How Do You Hit A Moving Target? Addressing The Dynamics Of Students' Thinking

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Abstract. From the standpoint both of research and instruction, the variable and dynamic nature of students' thought processes poses a significant challenge to PER. It is difficult merely to assess and characterize the diverse phases of students' thinking as they gain and express understanding of a concept. (We might call this the "kinematics" of students' thought processes.) Much harder still is uncovering the various factors (instructional method, student characteristics, etc.) that influence and determine the trajectory of students' thinking. (We could call this the "dynamics" of students' thinking.) The task of deciphering the mutual interaction of these factors adds to the challenge. I will outline some of the initial work that has been done along these lines by various researchers, and I will identify some directions for future research that I think might be fruitful for workers in PER.

INTRODUCTION

Our goal as educators is to better understand the *process* of student learning so as to be able to influence it more effectively. Students' learning of physics is characterized by a knowledge state that is a generally increasing function of time. Often, however, the inherent time-dependence of this process is given inadequate examination, in part due to the difficulty of investigating students' thinking at multiple time points during its evolution.

Characterization of a time-dependent process requires a bare minimum of two probes at different time points, while a varying rate requires three such probes. Alternatively, a probe may be carried out over a continuous (brief) time interval and variations during that interval observed. (This type of probe is characteristic of so-called "dynamic assessment" [1] and the "teaching experiment" [2].) In any case, such repeated probes of student thinking are logistically difficult to implement within actual classroom settings involving ongoing instruction.

In this paper I will outline some of the work that has been done by various researchers in exploring changes in student thinking over time, and I will identify some directions for future research that I think might be fruitful for workers in PER.

ASSESSING STUDENTS' MENTAL STATES AT A PARTICULAR TIME

It is useful to recall the complexity of a thorough probe of students' thinking at even a single point in time. Such a probe would require analysis not only of a students' ideas about a set of physics concepts and the relationships among them, but also of the ways in which the student perceives and implements the learning process itself.

Students' "Knowledge" State

At any given moment a student has a collection of ideas related to specific physics concepts, and a related set of ideas corresponding to the expressed or implied interconnections among those concepts. These ideas are in significant part dependent on context, that is, they often depend on the physical setting of a given problem, the form of representation employed in the problem, and so forth. One can try to assess this

CP790, *2004 Physics Education Research Conference*, edited by J. Marx, P. Heron, and S. Franklin

collection of student ideas by posing questions involving diverse contexts and a variety of representations [3-9]. In this fashion one can try to determine the "distribution function" of ideas (sometimes called the "mental model" [4,5]) characteristic of a particular student, or of a particular student population.

Students' "Learning State"

Another key component of students' thinking is the set of their ideas related to the practice of learning physics, along with the methods they actually employ to learn. This includes their study methods, their attitudes toward physics and physics learning, their motivation to learn, etc. One can attempt to assess these factors through a number of methods including observations of learning practices [10], attitudinal surveys [11,12], "dynamic assessment" [1], "teaching experiments" [2], etc.

CHARACTERIZING THE PROCESS OF STUDENT LEARNING

If we are to carry assessment beyond a single time point, we must determine the specific parameters needed for an assessment of the overall learning process. If we can obtain observable data corresponding to those parameters, we then need to determine how exactly to analyze those data.

Qualitative Parameters

The basic elements of a time-dependent analysis of student learning include *sequences* of the various parameters that characterize students' knowledge. These include the following: (1) The *sequence of ideas* and of *sets* of ideas (mental models) developed by a student during the process of learning a set of related concepts; (2) The *sequence of difficulties* encountered by a student during that learning process (difficulties are related to "*ideas*," but are not necessarily the same thing); (3) The *sequence of knowledge resources and study methods* employed by the student during that process; (4) The *sequence of attitudes* developed by a student during that process.

The fundamental assumption in this analysis is that all of the various elements may (and probably do) undergo change over time. There will always be a question of how rapidly this change occurs and, consequently, how frequently an assessment must be made in order not to overlook key stages of the process.

Quantitative Parameters

In addition to qualitative parameters, one can identify a number of potentially relevant measures to which numbers can be attached. These include the following: (1) The progression in *depth of knowledge* as measured by probability of correct response on a set of related questions (e.g., score S, range [0.00,1.00]); (2) The *average rate of learning* R of a set of related concepts (e.g., $R = g/\Delta t$ where g = normalized gain calculated using $S_{pretest}$ and $S_{posttest}$); (3) The *variations in the learning rate* V encountered by a student during that process (e.g., $V = \Delta R/\Delta t$); (4) The *time-dependent distribution function* characterizing the idea set of a student population. (This might be defined through a method analogous to that of Bao [4,5].)

Phase I: "Kinematics" Of Students' Thinking

The first level of investigation is to characterize the pattern of students' thinking as it *evolves* during the learning process. In principle the objective is to determine, at a number of different points in time, the set of students' ideas, difficulties, learning resources, etc. with respect to a well-defined concept or set of related concepts. (For instance, one might acquire data related to students' understanding of Newton's second law of motion.) Then, based on this time-series data, one can try to determine the *normal course of evolution* of those ideas and difficulties under a variety of standard learning situations.

Phase II: "Dynamics" Of Students' Thinking

The second phase of the investigation would be to determine the factors that *influence* the evolutionary pattern of students' thinking during the learning process. One might describe this objective as an attempt to answer the question, "What are the social and pedagogical forces that determine the path of a student's 'learning trajectory'?" More specifically, one could ask: What is the *relative* influence of (a) individual student characteristics (preparation, background, etc.) and (b) instructional method (including pedagogical techniques, classroom environment, etc.), on the observed sequences of ideas, difficulties, and attitudes? A crucial question would be to determine the extent to which the observed sequences might be altered due to efforts of the instructor and/or the students.

PREVIOUS WORK

A number of workers have investigated various aspects of the issues discussed in this paper. However, many related issues have been explored little or not at all. Here I will outline some of this previous work.

Sequence of ideas: A number of investigators have described shifts in mental models by analyzing the differences in typical student response patterns between pretests and posttests [4,5,7-9]. Savinainen et al. have also explored such patterns at mid-instruction points (between pre- and post-instruction) [8,9], while other workers have attempted to describe and characterize the sequence of ideas acquired by students during the learning process in a more detailed, step-by-step fashion [13-15]. Some workers (e.g., Thornton [3] and Dysktra [6]) have postulated the existence of specific "transitional states," which are well-defined sets of ideas occurring during the transition from novice to expert thinking.

Sequence of difficulties: The generalizability of *patterns* of learning difficulties is well established [16], but that of difficulty *sequences* has not been thoroughly investigated. In general, there has not been much detailed exploration into how the specific learning difficulties students encounter may change and evolve over the course of a semester or year.

Sequence of attitudes: There is evidence of regularities in attitude change during instruction [11], but also evidence that these regularities are dependent upon instructional context [12].

DYNAMIC ASSESSMENT

As an alternative to assessment of student thinking at a single instant (through a quiz, exam, etc.), a preplanned sequence of questions, hints, and answers may be provided and the students' responses observed throughout a time interval. This method has been formalized under the rubric "Dynamic Assessment" [1]. One first attempts to determine what types of problems the students can solve on their own, without additional assistance. One then continues by providing carefully measured and sequenced assistance through hints and answers, in order to assess the students' ability to respond to instructional cues with efficient learning. Among the assessment criteria are the amount of assistance required, the rapidity and depth of response, etc. A similar method is the "teaching experiment" [2], in which a mock instructional setting is used as a means to probe students' responses to various instructional interventions.

QUESTIONS FOR FUTURE WORK

Here I will list a number of questions that might serve as a basis for future investigations on these topics. For convenience, I will divide them according to whether they refer primarily to *characterizations* of the evolutionary process of students' thinking ("kinematics"), or to the factors that *influence* that process ("dynamics").

I. Kinematics

(1) Can one confirm the existence of *well-defined* "transitional mental states" related to learning of specific concepts, that is, sets of ideas concerning those concepts that are intermediate between those of a novice and those of an expert? If such transitional states do exist, do they vary among individuals according to differences in their background and preparation? Are different transitional states observed in traditional and reformed instruction?

(2) More broadly, one can ask: Does the individual "mental model" distribution function evolve according to some characteristic pattern? (This "distribution function" refers to the collection of student concepts related to a specific topic, as reflected for instance in the set of responses to a group of related diagnostic questions [4,5].) Is the evolution pattern correlated with individual characteristics (demographics, preparation, etc.) and/or with the nature of the instructional method?

(3) How does the population "mental model" distribution function evolve in general? (Here we refer to the average set of responses given by an entire class of students, or a number of similar classes.) Is the evolution pattern correlated with population demographics?

(4) Are there common patterns of variation in learning rates? For example, do learning rates typically increase or decrease monotonically throughout the course of a semester?

(5) Is the magnitude of the learning rate at an early phase of the process correlated with the long-term learning rate [17]?

(6) Is the picture of a student's learning trajectory provided by "dynamic assessment" (or teaching experiments) over a brief time interval more complete and accurate than that provided by a single standard quiz or exam?

II. Dynamics

(1) Can one trace back, in a causal fashion, the set of student ideas at a particular time, to the specific set of ideas and difficulties that had been acquired at an earlier time? More specifically: To what extent does the student's present set of ideas and difficulties determine the pattern of his or her thinking in the future?

(2) Are transitional states (if they exist) actually influenced by differences in students' preparation, and/or by the nature of the instructional method?

(3) Are the sequences of individual and population "idea distribution functions" (mental models) influenced by individual background and/or instructional mode?

(4) Are learning-rate variations influenced by individual background and/or instructional mode? More broadly, what are the factors that influence the trajectory of student learning, and what is the nature of the interaction among the various determining factors?

SUMMARY

The dynamic, time-dependent aspects of the student learning process are essential features of that process, and yet they are logistically difficult to observe and analyze. Future investigations in this area have the potential to yield valuable information that could help instructors increase the effectiveness of instruction in physics.

ACKNOWLEDGMENTS

The work of the Iowa State Physics Education Research Group has been supported by grants from the Iowa State University Center for Teaching Excellence, and from the National Science Foundation through the Division of Undergraduate Education, Division of Research, Evaluation and Communication, and Division of Physics.

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15. There are also a number of "case studies" in the literature in which very detailed, diary-like expositions follow small numbers of students on almost a week-to-week basis. It is hard to know whether and to what extent such descriptions might be generalizable to broader student populations.
16. For example, see the many studies referenced in McDermott, L. C., and Redish, E. F., *Am. J. Phys*. **67**, 755-767 (1999).
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