach. This strategy makes good pedagogical sense, because not all prior knowledge brought to learning situations is canonically viable. This knowledge is sometimes content, context or procedurally specific. But physics-methods instructors in teacher-education programs and high school physics teachers do not always dialectically reflect on the knowledge they bring to the activities and experiences they design for their students.[1] Instead, most of them tend to focus on the knowledge the students bring to the learning experiences. In other words, teachers often do not reflect on or think about their own thinking.

Metacognition and Understanding

Metacognition is the act of thinking about one's own thinking processes, making distinctions and comparisons, and how one can make self-corrections (Gunstone 1994; Nashon 2001; Ornstein and Lasley 2000). In other words, metacognition is not just a process of reflection but also an internal awareness and control of one's own learning processes (Flavell 1979; Garner and Alexander 1989; Thomas 1999). A number of studies of student learning in classroom environments provide strong evidence that when students are helped to become aware of their own learning processes (that is, to engage in metacognition), they gain much richer understandings of the content of their learning and also become more empowered learners (Baird 1986; Thomas 1999; Thomas and McRobbie 2001).

Consequently, through their own lack of metacognition, teachers could deny their physics students opportunities to take control of their learning and think critically about their thinking. For instance, if a teacher holds a flawed view similar to that of the students, then the students operate in a flawed framework unnoticed, which then affects their conceptions of everything else. Our experience of our own flawed reasoning led us to share in this article our episodic laboratory experience and how possessive and encapsulating plausible reasoning in physics can be. We share our experience of freeing our minds from attractive yet flawed reasoning to illustrate the power of metacognition in making sense of physics activities and their outcomes—sort of conflict resolution regarding counterintuitive outcomes.

Through an hours-long metacognitive process of reflecting on our assumptions, our errors and the data before us, we arrived at a rational conclusion, as described below.

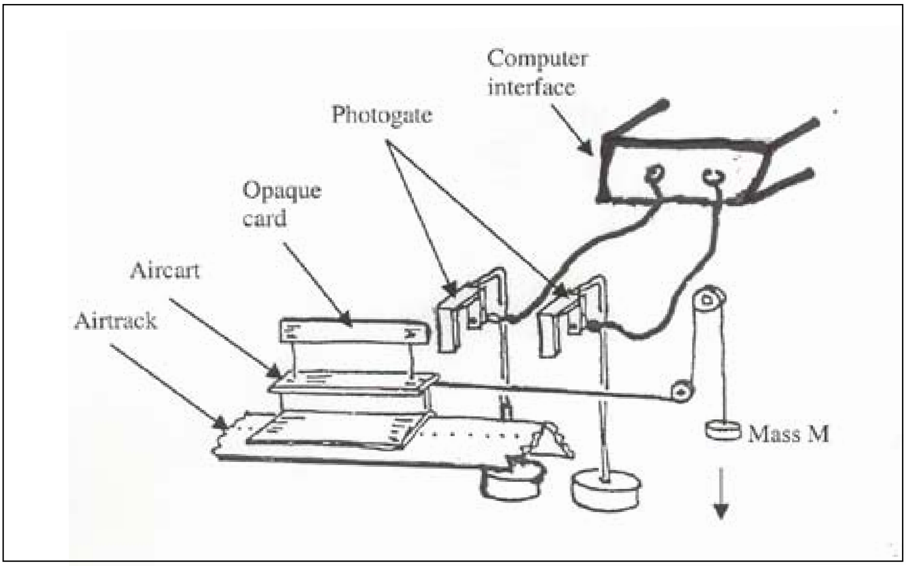
The Laboratory Activity: A Case Illustrating the Value of Metacognition

In this laboratory activity, preservice physics teachers were to determine the acceleration *a* of an air cart caused to move on an air track by a free-falling mass *M* attached to it with a string passing over two pulleys (as shown in Figure 1).

Two photogates connected to a computer interface operated by Vernier Software were placed along the air track at a distance *d* apart and were to be used in determining average velocities at two locations along the track during the cart's motion. The velocities were then displayed on a computer monitor. An opaque card 20.3 cm long was mounted on the cart so that the time the cart took to pass through each photogate and the respective average velocities v_1 and v_2 could be processed and displayed on the computer screen.

We did the experiment ourselves before giving it to our preservice teachers. Before releasing *M* to fall freely, causing the cart to move along the air track, we made what we thought was a plausible prediction. We predicted that *a* would equal the acceleration of any free-falling mass. This we "knew" would be *g*—the knowledge

Figure 1



we brought to the laboratory activity. Because the air track was frictionless and *M* was falling freely, we thought it reasonable to claim that *a* would be equal to *g.* We calculated the value of *a* using the equation of linear motion,

$$v_2^2 = v_1^2 + 2ad$$

The result for *a* was different from what we predicted. We tried several values of *d,* but the discrepancy between the predicted and the determined values of *a* remained. The temptation to explain away the error or attribute it to a fault in the software was at times overwhelming because of the seeming plausibility of both our reasoning and our assumption that the air track was frictionless.

Reflections on the Experience and Our Learning Processes

When we look back at our laboratory experience and our cognitive wrestling during the two-hour episode, we find many valuable lessons for physics educators. Indeed, sharing our metacognitive reflections has given our preservice teachers useful insights for their pedagogical practice but also deeper insights about learning to become better learners. We view the process of freeing ourselves from dissonance (cognitive conflict) in terms of a conceptual-change framework, the lens through which metacognition can best be acknowledged and appreciated. The conceptual-change theorists (Posner et al. 1982; Posner and Gertzog 1982; Hewson 1981; Hewson, Beeth and Thorley 1998) assert that four conditions must be met before conceptual change can occur:

1. There must be some *dissatisfaction* (or *dissonance*) with the existing conception.
2. The new conception must be *intelligible* to the learner.
3. The new conception must be initially *plausible,* reasonably fitting the conditions of the problem.
4. The new conception must be *fruitful,* serving the problem in productive ways.

Generally speaking, people will not change their existing conceptions without good reason.

Metacognition: Freeing Ourselves from Our Obsession with *g*

In our experiment, the repeated discrepancy between *g* and the determined values of *a* provided us with cognitive *dissatisfaction.* This situation motivated us to draw more widely on our combined knowledge resources. We used the phrase "calling in the reserve knowledge troops" as a military metaphor for this process. We recognized that the knowledge we deployed in the service of the immediate situation was useful but not sufficient to resolve our dissatisfaction, and hence we needed to call on additional knowledge troops not currently in service. These knowledge troops were our shared consensus knowledge and understanding of the domains and principles of physics we have constructed over many years of study of the discipline and practice as physics educators. However, the metaphor can be applied to any learner, regardless of expertise or experience in a given subject. The notion that knowledge exists within the learner in a latent state and can be employed in active service is important in considering the nature of knowledge development and learning in the pedagogy of teaching physics. We will discuss that notion in the section on implications for teaching.

Our dissatisfaction with the experimental results had two dimensions. First, we were dissatisfied with the results being a factor 10 in error (1.2 $\mathrm{ms^{-2}}$); second, we were dissatisfied with the initial knowledge we held and deployed in the service of the situation.

In resolving our dissatisfaction, we called in our first wave of knowledge troops to examine the potential sources of our error. We explored possible explanations for the discrepancy, including such factors as the friction between the string and the pulley, the air resistance of the cart and even the mass of the string. However, we soon deemed these influences implausible in accounting for the factor 10 errors in our experimental values of *a,* which we had expected to equal *g,* and thus we resorted to calling in additional knowledge troops to break us free from our obsession with *g.*

The second wave of knowledge troops centred on notions of the inertial mass of the cart. We agreed that these troops, unlike the first wave, provided us with an *intelligible* and *plausible* account for the discrepancy. Varying the mass of the cart by attaching additional masses and repeating the experiment several times yielded values of *a* consistent with our conceptual understandings of inertia and acceleration. Thus, our strategy and application of our conceptual understandings of inertial mass were *fruitful.*

However, we were keen to further verify our experimental findings and confirm that our initial notions that the cart should accelerate at *g* were unfounded. This was consistent with the scientific practice of ensuring reliability of results.

Through the third wave of knowledge troops, we tested our conclusion that the cart did not accelerate at *g* by simultaneously releasing from the same height the mass attached to the cart and an unattached mass of equal weight. We hypothesized that the masses would not hit the floor at the same instant. We were conscious that any mass would have sufficed to validate the test, but using equal masses was pedagogically good practice. This experiment affirmed our understanding that the cart and the falling mass were a single system accelerating as a function of a downward force, due to the falling weight attached to the cart and the cart's mass. Our collective troops provided a fruitful explanation for the acceleration of the cart and allowed us to safely abandon our previously held views. These frameworks allowed us to comfortably appreciate the relationship between the accelerations as

$$(M_1 + M_2)a = M_2g,$$

where M_1 is the mass of the cart and M_2 the mass of the falling weight. Indeed, additional metacognitive reflection caused us to draw on even more knowledge troops to formulate a deeper understanding and appreciation of the system.

We wonder how many times instructors encourage students to interrogate their experimental results in ways that are not only plausible but also intelligible and fruitful. Moreover, we wonder how often instructors present opportunities for learners in classroom settings to transcend metaconceptual reflection (thinking only about the concepts at hand) and think metacognitively (making one's own thought the object of cognition).

Implications for Teaching

On a fundamental level, we are all human learners; that is, we all engage in the process of bringing our knowledge and understanding to a given situation and attempting to make meaning out of our experiences. We see several valuable insights and implications for teaching emerging from our experiences wrestling with *g* and from our subsequent reflection on our learning processes.

Repeated Dialectic Reflection Makes Learners More Aware of Their Own Learning Processes

We learned a great deal about our own learning through thinking about and repeatedly reflecting on how we came to a fruitful determination of the value of *a,* beyond the limits of our two-hour laboratory episode. As former high school teachers and current instructors of preservice teachers, we are all too aware of the many factors that crowd a classroom curriculum. The debates about the quantity of material covered in a curriculum and the quality of learning are not new. However, our epistemological and pedagogical position, and indeed the laboratory experience described here, strongly confirms the value of metacognitive reflection to both the quality and the extent of learning and concept development. In short, we see great merit in providing students with opportunities, within the context of the task, to repeatedly dialectically reflect on their laboratory experiences (Baird et al. 1991). Dialectic reflection, and its consequent benefit of deeper conceptual understanding, does not usually happen in the typical 5–10 minutes of summation reflection at the end of a lesson or experience. Dialectic reflection is more longitudinal and involves revisiting the experience in the days and even weeks following the event, with each revisiting stage providing new and deeper insights into our own thinking and learning processes. Repeated dialectic reflection makes learners not only more knowledgeable about the content but also more aware of their own learning processes. Thus, it provides increased power for learners to become in control of these processes.

Repeated Dialectic Metacognition Makes for Emancipated and Empowered Learners

We see great benefit in openly sharing our deep metacognitive reflections with our students. In the case of our obsession with *g,* we gave the same experimental scenario to our preservice teachers and, without discussing our own struggles, asked them to predict and then determine experimentally the value of *a.* We noted with interest that many of the preservice teachers had struggles similar to ours. Toward the end of the laboratory session, we discussed the experiment from theoretical and pedagogical points of view. In addition to letting the preservice teachers share their insights and struggles, we shared our own experiences—our obsession with *g*, our deep metacognitive reflections and our understandings of our own metacognitive processes, which freed and empowered us as learners. Seeing the preservice teachers' reactions to our openness and vulnerability was extremely rewarding. They not only felt relieved that they were not alone in their struggles but also felt a sense of liberation, emancipation and empowerment as learners, which increased their confidence in their problem-solving strategies and abilities. This open sharing of our metacognition and the metacognitive processes of our TEP students continues to yield more confident, empowered learners and teachers of physics. We, therefore, see potential for the same benefits in physics classrooms if teachers and students are encouraged to share and discuss their learning processes.

Learners' Discovery of Their Relevant Latent Knowledge Gives Them Hope and Confidence

The notions of latent knowledge and knowledge employed in a given situation are valuable concepts for educators (Anderson, Lucas and Ginns 2003). We used the metaphor of calling in the knowledge troops to describe what was occurring for us at the cognitive and metacognitive levels in the laboratory. Students can also call in many different knowledge troops in the service of a learning situation. Even latent knowledge troops can be called into active service. There is great value in helping students become aware of these kinds of learning processes, in the metacognitive sense, and helping to foster them in laboratory learning. As educators and facilitators of experiences, we should not only teach content but also help students appreciate the learning process and equip them with both the awareness and the skills to call in the troops in metacognitive reflections. Helping students recognize that they possess latent knowledge empowers them. This discovery can increase students' confidence in their ability to solve physics problems that at first seem insurmountable. Through metacognitive thinking practices and the ability to call in additional knowledge troops, the notion of latent knowledge gives preservice teachers hope and confidence in their abilities as both learners and teachers of physics.

In conclusion, our obsession with *g* reminds us that learners (ourselves included) can inappropriately apply canonically valid physics knowledge (that is, knowledge that is both plausible and intelligible) to learning situations. This can steer learners in the wrong directions, causing them to develop more elaborate knowledge and understandings that are not canonically sound or viable. However, our experience demonstrates the tremendous power of metacognitive reflection on the learning process and product and the potential to develop rich and fruitful understandings.

Note

1. *Dialectic* is defined as the art of investigating the truth of opinions or the testing of truth by discussion, as inquiry into metaphysical contradictions and solutions, or as skilled logical disputation.

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How to Make the Teaching of Heat Transfer More Effective

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Maskill and de Jesus (1997, 781) write, "According to the constructivist approach, all learning starts from a basis of previous experience and develops in a purposeful fashion according to the usefulness or value which the new ways of dealing with the world have for each individual learner."

The field of learning today emphasizes the exploration of students' prior ideas and expectations, because knowing students' prior knowledge can help teachers proceed in a meaningful way. However, investigating every student's prior knowledge or alternative frameworks, especially in a large class, is challenging. An alternative strategy is to draw on the literature to find common alternative frameworks on a particular topic. However, this strategy assumes that all students' ideas match the findings in the literature, which may not be the case; context influences students' alternative frameworks. The question–answer technique is another alternative for exploring students' ideas, but this strategy may not give the students adequate time to think. There is no single effective technique for exploring students' prior knowledge. However, using a combination of techniques—such as brainstorming, written response and prediction—can be effective and interesting in eliciting students' ideas about a topic. Teachers can also give students various types of practical activities, ask them to make predictions and then test their observations.

In this article, we share our insights into how to make the teaching of heat transfer more effective in light of students' alternative frameworks.

Rationale

Teaching and learning are difficult, complex tasks. To teach effectively, teachers must constantly plan and reflect. Many factors can affect the processes of teaching and learning.

When we recently taught heat transfer to a class of 13- and 14-year-olds at a school in Pakistan, we applied techniques such as brainstorming, prediction and written response to elicit the students' prior knowledge. These techniques helped make our lessons more interesting, and the students seemed to enjoy the learning process.

Writing this article has helped us to further increase our understanding about teaching heat transfer and to carry on further in-depth exploration. It has also helped us to analyze the relationship between students' alternative frameworks, practical work and new learning. Finally, it has allowed us to reflect on how alternative frameworks hinder new learning and to determine what strategies and activities we can adopt to make our lessons interesting and the students' learning purposeful.

Data-Collection Strategies

This article is mostly based on our classroom teaching. We collected data from our unit plan, the students' worksheets, questions and answers, predictions, objective tests, observations, the facilitator's feedback and the literature. We also got data from after-lesson discussions with our classmates and facilitator during the Lower Secondary Science Module at the Aga Khan University Institute for Educational Development (AKU-IED) in Karachi, Pakistan.

Analysis and Literature Review

This article aims to reveal the importance of considering students' alternative frameworks in making the teaching and learning of heat transfer more effective. Our facilitator assigned us the task of delivering three lessons (one per day) on heat transfer to a class of 13- and 14-year-old students. For this purpose, we prepared a tentative and flexible unit plan (see the appendix for our reflection on our unit plan).

Our Plan in Action

Lesson 1

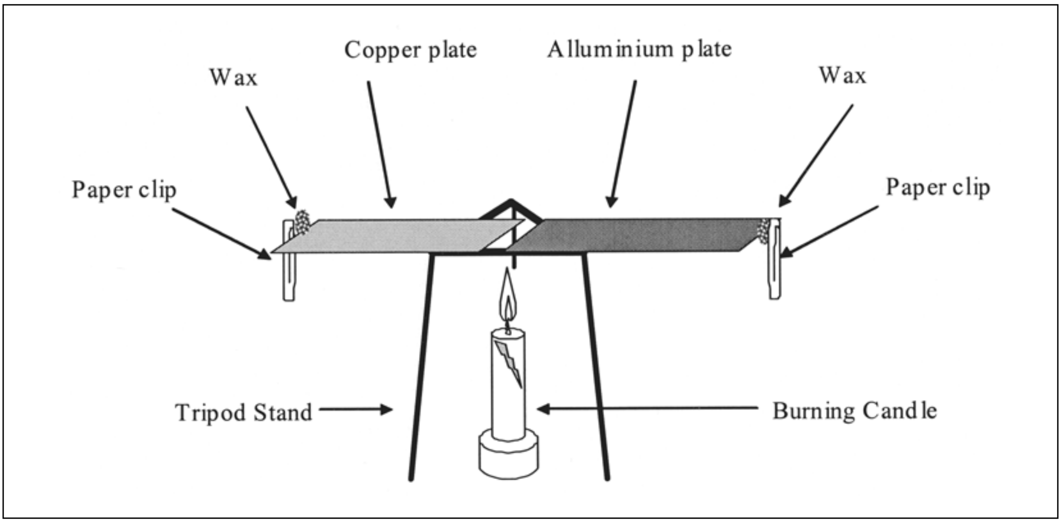
On the first day, we asked the students some exploratory questions and observed that only a few students responded, perhaps because the others did not have enough time to think or were not prepared for this approach.

We next applied the predict–observe–explain (POE) strategy. The students wrote down their predictions and participated in a class discussion. We gave the students activity sheets and metal plates (copper, iron, brass, aluminum and zinc) and asked them to predict which plate would best conduct heat and to then order the plates by conductivity. The students all ordered the plates differently. Most put iron at the top of the list. Upon testing (see Figure 1 for the set-up), when the wax on the copper plate melted first, the students were surprised and started reasoning about the observation. We recognized this as a good start for students to learn in light of their alternative frameworks.

As for copper and aluminum, there was little difference; therefore, the students repeated this activity three times by changing the angles and positions of the plates. This we interpreted as follows: when students find something that contradicts their prior knowledge, they become curious, keenly scrutinize the new findings and then ultimately reconceptualize. This strategy helped the students to rethink their predictions.

However, limited activities may not be enough, because alternative frameworks sometimes become so strong that, after continuous practice, students revert to them. Stevenson and Palmer (1994, 130) argue that, to bring about real learning, real reorganization of knowledge and understanding is needed: "This requires considerable effort and the use of sophisticated metacognitive strategies." Therefore, students should be given ample time to investigate.

Figure 1
Conductivity Experiment



During the discussion, some students asked why heat is transferred more easily through metal. The activity got the students to engage in critical thinking. At this point, we discussed the role of free electrons in heat transfer (Hoong 1997).

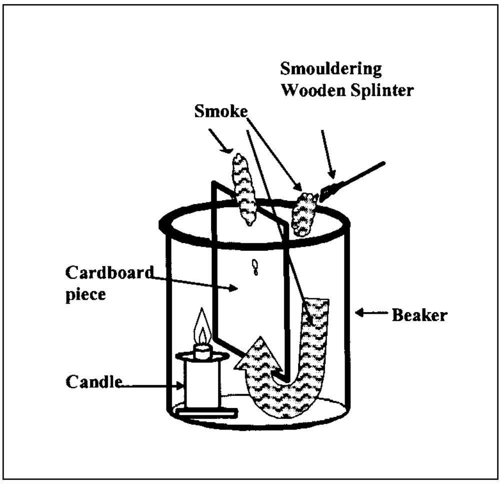
Lesson 2

On the second day, we changed our strategy slightly but still used POE. The topic was heat convection.

We asked the students to predict the movement of smoke in a smoke cell (see Figure 2).

Many of them wrote that the smoke would move up from the smouldering splinter. When the smoke went down to the other side, where the candle was, and came out of the beaker from the candle side, the students were surprised and started reasoning. When we asked one student why the smoke moved downward and toward the candle, the student responded that the candle flame attracted the smoke. We took the candle out and brought the smouldering wooden splinter close to the candle flame. The candle flame did not attract the smoke. We asked the student why. The student became silent (perhaps thinking about it). Then we asked the student why on a hot day a cool breeze blows toward land. The student responded, "It is the nature of air." Thus, we used the student's ideas as a starting point for discussion. We discussed convection current, which caused the flow of the smoke current in the smoke box. We then discussed how hot air expands, becomes less dense and rises upward while cool air, which is more dense, sinks and takes the place of the hot air, thus setting up a convection current (Hoong 1997).

Figure 2
Smoke Cell



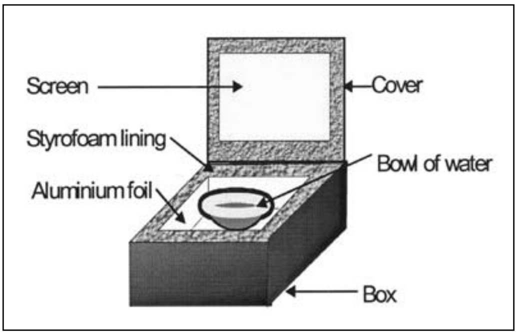
The students needed more activities and discussion to understand convection current. Otherwise, it was difficult to change their alternative frameworks because their ideas made sense to them.

Lesson 3

On the third day, we discussed heat radiation. We gave the students some activities, the most interesting of which was the solar box (see Figure 3).

We poured equal amounts of water into two small stainless-steel bowls of the same size. The students then took the temperature of the water in each bowl using the same thermometer. The temperature in both was 20°C. The children then put one bowl of water in direct sunlight and the other in the solar box (with the box facing direct sunlight like the first bowl). After 10 minutes, the students predicted the temperature of the water in each set-up. Nearly all the students said that the water in the bowl outside the solar box would be warmer because it was getting direct sunlight. The students then checked the temperatures. They were surprised that the temperature of the water in the bowl in the solar box was 34°C whereas the temperature of the water in the other bowl was only 24°C. They became curious and started asking questions and trying to make sense of the results. A number of students

Figure 3
Solar Box



said that the aluminum foil inside the solar box increased the temperature. This was the right moment to extend student response and discuss heat transfer by radiation and the greenhouse effect (Hoong 1997). We also discussed how aluminum foil acts as a reflector of heat and how Styrofoam is a poor conductor of heat.

We then drew on students' real-life experiences: "Do you feel hotter inside the vehicle or outside on a sunny day?" Most of the students said that they felt hotter inside. We asked them why. Some explained it in terms of the greenhouse effect. When students are taught through exploration of their prior knowledge, they understand a concept better. To internalize the idea, the students needed more activities, but time constraints did not allow this.

When we gave the students the materials to make the solar box, they became engrossed in the task. One group completed the box during class time, but the others only partially finished. The students were enthusiastic and did their practical work with interest. They asked many questions. One student inquired, "Where can I buy aluminum foil?" The students were interested in making the solar box at home. Hofstein (1988) suggests that involving children actively in practical work enhances their interest and learning.

Our experiences in this science classroom reveal the important role students' prior knowledge plays in teaching and learning. McCloskey and Kargon (quoted by Stevenson and Palmer 1994, 125) refer to this view as "the intuitive impetus theory" and write, "Intuitive theories that are misconceived can have serious consequences." Thus, we believe that these theories should be addressed. Otherwise, pre-existing ideas might create conflict in students' minds, and the students may not be ready to accept the new concepts.

What We Learned

It is not easy to change students' alternative frameworks in a short time. The process requires more time, work and reflection. Driver, Guesne and Tiberghien (1985, 148) believe that "when new ideas conflict with children's point of view they can be an obstacle to learning." They further remark that children internalize experiences that are partially their own, and their personal ideas influence the newly acquired information. This means that a teacher who teaches without knowing the students' prior knowledge will not understand the students, and this could create further misconceptions. White and Gunstone (1992) also argue that learners enter the classroom already holding personally constructed ideas and beliefs. They observe and think about new findings critically and try to make sense of them. Maskill and de Jesus (1997, 788) write, "Pupils are making a serious effort to understand why their previous ideas are not scientifically correct and are seeking help to learn the difficult ideas." We observed a similar situation in our classroom teaching: the students started reasoning about and reflecting on the topic when their findings did not match their predictions.

Students' prior ideas are crucial in teaching and learning, but how should the teacher explore these ideas? As already mentioned, teachers can use many techniques—including question–answer, brainstorming, written response, literature and POE—to reveal students' alternative frameworks. During question–answer, we found that most children felt threatened or did not have enough time to think deeply. Also, some children might not have understood the questions (Maskill and de Jesus 1997). Maskill and de Jesus (1997) recommend that teachers provide written questions to give students enough time to think and to express themselves. When we gave the students written questions during activities, almost every student wrote something on the worksheet, which helped us greatly in understanding their prior knowledge.

Another way to reveal students' alternative frameworks is examining research on alternative frameworks in a specific topic. However, the alternative frameworks noted in the literature may not match those of the given students, because students have different cultural and contextual backgrounds and experiences. Examples of students' alternative frameworks about heat transfer noted in the literature include the following:

- "Heat acts as a fluid. It accumulates in one spot until that spot is filled" (Stepans 1994, 77).
- "Metal is colder than plastic because cold passes through it more quickly than plastic" (Stepans 1994, 77).
- "When they [students] wear lots of clothes they heat up" (Newell and Ross 1996, 35).

We found different alternative frameworks during our classroom teaching, even though the topic was the same. Also, different teaching approaches can affect students' learning in different ways. Children get their prior ideas from their parents and peers and through observing their surroundings. They also get prior ideas through trial and error in society. Lynch (1996) designates culture, language and the way the same word may have different meanings in different contexts as the main sources of alternative frameworks.

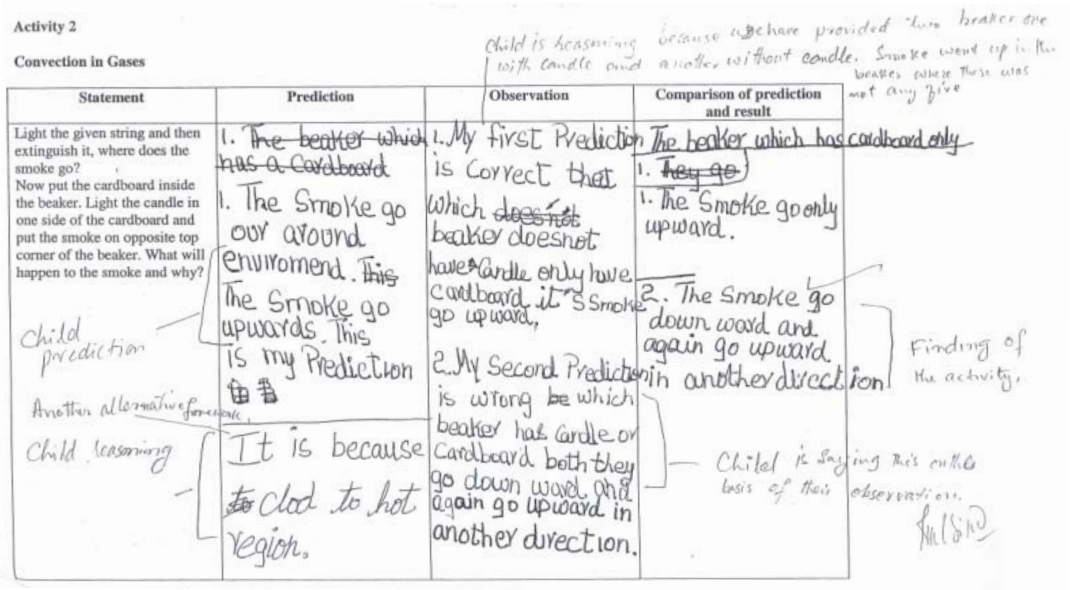
In light of the above insights, we predominantly applied the POE strategy and written response to reveal students' prior knowledge and alternative frameworks. White and Gunstone (1992, 45) write, "POE is often more direct than the usual style of question in revealing understanding."

Practical work plays an important role in teaching and learning. Leach and Scott (2000, 68) write, "Practical work is one of the hallmarks of science, and many educators argue that a science education without practical work fails to reflect the true nature of scientific activity." Thus, practical work is crucial to understanding scientific ideas. Bentley and Watts (1989) also argue that practical work is necessary for developing students' skills in science. Students internalize new concepts better through hands-on activities. During our three days of teaching, we also found that the students learned better through practical work. We assessed their learning through question–answer, observation, worksheets and a short test (see Figure 4) and found that most students could provide answers in their own words.

White (1991) also favours practical work and writes, "It is necessary to see the process of practical work particularly if the focus is on conceptual restructuring." However, engaging students in practical work without exploring their alternative frameworks is not as effective.

Providing challenging activities involving questions, prediction and problem posing can make lessons more effective. During our three days of teaching, we made our activities more interesting and enjoyable by exploring students' prior knowledge through POE and question–answer techniques. We now realize that there are a variety of techniques for making teaching and learning effective. More important, we now believe that hands-on activities that explore students' alternative frameworks play a significant role in students' learning.

Figure 4
An Example of POE



Activity 2

Convection in Gases

Child is reasoning because we have provided two beaker one
with candle and another without candle. Smoke went up in the
beaker where there was
not any fire

Statement	Prediction	Observation	Comparison of prediction and result
Light the given string and then extinguish it, where does the smoke go? Now put the cardboard inside the beaker. Light the candle in one side of the cardboard and put the smoke on opposite top corner of the beaker. What will happen to the smoke and why?	1. ~~The beaker which has a Cardboard~~ 1. The Smoke go our around enviromend. ~~This~~ The Smoke go upwards. This is my Prediction [illegible] It is because ~~to~~ clod to hot region.	1. My first Prediction is Correct that Which ~~doesn't~~ beaker doesnot have a Candle only have Cardboard it's Smoke go upward, 2. My Second Prediction is wrong ~~be~~ which beaker has Candle or Cardboard both they go down ward and again go upward in another direction.	The beaker which has cardboard only 1. ~~they go~~ 1. The Smoke go only upward. 2. The Smoke go down word and again go upward in another direction

Child prediction

Another alternative framework

Child reasoning

Finding of the activity.

Child is saying this on the basis of their observation.

Implications

Ausubel (quoted by Cockburn 1999, 13) writes, “The most important single factor influencing learning is what the child already knows.” We can make our lessons more effective through exploring students’ prior knowledge. But simple, short questions and answers are not enough because sometimes students do not take questions seriously and respond with whatever comes to mind. Therefore, teachers should further probe during the question–answer process by using *what, why* and *how* questions.

Giving students different types of activities without exploring their alternative frameworks poses difficulties for their understanding of new concepts. When children encounter a new concept, they naturally think of it in terms of what they already know. Students’ prior knowledge has far-reaching effects on their learning.

Teachers should use POE and written response to explore students’ alternative frameworks because this strategy will make practical work more challenging and help students to think more critically. Students become engrossed in hands-on activities when such activities are assigned to them after exploration of their alternative frameworks.

Teachers can use a variety of activities to make lessons challenging for students. For example, a teacher can put a Thermos in front of the students and ask them why its outer and inner layers are silvery and shiny, and why there is a space between the inner and outer layers.

After an activity, teachers should give students enough time to discuss the topic and should listen to their points of view carefully, because there can be strong reasoning behind them.

Conclusion

The minds of students are not like empty vessels (Lynch 1996). They contain ideas gathered from various sources. When students encounter something new, they see it in light of their previous knowledge. During our three days of teaching about heat transfer, we tried to explore students’ ideas through prediction and written questions. We found that students do have ideas about abstract topics such as transfer of heat. In light of these alternative frameworks, we gave them hands-on activities and found that they became curious when something went against their predictions. They asked questions and tried to find the real cause. We now realize that we can make teaching heat transfer more interesting and enjoyable by exploring students’ alternative frameworks and using hands-on activities.

Appendix
Unit-Plan Reflection

With guidance from our facilitator, we developed our unit plan in a systematic and sequential manner. We started with the conceptual framework and then developed three lesson plans and activities. The facilitator read the lesson plans and gave us feedback.

We were also given the opportunity to discuss and modify our unit plan with classmates teaching a similar topic. We shared and learned from each other and from the facilitator’s feedback. This helped us to enrich our unit plan. Also, we engaged in self- and peer evaluation using criteria provided by the facilitator. Furthermore, we modified our unit plan and experiment designs after trying the experiments ourselves. This was followed by a briefing on how to proceed with the actual teaching. In the process, we clarified our own concepts and developed trust between us, our classmates and the facilitator.

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Reflection on Learning About Forces

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Force is a basic concept in the physical sciences. It is included in Pakistan's national curriculum from the primary level through the higher levels. Because of the abstract nature of the concept of force, both students and teachers have alternative frameworks in this area. This was revealed in our classroom discussions on force during the Lower Secondary Science Module of the M.Ed. program at the Aga Khan University Institute for Educational Development (AKU-IED) in Karachi, Pakistan.

In-depth discussions and a variety of activities we carried out while teaching about forces challenged our previous concepts and allowed us to think critically about the teaching and learning of forces. In this article, we reflect on our teaching and learning experiences and possible ways, in light of our new learning, to make the concept of force understandable to students.

Rationale

The module made us realize that our understanding of the concept of force was linear (that is, not applicable in diverse situations) and that in some cases we held alternative frameworks. The detailed discussions and experiments helped us rectify our alternative frameworks. Also, because of our lack of content knowledge and pedagogical skills, we had difficulty designing activities and clarifying the concept of force for our students. The module's emphasis on activity-based teaching rather than lecture-based teaching prompted us to write this article about our experiences and learning at the AKU-IED. Writing this article has prepared us to teach about forces more dynamically. We also wrote the article to develop a critical stance toward our practical experiences at the AKU-IED and their implications for the classroom, to develop an approach using prediction and observation in the classroom for students' conceptual understanding, to explore how to help students understand the concept of force using simple materials and, finally, to reconstruct our learning and reflect on our previous understanding of forces.

Previous Teaching and Understanding of Forces

Science is a human activity, and its teaching should be related to real-life situations. In Chitral, a remote mountainous district of Pakistan's North-West Frontier Province, teachers teach science without relating it to daily life. They give students only the textbook definitions of scientific concepts for memorization. This approach, we have come to believe, does not help students develop conceptual understanding. Before coming to the AKU-IED, we taught in a similar way.

We used to teach the concept of force the way we were taught. In the physics textbook for 15- and 16-year-old students, *force* is defined as "an agent which moves or tends to move a stationary object or stops or tends to stop a moving object." That is what we taught our students. For further explanation, we used only the examples in the textbook. Thus, our teaching of forces was limited to the textbook. This is why our students' conceptual learning did not expand. We also taught the concepts of magnetic and gravitational forces but did not use hands-on activities or relate the concepts to real-life experiences. The categorization of forces into contact forces and noncontact forces was also not clear to us, which is why our students could not differentiate between the two and had alternative frameworks. Tobias (quoted by Stepans 1996, 4) states, "Science is made difficult by the way it is presented in textbooks and in classrooms." Teachers do not try to explain the concepts beyond the textbook, and sometimes textbooks are the source of alternative frameworks. In fact, Riche (2000) declares that textbooks are the most significant source of alternative frameworks in the physics classroom. Prior to our AKU-IED experience, we did not think of analyzing the textbook definitions or exploring students' prior knowledge about forces before introducing the concept.

In everyday language, the word *force* is used in a variety of contexts and has many meanings (for example, *force of argument, military force* and *task force*). In science, *force* has a technical meaning at variance with its common meanings. Students come to school knowing the everyday meaning of *force,* which is difficult to change when they come across the scientific concept of force. Riche (2000) notes that perceptions of the natural world are popular conceptions rooted in everyday experience; therefore, they influence the learning of new ideas.

The concepts of force and motion are vague, complex and abstract. According to Gunstone and Watts (1985, 89), "the concept of force itself has quite a curious history. Even comparatively recently the concept was vague and not clearly isolated in science." Scientists such as Aristotle, Buridan and Newton tried to explain the concepts of force and motion. The current theories of force and motion are based on Newtonian theory. Gunstone and Watts hold that Newton's conceptions of force possess some old beliefs such as inertia being an internal force rather than an external, applied force that changes the velocity of moving objects. Many people continue to believe in the old conceptions of force and motion. Thus, it is not surprising that schoolchildren of today hold the conceptions that were considered correct by most people, even scientists, in ancient times. Teachers should acknowledge this tendency and then use scaffolding to teach students in an easy, comprehensible way.

Here, we share two alternative frameworks that we had prior to the AKU-IED science module and that, without knowing, we taught to our students. The literature reveals that teachers in other countries also hold these alternative frameworks. The first alternative framework is the idea that if a body is moving, a force is acting on it (Kruger, Palacio and Summers 1991; Gunstone and Watts 1985; Palmer 1998). The second is the idea that "if an object is at rest (like a book on a table) then no forces are acting on it" (Driver 1983).

These alternative frameworks are based on the daily experiences of learners. It would make no sense to the students if the teacher told them that two forces are acting on a book resting on a table and that the two forces are equal in magnitude but opposite in direction and, therefore, cancel each other's effect, causing the book to remain stationary. Although we had textbook knowledge of this concept, because of our lack of pedagogical content knowledge, we never considered the difficulties our students might have in grasping the concept.

Similarly, most students believe that a heavier object will reach the ground faster than a lighter object when the objects are dropped simultaneously. The scientifically accepted idea is that the objects will hit the ground at the same time in the absence of air resistance. This, as we learned during the module, can be explained by Newton's second law of motion ($F_{net} = ma$) and the concept of the weight of the object. We further tested the idea through a simple activity: dropping a coin and a stiff paper disc of the same size from the same height. The coin hit the ground first. Next, we put the paper disc on top of the coin and dropped the assembly. The coin and the paper disc reached the ground at the same time. Unless teachers engage students in appropriate activities and discussion, the students will find it difficult to understand the idea that heavy and light objects hit the ground at the same time.

Students also have difficulty accepting friction and gravity as forces, because we do not consider them to be so in daily life. Bushell (2000) points out that one cannot literally see gravity and friction. For instance, when something falls to the ground, a child does not see the presence of gravitational force. Similarly, when a moving ball slows down, a child does not assume that it is because of the existence of frictional force. Once again, appropriate activities followed by discussion help students develop understanding of these phenomena.

How to Deal with Students' Alternative Frameworks

Teachers must recognize students' alternative frameworks and bring them to the surface. However, teachers should be aware of their own alternative frameworks before exploring those of students.

After analyzing the information obtained by eliciting students' ideas, teachers can design activities that challenge the alternative frameworks. Gunstone and Watts (1985) suggest that giving students opportunities to elaborate their viewpoints, challenging those viewpoints and discussing the resulting conflict between ideas help students learn the new ideas. Conceptual conflict serves as strong motivation for further learning. Gunstone and Watts further propose that the "new view must be intelligible, plausible and fruitful" (p. 100).

During the module, we learned the strategy of predict–observe–explain (POE) and realized that POE is an effective way of developing students' conceptual understanding. In fact, discussion is at the heart of the learning process. Discussion helps students clarify their alternative frameworks and enhance their understanding. Teachers should pose thought-provoking questions to make discussion meaningful for students.

We also learned that illustrating forces through free-body diagrams with arrows is a useful strategy. For example, the forces acting on an object at rest can be represented by arrows. We knew that force is a vector quantity and that arrows can represent it, but the idea that arrows can also represent the magnitude of force was new to us.

From classroom discussion, we learned that using an analogy between a known concept and an unknown concept can help students learn new information and discard or modify alternative frameworks. Clement (1987) suggests using anchoring conceptions and bridging analogy, where the targeted problem presented is analogous to a commonly understood physical phenomenon. For example, to convince students that a table exerts upward force on a book lying on it, Clement suggests using the analogy of force exerted by a spring on a hand that is compressing it. This bridging analogy helps students to imagine the force exerted by the table on the book. Similarly, a teacher can use an analogy to give students the idea that pull is experienced not only by objects, such as a falling ball, but also by Earth. The difference is that Earth, being massive, does not move like the ball does. The teacher can attach two table-tennis balls to a rubber band, place the arrangement on a table, pull the balls apart and let them go. Both balls move and collide midway. Next, the teacher can try the same thing with a table-tennis ball and a soccer ball. The soccer ball does not move, but the table-tennis ball does. The soccer ball represents the Earth and the table-tennis ball represents an object in Earth's field. Teachers must be careful to avoid giving students further alternative frameworks when using analogies and metaphors. For example, the analogy uses rubber bands, but in actual Earth–object systems, there are no such concrete materials connecting the Earth and the object.

Novak and Gowin (1984) recommend helping students "learn how to learn," which is called metacognition. Metacognition helps students to be conscious of and monitor their own learning to enhance it.

Implications

The findings of this inquiry have the following implications for teachers and teacher educators:

- Exploring students' preconceptions and using them as a starting point helps in developing their conceptual understanding.
- Students have different learning styles and interests; therefore, using a variety of teaching strategies and activities involving simple materials such as charts, pictures, drawings, free-body diagrams and careful use of analogies helps clarify the concept of force.
- Using simple language and consistent scientific terminology according to the level of the students is helpful.
- Holding a discussion based on POE and problem solving helps clarify the concept of force.
- Teachers should be aware of the common alternative frameworks held by students about the concepts of force and motion.

Conclusion

The concept of force is complex and, therefore, challenging to teach in the classroom. Students, and even adults, hold alternative frameworks in this area. The ultimate responsibility of teachers is to provide opportunities for students to rectify their alternative conceptions and gain conceptual understanding by using anchoring examples and bridging analogies. POE and hands-on activities play important roles in constructing students' conceptual understanding.

Teachers must examine and rectify their own conceptual understanding so that they can present clear concepts to students. The concept of force should not be presented as just a rote-memory item. Pedagogy and content knowledge should be integrated so that teachers can address students' alternative frameworks and design teaching accordingly.

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Helping Students Understand the Particulate Nature of Matter

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Whenever I taught about the particulate nature of matter in solids, liquids and gases, I often had difficulty explaining this abstract concept to my students. The students, in turn, had much difficulty conceptualizing the structure and behaviour of the particles, which ultimately led to difficulties in understanding the complex configuration of particles in matter at various levels.

This article focuses on studies that reveal students' alternative frameworks for the particulate nature of matter in solids, liquids and gases. Also, I suggest factors that contribute to these alternative frameworks, incorporating my own experiences in developing an understanding of this concept. Finally, in light of these alternative conceptions and difficulties, I consider strategies for effectively teaching this abstract concept.

Rationale

During my teaching experiences, students often asked me thought-provoking questions like "How small is an atom, and what does it look like?" In responding to these questions, I was often compelled to use textbook explanations. I explained concepts to my students in the same way they had been explained to me in school. I would tell them, "Atoms are very small and cannot be seen with the naked eye." During the Primary Science Module and the Lower Secondary Science Module at the Aga Khan University Institute for Educational Development (AKU-IED) in Karachi, Pakistan, I realized that my explanations did not facilitate my students' conceptual understanding of the particulate nature of matter.

This realization provoked my interest, and I decided to review the research literature on students' and teachers' alternative frameworks for the particulate nature of matter and the factors that contribute to these alternative frameworks. Most of the research links alternative frameworks to the following factors:

- The teacher's inadequate explanation of the concept
- The textbook's vague explanation and representation of particulate theory
- The atom as an abstract concept
- The use of fewer hands-on activities in teaching the concept

After my research, I planned to explore teaching strategies that could improve students' conceptual understanding of the particulate nature of matter.

Students' Understanding of the Particulate Nature of Matter

The particulate theory of matter is fundamental in science. Scientists use it to explain the behaviour of matter and the complex configuration of the materials that make up objects. The arrangement and behaviour of the particles in materials are abstract concepts because of their invisibility at the macro level. The abstract nature of matter is thus beyond the understanding of primary and secondary students, as well as many teachers.

The problem begins in the elementary science curriculum, where children are not given opportunities to classify the various types of materials they encounter in their daily lives. Peacock and Smith (1992) found that elementary students had great difficulty distinguishing between objects and the materials that make up the objects. Moreover, textbooks rarely address this satisfactorily. These difficulties remain with students until they are introduced to particulate theory in secondary school.

Research shows that understanding what *particle* means is crucial to understanding the particulate nature of matter. Students often think of a particle as matter like a grain of sugar or sand because in everyday language the word *particle* is used to refer to bits of matter in a solid. This tendency was evident in the students I worked with during the modules. The students associated the properties of the particle with those of a grain of sand. Driver et al. (1994) found that children attribute to an atom properties such as hardness, hotness, coldness and colour—the physical macroproperties of solid bits. This conception of particles often creates difficulties for students in understanding the intrinsic movement of particles and the spaces between particles in the three states of matter. I, too, used to think of atoms as bits of solid, like sugar grains; from that perspective, the particles in a solid would be motionless and have no spaces between them. This conception is contrary to the scientific view of particles of matter. Particles of matter represent atoms and molecules.

I will now discuss students' ideas about the three states of matter in light of research and my experiences. Dow (cited in Driver et al. 1994) explored secondary students' ideas about atoms and their arrangement in a solid and found that, although the students could explain particles in a solid, they could not rationalize the attraction between the particles or their rigidity. Students often do not believe that there are spaces between the particles of a solid and that these particles are in constant motion; the idea is at odds with their existing conception of solid matter. For students, this raises the question, If the particles in a solid object are moving, then why is the object itself static?

In our exploration of students' understanding of the particulate nature of matter during the Primary Science Module, we asked the students to draw the arrangement of particles in a liquid, a solid and a gas. The students' drawings did not indicate an understanding of a liquid and a solid as being composed of particles (see Figures 1 and 2). Yet their descriptions (based on their learning from the textbook) did. Furthermore, the students did not accept that these particles are constantly moving.

It is obvious from the drawings that the students see the world as concrete. Thus, a liquid is to them a continuous substance; in fact, the students' explanation of particles was that they are small droplets of a liquid, which they often associated with a molecule. The problem with the students' models of the particles of a liquid is that they do not explain evaporation and similar natural phenomena.

In the case of a gaseous state, the students had great difficulty understanding the particles of a gas and their free movement (see Figure 3).

When I taught this concept in my classroom, my students believed that they could see the movement of particles in a sunbeam falling in a dark room. They had confused dust particles with particles of a gas present in the air. My conception was similar to that of my students. This is due to the association of the visual particles of a solid substance with the abstract

Figure 1
A Student's Drawing of the Particles in a Solid

These are
many Small
particalsinside
the peice of
wood. The particals are very close to each other

particles of a gas. Similarly, Driver, Guesne and Tiberghien (1985, 106) found children explaining, “Air is something which exists but cannot be seen or touched, something which circulates, gets in and out of places where matter is unable to go.” This conception isolates air from matter, which ultimately leads to difficulties in believing that gases are present in the air and that the particles of gases are constantly moving.

When the scientific concept of particles is introduced, students find it difficult to understand because it does not match with their prior conceptions. This mismatch results in what Driver et al. (1994) call a “concept-confliction.” Does school science, including textbooks and additional resources, address students’ existing difficulties? Do current teaching approaches challenge students’ prior conceptions? No. In fact, current resources and approaches tend to create further confusion. For example, many junior and intermediate science textbooks in Pakistan provide two-dimensional examples of the atom’s structure that contradict the scientific image of the atom.

Some illustrations in textbooks in Pakistan show large spaces between the particles of a liquid. I used to think that these spaces represented some kind of continuous material holding the particles together. I had no conception of attractive forces. My alternative framework interfered with my understanding of the scientific view of particles of matter and their arrangement. The same is true with students.

Language also affects the explanation and interpretation of a concept. Sometimes students’ alternative frameworks are the result of lexical limitation or the use of words with different meanings in everyday language and scientific terminology. This can create difficulties for students in comprehending the scientific conception. For example, in everyday life, the word *particle* is commonly used to refer to solid bits and *air* is used to describe the gases in the atmosphere. Also, students have difficulty applying scientific concepts to the real world when scientific language is used to clarify the phenomena.

These alternative frameworks can hinder students’ understanding of the scientific conception of particles of matter. This then leads to difficulties in understanding and explaining many scientific phenomena. During my M.Ed. teaching, I noticed that students often had difficulty understanding physical and chemical phenomena such as evaporation, sublimation, decomposition, condensation and diffusion in terms of the particulate nature of matter. Even science teachers face this difficulty. For example, I experienced difficulty comprehending phenomena during the Lower Secondary Science Module. To me, a burning candle was an example only of a physical change. I was surprised to find that it is also an example of a chemical change. Until then, I had read in my textbooks and heard from my teachers only about physical change.

How can teachers make teaching and learning more effective for students?

My Understanding as a Teacher

Based on these findings, I have concluded that children (and adults) have their own understanding of the world. They develop their particulate schema of matter through a series of experiences. Teachers usually ignore these prior experiences in the science classroom. Therefore, students encounter conflicting conceptions. Gega (1990, 39) writes, “Children do not simply receive or absorb incoming information like a sponge; instead they actively

Figure 2
A Student’s Drawing of the Particles in a Liquid

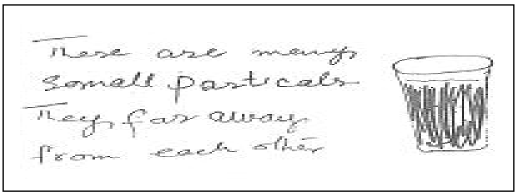

Figure 3
A Student’s Drawing of the Particles in a Gas

construct meaning by referring to related information already stored in their long-range memories from previous experiences." In other words, students do not enter the science classroom with blank minds; rather, they bring with them their own experiences and interpretations of the world.

The findings on students' ideas about the particulate nature of matter have implications for science teachers and the science curriculum. Teachers must develop effective instructional strategies and provide more comprehensive explanations. The concept of the particulate nature of matter in the three states is best introduced after the students have successfully identified the physical properties of selected materials. Teachers often introduce this concept very late and rush through it without making sure that the students understand the physical properties of materials at the macro level. The concept should be brought from primary science into secondary science in a way that helps develop students' understanding of the concept from the macroscopic level to the microscopic level.

In the case of the gaseous state, students must understand the concept of particles for different gases present in the atmosphere. Several practical activities can help children to understand that air, as an example of a gas, contains many tiny particles that are far apart. For example, students can do experiments that involve compressing air in a syringe. A simple experiment such as spraying perfume in the air followed by discussion will also illustrate that particles in the atmosphere are in constant motion, travelling from place to place.

In the case of a liquid, most of the empirical evidence reveals that under ordinary conditions students perceive liquid as a continuous substance. This was true with my students (see Figure 2). A simple experiment such as dissolving salt or copper sulphate in water will help make the concept of particles in liquid comprehensible to students. It will also establish that there are spaces between the particles and that the particles of a liquid move.

Finally, teachers' explanations greatly affect students' understanding of the particulate theory. In teaching this abstract concept, teachers must be confident enough in their content knowledge to clarify the concept for the students. Effective teachers carefully explain the concepts and expose the students to everyday situations that illustrate the concept, which consolidates understanding of science. This approach also links school science with real-life phenomena, such as the evaporation of water from clothes and the condensation of water droplets on the outside of a glass full of ice.

Implications for the Science Teacher and the Teacher Educator

These findings have significant implications for the professional development of a science teacher.

To teach this concept, teachers must provide clear explanations and representations of the particulate model at the macro level. Where the macrorepresentation of particles is not sufficient to give students a visual image of the microperspective of particles, teachers must demonstrate the hybrid model of the macroperspective and the microperspective. The research also shows that the particulate theory of matter is an abstract concept. The teacher's own content knowledge and knowledge of resources play important roles in the students' understanding; in my context, these are the most crucial issues. Helping students understand the concept is possible only when the teacher clarifies his or her own conception of the particulate nature of matter and develops appropriate resources. The teacher must have sufficient content knowledge and pedagogical content knowledge at the secondary level to teach concepts comprehensively.

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