

EMPIRICAL INVESTIGATIONS OF STUDENT UNDERSTANDING

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Why study student understanding of physics? For some of us, “because it’s there” is a large part of the reason. However, many of us are also strongly committed to using our findings to improve teaching at the classroom level. One type of investigation that has proven fruitful as a guide for improving student learning is discussed in the article. The underlying goals and assumptions are discussed in general terms. A specific example provides a context for discussing the interpretation of student thinking.

I. INTRODUCTION

The perspective on research and curriculum development of the Physics Education Group (PEG) at the University of Washington (UW) was described by Lillian C. McDermott in the proceedings of a 1988 conference as follows:

“The point of view taken here is that of a physics instructor whose primary motivation for research is to understand better what students find difficult about physics and to use this information to make instruction more effective.” [1]

The practical, empirical approach of McDermott and her colleagues has been shared by a number of other influential researchers. Rosalind Driver and Gaalen Erickson eloquently presented a similar set of goals and principles in a 1983 article:

“We ought to engage in research endeavours which will uncover student frameworks, investigate the ways they interact with instructional experiences, and utilise this knowledge in the development of teaching programmes. ...It should be emphasized however, that we are not claiming that this sort of work is atheoretical. Clearly it is not, and cannot be, as some form of theoretical commitment or speculation will always be present in any form of empirical enquiry. ...We must make certain assumptions about the nature of knowledge and of the nature of the learner which establish the frame for interpreting and manipulating the teaching/learning environment. The

important point is whether the frame itself is the subject of inquiry. In the problem-oriented research programme the primary focus is the development of instructional practices which improve science teaching, as opposed to making a claim about the model or theory being used.” [2]

II. FRAMEWORK FOR RESEARCH AND CURRICULUM DEVELOPMENT

The framework within which the UW PEG operates includes *goals* (which reflect our values), *assumptions* (which reflect our interpretation of empirical observations), and *specific objectives* (which reflect our judgment about the most productive way to proceed).

A. Goals

The primary (but not only) goal of our group is to improve student understanding of physics. For the purpose of this paper, a student will be considered to ‘understand’ a topic if, when faced with a problem not previously encountered, he or she selects the appropriate concepts and principles, applies them correctly, and constructs a logically sound solution. (Note that this criterion includes not only what the student is *capable* of doing, but what he or she actually *does*.) Accordingly, instruction will be considered to be improved if more students do this more of the time.

We work toward this goal by conducting research, disseminating the results, and developing and disseminating instructional materials for standard university physics courses [3] and courses that help prepare K-12 teachers to teach physics as a process of inquiry [4].

B. Underlying assumptions

It is well known that in spite of careful instruction by skilled and knowledgeable teachers, many physics students respond incorrectly to certain types of questions that require qualitative reasoning rather than formula manipulation. In some topic areas there is extensive documentation in the research literature of common student errors [5]. Such observations form the basis for several generalizations that guide our efforts in research and curriculum development [6]. Two assumptions that are consistent with the evidence are discussed below.

- *Many student errors reflect the presence of knowledge, not its absence.*

As McDermott observed in 1988: “Students have certain incorrect ideas about physics that they have not learned through formal instruction, or at least that they were not intentionally taught.” [1]

- *Taking students’ ideas into account is necessary (but not sufficient) for more effective instruction.*

Many efforts to improve instruction involve changes in the presentation of the concepts by re-sequencing topics or through the use of novel demonstrations or simulations. Other efforts target the mode of presentation – shifting from traditional “passive” lecture instruction to more interactive, “student-centered” approaches. In many cases in which improvements in student learning have been convincingly documented, there are many variables that are difficult to separate. Chief among these is the familiarity of the instructor (or curriculum designer) with student difficulties with the specific topics in question. A study by Hake that is often cited as evidence that “interactive engagement” techniques are more effective than traditional ones is a case in point. The study dealt with a topic (Newtonian mechanics) for which a great deal is known about student difficulties [7]. However, it is not clear that the use of “interactive” techniques would be as effective for topics in which little is known about student difficulties. In fact, there is evidence that instruction in a ‘studio’ or ‘workshop’ format may not be significantly more effective than traditional lecture-based instruction [8]. Therefore we continue to view detailed, topic-specific knowledge of student knowledge as

indispensable (although not sufficient) for improving instruction.

C. Specific objectives

In 1988, McDermott outlined a research agenda that continues to guide fruitful investigations and that has broadened in scope to include topics beyond the introductory level.

“To guide the design of curriculum, we need answers to questions such as those below for all topics in introductory physics:

- What ideas do students have before instruction that might interfere with the development of a sound conceptual understanding?
- Which ideas can be built upon to promote student learning and which need to be changed?
- Are linguistic elements of such critical importance that they need to be singled out for special attention?
- What conceptual difficulties do students encounter during instruction?
- What strategies can help overcome these difficulties?” [1]

These questions can be answered only through empirical investigation. Intuition, experience, and specific theories all provide guidance but are not reliable predictors.

III. EXAMPLE OF AN EMPIRICAL INVESTIGATION

The major sources of data used in our research are students’ responses to questions asked in interviews and on quizzes or course examinations. The design of these problems and the analysis (both qualitative and quantitative) of the responses are illustrated in detail in many other articles by our group. A brief example is given here.

In a report of an investigation of student understanding of the first law of thermodynamics, we identified several *specific difficulties* [9]. This term refers to incorrect or inappropriate ideas, or flawed patterns of reasoning. The investigation centered on a series of problems on the adiabatic compression of an ideal gas. In the most common version, used in interviews and on written questions, students were asked to consider a quick compression of the air inside a sealed plastic

bicycle pump. They were asked whether the temperature of the air would increase, decrease, or remain the same, and to explain their reasoning. They were expected to recognize that since the compression is quick, it can be considered to be adiabatic and therefore the work done by the piston will raise the internal energy. They were also expected to treat the air as an ideal gas and conclude that the temperature will increase [10].

Most students stated correctly that the temperature would increase. However, few gave correct explanations. Many seemed to assume that the smaller volume would ensure higher temperature. Some students argued (erroneously) on the basis of the ideal gas law that a smaller volume implies a higher temperature [11]. Others referred to processes at the microscopic level. The explanations varied in complexity. Some represented mechanistic reasoning: "If the distance between the molecules is smaller, then there is more chance of a collision between the particles, and so when they collide energy is released and the temperature rises." Other explanations more closely resembled statements of fact: "The molecules of gas are closer together, making the energy higher."

Describing student ideas in terms of difficulties is, in part, an acknowledgment of this variation. The decision to discuss student knowledge in terms of difficulties also reflects the practical, instruction-oriented approach taken by our group. Identification of a difficulty provides a target for instruction. Moreover, in communicating with traditional physicists (including most university physics instructors), the idea needs no further explication and no introduction of new terminology.

Hammer takes a different, but similarly inclusive, approach in describing student knowledge as consisting of 'resources' [12]. In this framework, tackling a physics problem is viewed as a process of activating resources. Student errors are attributed to the activation of inappropriate resources, of which diSessa's *phenomenological primitives* or *p-prims* are one species [13]. As Hammer points out, resources and difficulties are not complementary. However, they are related. For instance, the p-prim 'closer means stronger' can be thought of as a value-

neutral resource. It is appropriate in some circumstances (*e.g.*, the attraction or repulsion between magnets varies with the distance between them) and inappropriate in others (*e.g.*, the brightness of lightbulbs in a circuit does *not* vary with proximity to the battery). We interpret the latter claim as a *difficulty* that must be addressed in instruction on circuits.

Niedderer and Schecker identified two types of descriptions of student knowledge:

"Operational descriptions give reports of student behavior in specific situations. Theoretical descriptions try to make inferences about conceptions, concepts, ideas, schemes, or abilities students show over a range of different situations." [14]

Descriptions of student difficulties may be of either type (or somewhere in between), depending on the circumstances.

Some difficulties we identified were described in 'operational' terms. For example, 'arguing erroneously on the basis of the ideal gas law' is operational in the sense that it reports *what* happened, without speculating as to *why*. Other difficulties can be described in more theoretical terms. We often label ideas that students express explicitly and defend strongly in the face of evidence and counter-arguments as 'beliefs.' The term is a convenient label for an idea that seems to underlie a common student response to a specific physical situation. The claim that the temperature of the air in the bicycle pump increases because collisions between molecules 'give off heat' or 'release energy' is an example.

It must be emphasized that the existence of a belief is an *assumption* on the part of the researcher. Specifically, if students *act as if* they believe something and if instruction intended to modify that belief is successful, then the assumption is justified *for this purpose*. (The criteria for making and retaining an assumption may be different if the goal is development of a theory of learning.) In many cases, such assumptions have proven highly productive. For instance, McDermott and Shaffer took into account student 'beliefs' about current and voltage in developing highly effective instructional materials on electric circuits [15].

IV. CONCLUSION

The example presented in this paper illustrates the challenge of trying to understand student thinking. Any description of knowledge in which a complex web of ideas is reduced to simple summary statements is risky. In communicating the nature of student ideas one must be careful not to strip away the context in which they are expressed. The nature of the description should reflect a judgment as to what is most useful to the intended audience – instructors, curriculum developers, or researchers. Ultimately, the critical requirement is that the evidence be described in sufficient detail that the reader can evaluate the interpretation offered.

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