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Physics Education Research in the United States: A Summary of its Rationale and Main Findings

Investigaciones sobre la Enseñanza de la Fisica en los Estados Unidos de Norteamérica: Fundamentos, Resumen y Hallazgos

Wilson J. González-Espada

Department of Physical Science, Arkansas Tech University

1701 North Boulder Avenue (McEver 34E), Russellville, AR 72801,

e-mail: wilson.gonzalezesp@mail.atu.edu

Abstract

Despite our experience, academic preparation and effort, it is very difficult to teach quality physics to secondary and post-secondary students. We now recognize how difficult is for them to make connections between physics and everyday phenomena, to rationalize the use of a particular formula for a given problem, and to go beyond algebraic substitutions to really make sense of physics in a meaningful way. Although science educators have been doing some research in physics teaching and learning, more recently physicists with an interest in understanding the details of physics teaching, learning, and assessment have become much more involved in doing research. With their expertise and perspective, these physicists, commonly known as physics education researchers, have contributed significantly to the science education literature. The purpose of this article is to provide a rationale for North American physicists to become involved in education research and to summarize some of their main findings and how they should impact the practice of teaching physics internationally.

Keywords: physics education research, physics teaching, learning, assessment, science education, United States.

Resumen

A pesar de nuestra preparación académica, experiencia y esfuerzo como maestros de física, enseñar esta materia de manera efectiva resulta muy difícil. Muchos de nuestros estudiantes confrontan problemas al relacionar la física con su diario vivir, al analizar la selección y uso de ecuaciones matemáticas para problemas o ejercicios específicos y al trascender la simple sustitución numérica para explorar hasta qué punto la física es significativa y tiene sentido. A pesar de que en el pasado investigadores en el área de enseñanza de las ciencias han estudiado el proceso enseñanza-aprendizaje de la física, recientemente varios grupos de físicos profesionales han demostrado interés en cómo la física se aprende, cómo debe enseñarse y de qué formas debe evaluarse, involucrándose cada vez más en trabajos de investigación sobre el tema. Estos físicos o “Physics Education Researchers”, con su pericia y especial punto de vista, han contribuído de manera significativa a la literature sobre la enseñanza de esta materia. El propósito de este escrito es exponer qué motivó a estos físicos profesionales a dedicarse a la investigación educativa, cuáles han sido sus hallazgos principales y cómo esta información es capaz de influenciar la enseñanza de la física a nivel internacional.

Palabras clave: investigaciónes en enseñanza de la física, enseñanza y aprendizaje de la física, enseñanza de las ciencias, Estados Unidos de Norteamérica.

Introduction

Research has shown that many students who took introductory physics courses in the standard lecture-recitation format learn to solve quantitative problems, but do not develop a real understanding of physics concepts, and keep most of their misconceptions in this area (Redish & Steinberg, 1999; Thacker, Kim & Trefz, 1994). Redish (1994) simplified this reality by sharing his frustration as a college physics professor:

> Many of us who have taught introductory physics for many years recall with dismay a number of salient experiences: a reasonably successful student who can produce a graph but cannot say what it means; a top student who can solve all the problems but not give an overview or simple derivation; many students of varying abilities who memorize without understanding despite our most carefully crafted and elegant lectures (p. 796).

Implicitly in Redish's words are two underlying truths: that the lack of understanding in introductory physics is visible across all possible students' abilities, and that, in spite of the professor's best efforts, many students finish a physics course with "serious gaps in their understanding of important topics" (McDermott & Redish, 1999).

Of course, these are not "modern" news items. Robert A. Millikan, a Nobel Prize winner experimental physicist and excellent teacher, expressed his views about physics lecturing when he was assigned to revise the curriculum of the introductory physics course at the University of Chicago in 1896 (Millikan, 1950):

> I had to become thoroughly disillusioned by the ineffectiveness of the large general lecture courses of which I had seen so much in Europe and also in Columbia, and felt that a collegiate course in which laboratory problems and assigned quiz problems carried the thread of the course could be made to yield much better training, at least in physics (p. 40-41).

If traditional methods of teaching are not producing the scientific process and product learning that students need, implying that the difference between what is taught and what is learned is often greater than most instructors realize (McDermott, 1993), then, is there something that can be done?

In the last twenty years, physicists have begun to approach the problems and challenges of physics teaching, learning, and assessment from a scientific perspective by conducting research on the learning and teaching of physics (McDermott & Redish, 1999; Redish & Steinberg, 1999). Physics education research has been growing both in quantity, and in the quality and rigor of the research. This growth is international (McDermott, 1991). A difference must be made, however, between physics education research and science education. In the latter, science educators are the one doing research. In physics education research, professional physicists are the ones who combine a deep understanding of physical processes with the interest in unraveling the intricate details of how students process the physics information they receive.

More than one dozen physics education research groups are working all over the United States (University of Maryland, Montana State, University of Nebraska-Lincoln, North Carolina State, University of Washington-Seattle, Ohio State, University of Massachusetts-Amherst, Arizona State, Dickinson College, Kansas State, Indiana University, University of Maine, University of Minnesota, Northern Arizona University, University of Oregon, Rensselaer Polytechnic Institute). Also, many others are researching in Latin America (e.g. Universidad Católica del Perú; Universidad de Caece in Argentina; Universidad Pedagógica de Matanzas in Cuba), Europe (e.g. University of Aveiro in Portugal; University of Vienna in Austria; University of Glasgow, United Kingdom; Adam Mickiewicz University in Poland; Universities of Trento and Naples in Italy; Vilnius Pedagogical University in Lithuania; Universities of Augsburg, Berlin, Bremen, Kiel, and Postdam in Germany; Universidad de Alicante in Spain), and Australia (e.g. Sydney University). These physics educators are producing excellent pieces of research that are beginning to draw a much clearer picture of the processes of physics learning, what strategies can improve physics teaching, and what alternative assessment techniques can be useful in physics courses. A summary of the main findings of physics education research is presented in the following section.

Main Findings of Physics Education Research: Physics Teaching and Learning

Physics education is a much more complex event than most people think. Some of the results of physics education research, consistent with general contemporary approaches to teaching and learning, can be condensed in the following assertions:

First, physics must be perceived by the students as an exciting way to actively explore our physical world, and not as an inert and encyclopedic body of knowledge (McDermott, 1991). Physics is much more than a textbook, or a CD-ROM. Physics is the active involvement of the observer in trying to identify and explain the mechanisms that makes the physical world what it is, instead of something else; behave the way it does, instead of some other behavior. Studying physics requires, more than anything else, a mind prepared to be receptive to new ideas and able to view things from a variety of perspectives. It also requires curiosity and a deep sense of respect for the "complex simplicities" of physics laws. That curiosity and desire for a better understanding of our surroundings may not be promoted by reading a textbook, listening to a lecture, or by substituting numbers in a formula.

Second, engaging students in primarily laboratory based, inquiry oriented, hands-on activities in which social interaction is present (Redish & Steinberg, 1999) promotes student engagement, active learning, and academic achievement (McDermott, 1991). The only way in which students can develop scientific skills, attitudes, and abilities is by doing physics, not by merely hearing about physics. The laboratory is one of the most powerful tools that physics educators have. In the laboratory our students observe most of the laws of physics in action. However, not all laboratory activities are equally appropriate. Only those laboratories in which the students apply their knowledge to new situations, or those in which they must explain the reason for some physical phenomena, are meaningful. That meaningfulness, in turn, will deepen their learning. Critical thinking and conceptual understanding must be stressed in all laboratory activities. In terms of social interaction, research presents evidence that supports the argument that learning is a social process in which dialogue and debate among peers and the instructor can help student dissipate their doubts and misconceptions, while developing strong and correct schemas about physical processes. An application of this finding is the use of curricular materials that promote student engagement, active learning, and academic achievement, for example Workshop Physics (Laws, 1997), or Physics by Inquiry (McDermott, 1996).

Third, by teaching students in the way we were taught, we overlook that individual differences cause difficulties for some students to learn (McDermott, 1998; McDermott, 1991). We often assumed that physics students would learn just as we did (Redish & Steinberg, 1999). Unfortunately, a hard-to-believe reality is that if some particular mode of instruction worked for me, it may not work for everybody else. The students need an enthusiastic and intellectual engagement with physics ideas.

Research suggests that teaching by telling is not an effective mode of instruction for most students, and that "no matter how lucid the lecture, nor how accomplished the lecturer, meaningful learning will not take place unless students are intellectually active" (McDermott, 1993). By using multiple strategies of instruction, it is possible to reach more students than with what Silverman (1995) named the lecture-oriented "standard model" of college teaching. For example, when I taught the concept of free fall, I used different methods: (a) a historical argument, in which some classical texts are studied and interpreted, (b) logical inconsistencies that arise when the student's explanation of free fall did not explain some phenomenon, (c) mathematical argument, in which the free fall formulas are presented and interpreted, both quantitatively and dimensionally, (d) audiovisual resources, in which I presented videos of free falling objects and measurements can be taken, and (e) hands-on experiences, in which student throw objects with different mass and observe how they fall.

Fourth, concepts, reasoning ability, and representational skills should be developed in stages, in a spiral way within the same unit (McDermott, 1991). Research suggests that the development of conceptual understanding is a principal component of meaningful problem solving (Redish & Steinberg, 1999). That is something that students do not develop just by working numerical problems, but by explicit instruction of qualitative interpretations of physics problems. Did you know that some students fool us by doing great in numerical problems solving, but cannot explain how the solution of a problem is an inevitable consequence of the laws of physics? An example of this is the inability of some students to explain the physics behind the math in many instances, like when they fail to explain why putting more resistors in parallel will reduce the effective resistance, even though they might be extremely skilled in using Ohm’s law to calculate its value. If a student can explain verbally why a system behaved in the way it did, that means that the student is thinking at a higher cognitive level, and that should be one of our most important goals in college science teaching. An application of this finding is to emphasize equally quantitative and qualitative questions. In the case of the pendulum, for example, a quantitative question might be to determine the length of a pendulum with a period of 2 seconds. A qualitative question might be to determine how and why the period of the pendulum will change if we use a steel chain instead of a string.

Fifth it is necessary to emphasize the development of connections between the theoretical aspects of physical phenomena and real life applications (McDermott, 1991). Research demonstrates that it is very difficult for humans to learn facts, concepts, and principles without some kind of contextual information. As a known context is presented, students can use it as a scaffolding to build their understanding. There are everyday applications of physics concepts and laws around us. It is just a matter of taking some time to find the best examples, and use them in instruction.

An application of this finding in the assignment of special projects that let students discover the applications of physics in their everyday activities. This can be as simple as analyzing how various forces affect the design of a bridge, or as complicated as determining how many physics concepts they can find in a car and explaining them.

Sixth, to foster the acquisition of analysis skills to solve a problem from multiple perspectives, the back and forth "translation" between real and graphical representation of a problem must be stressed (McDermott, 1991). One of the skills that must be developed in formal education settings is the one related to graphical interpretation of particular phenomena. Graphs can be found in different forms of mass communication, including research journal in science. This skill is much more relevant in physics, especially because a single graph can provide an incredible amount of data about the behavior of a physical system. Interestingly enough, there is evidence that suggests that, although a student can draw a graph correctly, his/her ability to interpret and "squeeze" all the useful meaning from that graph may be surprisingly limited. For example, the concept of linear acceleration can be investigated from a geometrical perspective, an algebraic perspective, or an everyday perspective, like motion sickness, or an automobile breaking distance.

Seventh, since some misconceptions can be deeply embedded in a student's mental representation of physical phenomena, those misconceptions must be explicitly addressed with adequate instructional strategies, including conceptual change (McDermott, 1998; McDermott, 1993; McDermott, 1991). The conceptual change instructional strategy include four main components: (a) the student questioning of their own beliefs related to particular topics in physics, (b) the explanation of incoherencies between what the student think is correct, (c) the presentation of the correct physical explanation, and (d) the development of a carefully guided process to change student's incorrect beliefs (Dykstra, Boyle & Monarch, 1992). The most effective way to address misconceptions is knowing them, show that scientific inconsistencies are the result of the wrong notions, and demonstrating that the correct scientific explanations are much better in explaining the physical world. For example, there is a common misconception that astronauts in orbit experience weightlessness because of the absence of gravity. If this were true, then they will not be able to stay in orbit, according to Newton's First Law. What causes weightlessness is the constant falling of the spaceship around the Earth. This can be explained to students very carefully and thoroughly to erase the wrong idea.

However, this is easier said than done. It is extremely hard to convince students when their common sense ideas has serve them well all of their lives, no matter how carefully one presents the physics' case. It is hard, but not impossible.

Main Findings of Physics Education Research: Physics Assessment

As we all know, an essential component of education is evaluation. The usual measures of assessment common to physics courses, including memorizing definitions, cloning proofs made by the professor, and solving standard quantitative problems, although easier to grade do not provide detailed information on whether students are achieving the broader objectives of physics education (McDermott, 1991). In general, traditional evaluation, when it is done correctly and purposefully, can help us measure what the students know by the indirect way of measuring what they do not know, that is, by counting the wrong answers and comparing them with the right answers. Authentic problem solving in physics involves much more than "having agility with mathematical manipulations" (Redish & Steinberg, 1999).

Physics education research encourage a variety of ways to evaluate physics learning McDermott (1991), for example, suggest two ways: To use a recorded demonstration to ask in-depth questions about what is physically occurring: why is the system behaving in a particular way, what predictions can be made if one or more of the variables are changed, or if the apparatus is modified. Explanations of reasoning, and the presence and strength of misconceptions are emphasized and assessed in the dialogue.

This strategy is also supported by other researchers, like Lawrence (1994), who strongly suggest the use of video technology as a form of alternative assessment. His rationales are that: (a) video demonstrations require much less time for set up, (b) the teacher be more sure that nothing will go wrong, as usually happens in experimental set ups, (c) video demonstrations are less expensive compared to purchasing, maintaining, and replacing supplies and equipment, (d) video demonstrations provide an excellent opportunity to contrast and discuss students predictions, and the outcomes of the demonstration, (e) skills and process that cannot be measured in paper and pencil tests can be evaluated, and (f) they provide practical ways for students to work with the scientific methods.

Other researchers suggest other ways to evaluate students. Hewitt (1994) argues that we should rely less on quantitative problems and that we should give more emphasis to questions and problems that require qualitative reasoning and verbal explanations. There is research evidence that most students can solve quantitative problems in physics, but they do not fully comprehend the qualitative and conceptual subtleties of the problem and, as a consequence, they do not develop a "functional understanding of physics", defined as "the ability to do the reasoning needed to apply appropriate concepts and physical principles in situations nor previously encountered". Redish & Steinberg (1999)

encourage students to work a problem and use the technique of "thinking aloud" about the rationale behind the way to solve the problem.

Meltzer and Manivannan (1996) use the strategy of small group problem solving and debating during lecture time. These researchers develop a variety of strategies for promoting active learning in a typical lecture class, including the use of flash cards with letters to respond to problems that the group is solving as a whole. If there is not an answer that the majority agrees on, then arguments can be presented. Wenning & Mueshler (1996) use non-directed research projects, in which the physics instructor provides a topic and the students must come up with an experimental way of solving the problem, to assess their student's knowledge.

Finally, other science education researchers (Austin & Shore, 1995; Dykstra, Boyle & Monarch, 1992) favor the use of conceptual maps to determine their student's level of comprehension in physics. Dykstra, Boyle & Monarch (1992) summarizes the utility of conceptual maps in assessment:

> Conceptual maps enable instruction to focus on explicitly depicted aspects of student's understanding through the kinds of distinctions students make when they think about the physical world. That is, the maps organize and make explicit the essential content of student's knowledge which can be used to help select experiences to disequilibrate (challenge) it … [conceptual maps] enable us to monitor the learning process more precisely and to provide content to the instruction intended to effect that learning. (p. 633).

This brief summary of alternative assessment in physics demonstrates that there are many ways to determine the quantity and quality of student's understanding in physics, beyond paper and pencil tests. Of course, alternative assessment strategy should be implemented based on the context of particular classrooms.

Concluding Remarks

The professional literature proposes that there are at least three general ways in which physics education research can be a powerful tool for science instructors: (a) as a source of information about specific difficulties faced by physics students, (b) as a source of research-proven effective strategies for instruction, and (c) as a source of information for designing more meaningful and valid assessment instruments and procedures (McDermott, 1991) by designing distracters that reflect common mistakes and misconceptions that students present (Redish & Steinberg, 1999). These suggestions can be generalized to other areas of science, although research as extensive and complete as physics education research might not be readily available.

Notice that I did not provide step-by-step suggestions about how to improve your teaching based on the results of physics education research. Because of the multiplicity of factors than influence the education process, there is not a recipe for effective science teaching. Only after a period of thought and meta-cognitive introspection, in which we examine the evidence and the literature related to physics education research, we can determine which of these findings, and to what degree, can be implemented in our classrooms and our specific situations.

It is generally accepted that teaching is not rewarded with the same weight as research in some institutions of higher education. But it is the commitment to our students, and not external rewards, what should guide us in becoming excellent science faculty members. Physics education research is just an example of the varied amount of teaching, learning and assessment strategies that are shown to be more effective than traditional instruction in college science, and that are available in the professional literature in this area. The only additional ingredient is the desire to maximize our students' understanding of science.

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