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How We Think About and Prepare to Teach Physics

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How we think about and prepare to teach physics

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Abstract. We have been preparing physics teachers in the same manner for many decades. Yet, physics education research reveals for some observers disturbing evidence of little or no change in understanding the phenomena occurs as a direct result of physics instruction from elementary school through the college years. The apparent compatibility between these learning results and prevailing paradigm enables the construction of a description the paradigm. If it can be demonstrated that there is even just one alternative paradigm from which powerful alternative pedagogical practice is derived, are we not obligated to change how we prepare to teach physics?

INTRODUCTION

"...a physics major has to be trained to use today’s physics whereas a physics teacher has to be trained to see a development of physical theories in ... students’ minds."1

In recent decades those interested in science teaching and learning have investigated very carefully science learning. The rise in attention to an explanation of the origins of knowledge and evidence supporting the explanation has inspired a focus in physics education research (PER) on students’ conceptions of the phenomena studied in physics.

EVIDENCE ABOUNDS...

The “modern” era of this research began in the 1970’s, but articles on students’ conceptions about phenomena have been uncovered as far back as 1903. In the 1980’s several bibliographic efforts on students’ conceptions were coalesced into one bibliography.2 Maintained by Reinders Duit at the University of Kiel, it now contains 6,314 entries.

This body of research supports one of the more robust findings in educational research:

The general outcome of science instruction is no significant change in students’ conceptions of the phenomena studied in the classroom.

It is not possible in the space available to do more than show a few examples and invite the reader to consult the bibliography:2

Kinematics-acceleration: “The conceptual difficulties with acceleration that were encountered by the students in our study appeared to be very persistent. Often, …the procedures used by a particular student were the same before and after instruction. … A significant number of students from a wide variety of courses confused the concepts of velocity and acceleration. … At the completion of instruction, fewer than half of the students demonstrated sufficient qualitative understanding of acceleration as a ratio to be able to apply this concept in a real situation."3

Electric circuits: “We have examined students’ explanations of an extremely simple electric circuit, one that involved only three major components. …many students were unable to interpret the circuit correctly. … One suspects, therefore, that a significant proportion of students in physics courses will have this type of difficulty. …the misconception persisted in some students who had been through a calculus-based course in electricity which included five experiments on electric circuits."4

RECENT EXAMPLE IN DETAIL

To sample more of the population in order to find out how widespread these conceptions might be, multiple-choice format diagnostic instruments were developed. One diagnostic is the Force and Motion
Conceptual Evaluation (FMCE). This diagnostic is designed to discern the nature of a student’s conception or “physical theory” concerning the explanation of motion in terms of force, not merely to determine whether a student knows the “correct” answer.

An analysis of the FMCE responses of students in standard algebra-trig-level and calculus-level introductory students from state and private institutions of higher education across the U.S.A. over a dozen years was conducted by Dykstra. The analysis of this data was guided by that of Thornton.

Using a more coarse scale of analysis than Thornton, two keys to the responses in the FMCE were generated. One key is the set of choices consistent with a person-on-the-street (pots) explanation of motion in terms of force, i.e., velocity goes as the force. The other key is a set of choices consistent with a Newtonian-like (N) explanation of force, i.e., acceleration goes as the net force. Comparing a student’s responses to the each key yields a score in the range of 0 – 15 indicating the degree to which the student’s responses match the corresponding explanation of motion in terms of force.

### Table 1: Results of Traditional Instruction

<table>
<thead>
<tr>
<th>Algebra-Trig Level Intro Physics</th>
<th>Traditional, Content-Driven Instruction</th>
<th>Averages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effect Size (st dev)</td>
<td>Normalized Gain Loss</td>
</tr>
<tr>
<td>West Coast Public Univ. A</td>
<td>1990</td>
<td>99 0.59 -0.47 0.14 -0.09</td>
</tr>
<tr>
<td>&quot;Prairie State&quot; Public Univ.</td>
<td>2002 SP 112</td>
<td>0.66 -0.40 0.13 -0.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculus Level Intro Physics</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>North East State Public Univ.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>72 0.47 -0.30 0.15 -0.06</td>
<td>9.6 1.7 8.5</td>
</tr>
<tr>
<td>West Coast Public Univ. B</td>
<td>1999 W 87</td>
<td>0.60 -0.62 0.22 -0.30</td>
</tr>
<tr>
<td>1999 SP 73</td>
<td>0.38 -0.36 0.12 -0.01</td>
<td>9.1 2.3 7.6</td>
</tr>
<tr>
<td>2000 SP 115</td>
<td>0.59 -0.50 0.15 -0.10</td>
<td>9.2 2.4 7.2</td>
</tr>
<tr>
<td>West Coast Private Univ.</td>
<td>2000 SP 38</td>
<td>0.54 -0.08 0.09 -0.05</td>
</tr>
</tbody>
</table>

TABLE 1 gives some of the results of this analysis. Effect size is the shift between the pre and post scores in units of pooled standard deviations. Normalized gain is the fraction of the possible increase in the N score. Normalized loss is the fraction of the possible decrease in pots score.

From the average pre-scores in TABLE 1 these typical students, who have all had instruction on motion and force at least once before, are still answering in a manner consistent with the pots explanation. In the whole sample of students in this on-going study, now numbering nearly 1150 students, there have been only 5 whose pre-responses earned an N score high enough to be convinced they were using a Newtonian-like view of motion and force. With the second or third treatment of traditional, content-driven instruction in this study, while there is some change, the change is still very small after the semester’s instruction by Ph. D. physicists.

### EXPLAINING THE EVIDENCE

The prevailing paradigm apparently accounts for this long-standing state of affairs. If not, physics teaching and physics teacher preparation would have changed long ago. This enables us to develop descriptions of the standard paradigm on a phenomenological basis.

In the prevailing paradigm, the nature of the enterprise of physics teaching can be characterized in the following way:

*Physics teaching is the presentation of the official canon of physics by approved methods for the benefit of those who deserve it.*

As with other core elements of a paradigm, it is taken as given and so, goes unchallenged.

The word “deserving” means that a student has met two criteria in order to “learn” physics. (1) The student must be capable. Not all people are capable of this feat because “physics is hard.” (2) The student must work diligently. Failure to meet one of these two criteria is one of the general explanations why most students do not understand physics at the end of the semester. The other general explanation relates to the teaching of physics.

In this enterprise, in order to prepare to teach physics first one must know the official canon. Girded with the official canon, one needs be able to apply approved methods of presentation. Thus, degree programs for the preparation of physics are designed. Take the standard degree program in physics. Trim a little away to make room for the methods class and a chance to practice the methods in student teaching. There is no attention to the necessary fundamental issue Niedderer indicates the preparation of a physics teacher: the ability “...to see a development of physical theories in ...students’ minds.”

If the teacher presents the canon properly, the “deserving” student will “get” it. The canon is a commodity transferable from teacher to student under suitable circumstances. This is founded on a realist view of the nature of knowledge which postulates that: “...the objective existence of physical reality that can be known to our minds...with an ever growing...
precision by the subtle play of theory and experiment. The nature of knowledge, a taken as
given foundational aspect of this paradigm, is
whatever it is, independent of human beings. By clear
implication this knowledge can exist outside the mind
in order to be transmitted by physical means from
teacher to student and in order to have an independent
existence.

Having presented the established canon by
accepted methods, the responsibility of the teacher has
been met. If the necessary characteristics for student
success satisfactorily account for the “learning”
outcomes of physics teaching, there is no need to look
any deeper. Thus, we can understand the lack of
research in students’ understandings over literally
centuries until recent decades and resistance to the
findings of such research. No wonder that the findings
from PER have had so little effect on physics teaching.
In the standard paradigm, we are apparently doing
about as good a job as possible at physics teaching.

AN ALTERNATIVE PARADIGM

In the standard paradigm TABLE 1 is an example
of what we can expect of the most deserving students,
the science and engineering majors, in courses given
by instructors who know the established canon and use
approved methods. It should then be the case that
students less likely to be “deserving” would not be
able to show any more change in understanding than
the science and engineering majors.

Let us take a look at students more likely to be the
“less deserving.” The first six rows of results in
TABLE 2 are from non-science, non-engineering
majors in a course that satisfies general university
requirements in science. The data was collected using
the FMCE and analyzed in the same way. These
students experienced a pedagogical practice rooted in a
different paradigm. Clearly, the standard paradigm
belief that there is a limited set of “deserving” students
is contradicted by these results. The instructional
materials used were developed for the Motion and
Force Modules of the Powerful Ideas in Physical
Science (PIPS) Project of the American Association of
Physics Teachers.

Comparing TABLE 1 and TABLE 2, it is quite
clear that the shift in the response patterns is
considerably greater. The revised PIPS instruction
average effect size of 2.5 standard deviations and 61%
normalized gain in the N scores for the college
students far exceeds that of the science and
engineering majors in TABLE 1. Clearly the notion
that the status quo in physics teaching is about as good
as we can expect is totally discredited by this repeated
example of a different pedagogy based on an
alternative paradigm.

TABLE 2: Results of Alternative Paradigm Instruction

<table>
<thead>
<tr>
<th>Conceptual Physics--Standard PIPS Instruction</th>
<th>Student Understanding-Driven Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year</strong></td>
<td><strong>Term</strong></td>
</tr>
<tr>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Boise State University</td>
<td>1999 SP</td>
</tr>
<tr>
<td>Boise State University</td>
<td>1999 FL</td>
</tr>
<tr>
<td>Conceptual Physics--revised PIPS Instruction</td>
<td>2000 FL</td>
</tr>
<tr>
<td>Boise State University</td>
<td>2001 SP</td>
</tr>
<tr>
<td>Boise State University</td>
<td>2002 FL</td>
</tr>
<tr>
<td>Boise State University</td>
<td>2004 SP</td>
</tr>
<tr>
<td>High School Level--Standard PIPS Instruction</td>
<td>2001 FL</td>
</tr>
<tr>
<td>High School Level--Standard PIPS Instruction</td>
<td>2001 FL</td>
</tr>
</tbody>
</table>

PREPARING TEACHERS IN AN ALTERNATIVE PARADIGM

We arrive back at Niedderer’s statement: “a
physics teacher has to be trained to see a development
of physical theories in ...students’ minds.” The
phenomena studied in physics courses are what
the physical theories are about. Sadly, most physics
courses are not studies of the phenomena, but drill-
and-practice at the canon. They do not train a person to
see the development of explanatory knowledge in her
students’ minds.

A physics teacher candidate needs to be meta-
cognitive about the development of his own
explanatory knowledge and to interact with others
about this meta-cognition. The future teacher needs to
observe students to discern evidence of their
explanatory knowledge. The teacher candidate should
become familiar with the PER research literature. The
physics teacher candidate should also practice
strategies intended to maximize the chances of
disequilibration in students and to facilitate their
development of new explanatory schemes. Also, the
teacher candidates should study the historical
development of physical theories and the philosophical
analysis of the nature of knowledge and its
development.

In this alternative paradigm, the emphasis is on the
nature of understanding. The students’ understandings,
physical theories in student minds, are the primary objects of study and manipulation; not the phenomena, the apparatus, lab skills, mathematics or the canon. The teacher must be able to construct in her own mind effective models of the students’ understandings and to pick examples of experience the students will decide are challenges to their existing understandings.

PREPARING PHYSICS TEACHERS

To meet the challenge, we need to develop courses and degree programs to bring out the ability to see the development of physical theories in students’ minds. Two examples of courses to this end do exist.

A course sequence with an intense focus on the development of more powerful understanding and the ability to clearly, rigorously describe experiences within this understanding is offered at the University of Washington by the Physics Education Group (PEG). The course sequence is Phys 407 & Phys 408: Physics by Inquiry. At Boise State University a course is being developed to introduce teacher candidates to the “the development of physical theories” in the minds of students. The course, PHYSCI 497/597: Alternative Conceptions in Science, engages teacher candidates in two major activities. Teacher candidates study articles in the bibliography to develop a catalog of descriptions of conceptions their future students are likely to have when they come to class. They also study student work: responses on diagnostics, posters developed by students describing their ideas, writing assignments, electronic course discussions, etc. to discern evidence of student conceptions and of change in their theories.

CONCLUSION

Conventional, content-driven physics instruction fails at leaving students with deeper understandings of the phenomena they study. Student-understanding driven pedagogy does result in significant change in student understanding. Its existence places on us the burden of responding in our own practices and in how we prepare the physics teachers who come after us.

We need to assist physics teachers at developing the skills, habits, and points of view that enable the ability “to see the development of physical theories” in the minds of students. Courses to this end are being developed. More such courses need to be established and built into whole degree programs, not only for physics teachers, but also for all teachers.

ACKNOWLEDGMENTS

Without students willing to share their ideas none of this work nor the data would have been possible. Without the opportunity to interact with the PER community what quality there is in this work would be seriously diminished. On several occasions funding from NSF provided support as some of the data was collected and ideas herein were formulated.

REFERENCES