Successful Science and Engineering Teaching

Theoretical and Learning Perspectives

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This first volume is dedicated to my first wife Judy (Feb 23, 1946–June 29, 2006), our children Ben and Sam and our grandson Josh.

As I have indicated in the acknowledgment section, this work would never have come to fruition if it had not been not for my first wife's inspiration and ideas in addition to her unflagging support and encouragement. She was a truly great teacher and was a model for my own teaching.

Acknowledgements

Firstly, I credit my first wife, Judy Kalman (Feb 23, 1946–June 29, 2006), who has had many successes in teaching writing at Concordia University and Dawson College with inspiring much of my effort to bring writing into the science classroom. She also convinced me to set aside my initial skepticism of writing methods such as journaling to attend an intensive 2-day workshop at the University of Vermont that impressed me enough to try some new techniques myself (the course dossier). She and Marjorie McKinnon were instrumental in convincing me to use collaborative groups in my teaching. At the time, Marjorie was associate director of the Concordia University centre for faculty development. My first efforts in innovative teaching based upon computer assisted instruction would never have come to fruition without the help of Ron Smith and David Kaufman. Craig Nelson, whom I have never met, inspired my idea to follow conceptual conflict collaborative group exercises with a writing activity. Without the support and many discussions provided by Mark Aulls, I would never have come to my understanding of how reflective-writing works that is demonstrated in Chapter 3. I am particularly grateful to Wim Gijselaers, Editor of the book series "Innovation and Change in Professional Education". He went far beyond the duties of an editor in helping me make major changes to the draft of this book to bring it to the present form.

I would like to thank Igal Galili for permission to include a long excerpt of one of his papers that appears in Science and Education. I also would like to thank John Wiley & Sons, Inc. for permission to include passages from an article by Dykstra et al. that appeared in Science Education and Encyclopædia Britannica, Inc for permission to reproduce an excerpt from the first edition of the encyclopedia. The short papers in Chapter 8 were originally intended as a chapter on constellation courses that I had edited as my part of a book on Science and Society. Funding never materialized and thus the book never appeared. I would like to thank Joseph L. Spradley, Arlen R. Zander, Martin A. Ludington, Alan J. Friedman, Lawrence S. Lerner, and Judith Eger (widow of Martin Eger), who kindly agreed to have these articles published here. It may have been serendipity as to my mind, they are an essential part of this book. Some parts of this book have appeared in articles I wrote for American Journal of Physics, Science and Education and Academic Exchange Quarterly and the Journal of College Science Teaching.

Contents

Preface

The intent of this book is to describe how a professor can provide a learning environment that assists students to come to grips with the nature of science and engineering, to understand science and engineering concepts, and to solve problems in science and engineering courses. As such, this book is intended to be useful for any science or engineering professor, who wants to change their course to include more effective teaching methods, to instructors at post-secondary institutions, who are beginning their careers, and as a handbook for TA's. Since the book is based upon articles that I have had published in Science Educational Research and which are grounded in educational research that I have performed (both quantitative and qualitative) over many years, it will also be of interest to anyone engaged in research into teaching science and engineering at the post-secondary level. I have also tried to include enough background so that the book could be used as a text-book for a course in educational practice in science and engineering.

The book has two main axes of development. Firstly, how do we get students to change their epistemology so that their outlook on the course material is not that it consists of a tool kit of assorted practices, classified according to problem type, but rather that the subject comprises a connected structure of concepts. Secondly, helping students to have a deeper understanding of science and engineering.

In Part I "How students learn Science", I develop some basic background on current understanding of how students try to deal with courses in science and engineering. Perhaps this part would have had a better title as "How do students fail to understand science subjects in spite of the best efforts of well-intentioned instructors". The capstone of this section, Chapter 3 deals with the fact that students have perceptions of the subject of our courses that are very different than the conceptual framework found in our courses and that it is very hard to get students to rid themselves of these notions. Those faculty, who are already familiar with the literature on conceptual change theory can skip this part and proceed directly to Part II.

Part II, "Changing Students' Epistemologies" is the heart of the book. In develops the kind of scaffolding needed to assist the student to achieve a deeper understanding of the subject such as reflective writing and conceptual conflict activities based upon methodologies involving use of collaborative groups and various forms of writing activities. It also develops the modern notion that simple conceptual change programs are not efficient since they try and attack the symptoms that prevent students' success in science courses rather than the root causes that underlie this problem. Thus this part of the book examines the whole problem of helping students to become critical thinkers and helping them to change their epistemologies.

The final part of the book looks in two successive chapters firstly at the special problems of courses for non-science students and secondly at using the computer to tutor students.

Part I
How Students Learn Science

Chapter 1
Introduction

The Beginnings of the Study of Science Education at Colleges and Universities

Many students were failing science courses not because they lacked the ability to understand the courses, but because the courses were not meeting their needs.

1.1 The Beginnings of Physics Educational Research

Arnold B. Arons, caused a paradigm shift in the way science education is performed at the post-secondary level. He realized that his "lucid lectures and demonstrations were depositing virtually nothing in the minds of the students". This important point will be met with skepticism by most science and engineering professors. Indeed, when Arnold Arons first pointed this out, it was almost uniformly disbelieved. That Arnold Arons is right is illustrated in the following anecdote: Many years ago I attended a workshop given by Graham Gibbs, a noted expert on study skills. He related the following experience.

Gibbs had been asked by a noted historian to help his class with note taking. Consequently, he attended a class to observe and then during the last 5 minutes of class speak about note taking. The professor was speaking about voyages to North America. The professor was such an engaging speaker that Graham Gibbs forgot why he was at the class. He seemed to even smell the salt water carried by the wind. With a start, he remembered why he was there and looked around the class. Surprisingly, at even the most interesting parts, students were staring out the window! This revelation led him to tear up his notes. At the end of the class, he handed the professor a transparency. "Write down the three most important points that you wanted students to take away from this class", he instructed the professor. Then he asked the students to write down the three most important points that they had derived from the class. After the professor displayed the transparency, Gibbs asked how many students had written down all of the points that the professor had written on the transparency. Not a single student raised a hand. Gibbs then asked how many students had written down two of the points that the professor considered to be the most important points that students should have derived from the class. Not a single student raised their hand. When students were asked if they had written down one of the three points that the

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professor wanted them to take away from the class, a few students near the front timidly raised a hand.

Another difficulty with our science courses is that many students have great difficulty solving the assigned problems. Until midway through high school, students can be successful at solving problems in courses by memorizing templates for every situation encountered on an examination. That is, apply different templates to different knowledge subsets. Many students lack the ability to apply principles garnered from a problem to an apparently different problem. Other students can dismiss the conceptual basis of the problems, because their epistemology is formula driven and they accept calculated answers as a goal in itself.

Arons wanted to find out what student learning problems were at a time when talks on teaching sponsored by the American Association of Physics Teachers had concentrated on presentation of material (Arons, 1998). Arons became convinced that if the mode of teaching was changed, many more students could understand science. Many students were failing science courses not because they lacked the ability to understand the courses, but because the courses were not meeting their needs. At the time it was difficult to get anyone to examine the root causes as to why students were having problems with the courses. Arons notes that scientists felt that research on educational methods for college and university science/engineering students should consist of "refining the delivery systems, the exposition, the text presentation, lecture presentation, the films and so forth, to the point that where they were so clear and so perfect that any passive student mind would assimilate them simply by having it drop in. That was what research was going to be—delivery—and there was no conception of listening to what the students said when you gave them the opportunity to reflect or talk about something".

Arnold Arons was joined in his efforts to look at the reasons why students in the introductory college and university physics courses had difficulties understanding the material presented to them in the late 1960s by Robert Karplus of the University of California at Berkeley. This led ultimately to a workshop on intellectual development (based on Piaget's theory) on Feb 1, 1975 that I along 134 other members of the American Association of Physics Teachers (AAPT) attended in Annaheim, California. The day before, I had given a talk as part of a joint symposium of the AAPT and the American Physical Society on courses in physics and society. After that meeting, Roger Dittman, the chair of the symposium, I, and some others, decided to publish the proceedings. In the end, this did not happen. My part was to be on constellation courses (such courses attempt to relate physics and its developments to history, philosophy, religion, literature, the social sciences and the other natural sciences).

My first incursion into scientific educational research occurred in 1971. I decided to implement a computer assisted (CAI) instruction program to help students who were having conceptual difficulties with the introductory course. Careful testing of questions is necessary. We introduced our CAI calculus dialogues during a summer session. We tried the dialogues on a few students at a time and immediately interviewed the students with respect to the reasons why they chose to answer in each question. The answers provided us with additional keywords, alterations in the language of the questions and the need for logic changes in the programs. We would then change the dialogues before the next few students made their attempt. We also discovered that the original dialogue was too long and needed to be split into two parts. By the end of the summer session we had confidence in our dialogues (Kalman et al., 1974). Dave Kaufman used the work as the main thrust for what must be one of the first Ph.Ds. in physics educational research (1973). His Ph.D. work was presented at a meeting of the American Educational Research Association. (Kaufman et al., 1975). See Chapter 9 for details on computer assisted instruction.

1.2 The First Graduate Programs in Physics Educational Research

Around the time that Arons began discussions with Karplus, in 1968, Arnold Arons, moved to the University of Washington. There he began a collaboration with Lillian C. McDermott. This collaboration led to the formation of the Physics Education Group at the University of Washington. This was the formal beginning of a new field of scholarly inquiry for physicists: Physics Education Research. In the 1970s, Arnold Arons supervised the dissertation of a student who received a Doctor of Arts in physics at the University of Washington. Only this one student graduated in this program, which did not have the same requirements as a Ph.D. before the program was cancelled. In 1979, the physics department at the University of Washington awarded the first Ph.D. in physics for research in physics education to a student supervised by Lillian C. McDermott, director of the physics education group. Appendix D of the proceedings of the 1998 physics educational research conference lists a dozen such Ph.D. programs and four multidisciplinary programs that include physics education research in the USA. The importance of the University of Washington group was that it was not in a faculty of education. Professors were not solely trying to apply education and educational psychology principles to the study of science, but were "investigating difficulties students encounter in the study of physics and developing curriculum to overcome these difficulties" (Prospectus for new graduate students issued by The Physics Education Group, 1987).

1.3 Educational Research in Other Science/Engineering Disciplines

Discipline-based educational research in Mathematics began around 1988. Dubinsky at Georgia State University, began his research by extending Piaget's work. He works on exploring the subconcepts students need to grasp before they can understand key mathematics concepts. He has designed activities, to help students acquire these subconcepts. Schoenfeld at the University of California applies cognitive psychology in mathematics education. There are also many faculty members in astronomy, biology, chemistry, engineering and geology, who are trying to apply the principles developed in physics and mathematics education, but there are no discipline based educational groups.

In Biology there is the BioQUEST Curriculum Consortium (Beloit College). This project, was founded in 1986 by John Jungck, editor of The BioQuest Library

BioQUEST is a group of educators and researchers committed to providing students with biology research and research-like experiences. The Consortium began with an initiative of the Commission on Undergraduate Education in the Biological Sciences, established by liberal arts college biologists in the 1960s. The Consortium currently numbers more than 4,500 educators representing a diverse range of subject areas and educational levels. BioQUEST emphasizes the acquisition of scientific literacy through the collaborative intellectual activities of problem posing, problem solving, and the persuasion of peers. A major project has been the development of computer simulations that help students understand fundamental biological concepts. For example, students studying genetics can breed fruit flies and observe the inheritance of characteristics such as eye color. They can then augment their laboratory experience with software that simulates the breeding of thousands of virtual fruit flies, leading the student to discover the laws of genetics. The Consortium also conducts faculty-development workshops and distributes a free newsletter, BioQUEST Science and Mathematics Teaching Notes, three times a year to interested members of the education community.

In Chemistry, the ChemLinks project was initiated by Brock Spencer of Beloit College and developed with members of the Midstates Science and Mathematics Consortium. Over 100 faculties from more than 42-year colleges, 4-year colleges, and universities have developed and tested modules dealing with chemistry, the environment, technology, and life processes. ChemLinks modules cover topics relevant to contemporary issues and take 3–5 weeks to complete. Students are guided to develop the chemistry knowledge needed to deal with these complicated issues. Modules incorporate collaborative activities and inquiry-based laboratory projects that replace traditional lectures, exams, and laboratories.

As for engineering education, I want to mention Felder; for example Felder, R., Felder, G. and Dietz (2002). They discuss some work going on in engineering. In 1980, a consortium consisting of eight universities and the Center for Applications of Psychological Type was formed to study the role of personality type in engineering education. Felder has been particularly active in educational research in engineering. His work is found in the many references in Felder et al. (2002). Other active research includes an emphasis on setting up and solving a wide variety of problems of increasing complexity, with memory and rote substitution in formulas playing a relatively small role (Godleski, 1984). A longitudinal study carried out at the University of Western Ontario by Rosati (1993, 1997, 1999) examined factors related to success in the first year of the engineering curriculum.

Chapter 2
Intellectual Development and Psychological Types

According to Piaget, students cannot make the transition to a higher level of intellectual development until the student has reached the right level of maturity.

McKinnon and Renner 1971 state the hypothesis: "The majority of entering college freshmen do not come to college with adequate skills to argue logically about the importance of a given principle when the context in which it is used is slightly altered".

Students develop faster if they are in an inquiry-based course rather than a teacher-centered course. It is really up to us as teachers to move these students to a higher level of intellectual development.

Zone of Proximal Development (ZPD): Judging how well students can solve problems and at what level of difficulty is in Vygotsky's opinion only one measure of the student's developmental level. In his opinion, what the student can do with the assistance of others might be in some sense even more indicative of their mental development than what they can do alone.

2.1 Introduction

In Chapter 1, two points were introduced:

1. Lucid lectures and demonstrations often deposit virtually nothing in the minds of the students.
2. Many students lack the ability to apply principles garnered from a problem to an apparently different problem. Other students can dismiss the conceptual basis of the problems, because their epistemology is formula driven and they accept calculated answers as a goal in itself.

The first point means that instructors in science courses cannot rely solely on lectures to reach students. I should make clear at the outset that I am not opposed to lecturing – in all but one of my courses, I do it all the time. Rather, it is necessary to supplement lectures with other activities. In the last chapter of Part I, I introduce one such activity; collaborative groups and in the first chapter of Part II, I introduce another such activity reflective writing, which is part of a class of activities

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called writing-to-learn. Other writing-to-learn activities are found in the rest of Part II and Chapter 9.

This chapter attempts to explore the reasons why students are unable to apply principles garnered from a problem to an apparently different problem. In the next chapter, we will examine student's epistemologies and see that students enter science and engineering courses with misconceptions and that students undergoing instruction in traditional ways do not rid themselves of most misconceptions. We will begin to examine activities that can help students deal with their misconceptions. For a student to truly succeed in this endeavor, a student must change their epistemology, which is the subject of Part II of this book.

2.2 Piaget and the Intellectual Development of Students

Why do students lack the ability to apply principles garnered from a problem to an apparently different problem? The answer to this question became clear in the 1970s. In this section, we shall see that students develop intellectually at different rates. Students, who might be thought to be of lower intellectual caliber because they "lack the ability to apply principles garnered from a problem to an apparently different problem", have usually simply not yet developed that ability. Before the 1970s, the usual attitude of Science instructors towards their students was essentially that "cream rises to the top". That is their courses would separate out the students, who could succeed at Science, from the other students. The criterion for success in Science at the university was the ability to solve problems on the end of course final examination. The notion that students did not do well on these examinations, not because of intellectual ability per se, but rather because of the lack of certain reasoning skills was shown in a study by McKinnon and Renner (1971). In this study, McKinnon and Renner looked into the reasoning powers of entering students at Oklahoma City University. Their results are shown in Fig. 2.1.

McKinnon and Renner had been influenced by Robert Karplus to undertake this study. Karplus had been using the work of Piaget to examine the intellectual development of students in physics. According to Piaget, students cannot make the transition to a higher level of intellectual development until the student has reached the right level of maturity. A child's intellectual development proceeds through a series of stages shown in Table 2.1. A student in what Piaget refers to as the concrete operational stage can "assimilate data from concrete experiments and arrange and rearrange them in his head" (Renner and Lawson, 1973) (with Tony Lawson, who is a biology professor, science education research moved out of being solely physics education research).

Looking at the big picture using inductive and deductive reasoning is beyond a student at the concrete operational stage. Students who have not progressed beyond this stage are "object bound" cannot relate to verbally stated hypotheses. They "lack the ability to apply principles garnered from a problem to an apparently different problem". Students who have reached what Piaget refers to as the formal stage are capable of reasoning with propositions only and do not need to refer to

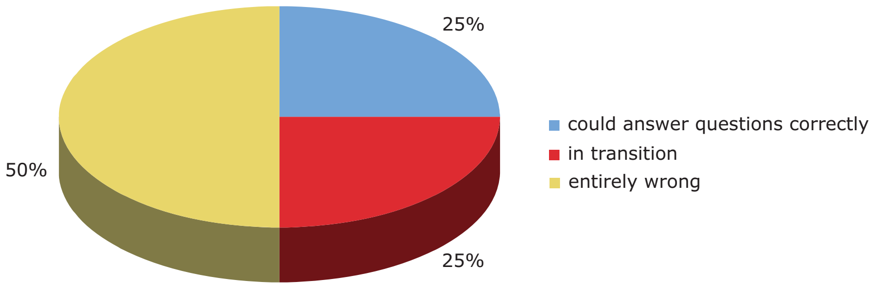

Fig. 2.1 Results for students answering McKinnon and Renner reasoning test

Table 2.1 Stages of cognitive development according to Inhelder and Piaget (1958)

Age	Stage
1–1½	Sensory-motor
1½–6	Preoperational I
(7, 8)–(11, 12)	Early concrete operational IIA
	Late concrete operational IIB
(14, 15)–Adult	Early formal operational IIIA
	Late formal IIIB

objects. We might think that students, entering post-secondary institutions would have developed beyond the concrete operational stage and made the transition to the formal operational stage. As seen in Table 2.1, Piaget had thought that the transition to the formal stage occurred around the age of 14 or 15.

2.2.1 Intellectual Development Levels of University Students

Renner and Paske (1977) (Fig. 2.2) found that "approximately 50% of entering college freshmen are concrete operational. In view of this fact, concrete instruction seems to recommend itself to colleges for the first two years". Prigo (1978) points out five studies that similarly find that "approximately 50% of incoming college students have not reached the intellectual stage of development where they can think abstractly (i.e. scientifically)". McKinnon and Renner (1971) find that many of the 50% of students, who have not reached the formal level are not even close to that stage. Seventeen percent of all college freshmen do not conserve quantity and another 10% failed to recognize the equivalence of volume. Thus, 27% of students, who were tested, were at the lowest concrete operational state or less.

Arons and Karplus (1976) put it this way: "Although the various investigations are beginning to reveal significant and interesting differences between social and economic groups, the grand averages have been emerging, with very little variation throughout the age and school level spectrum: about one-third have made the