DOCUMENT RESUME

ED 364 425 SE 053 940

AUTHOR	Hewson, Peter W.; Olsen, Timothy P.
TITLE	"Emotional Distress" in Teaching Force and Energy: A Physics Teacher's Story.
INSTITUTION	Wisconsin Center for Education Research, Madison.
SPONS AGENCY	National Science Foundation, Washington, D.C.
PUB DATE	93
CONTRACT	NSF-MDR-8954668
NOTE	32p.; Paper presented at the Annual Meeting of the American Educational Research Association (Atlanta, GA, April 1993).
PUB TYPE	Reports - Research/Technical (143) -- Speeches/Conference Papers (150)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	Case Studies; High Schools; *Physics; Science Activities; *Science Instruction; *Science Teachers; Secondary School Science; Secondary School Teachers; *Teacher Attitudes; *Teacher Behavior; Teaching Methods

ABSTRACT

Knowledge-in-action is a teacher's form of inherently knowing one's actions in the context of daily teaching activities. This article focuses on one physics teacher in a study and describes and analyzes his knowledge-in-action. Observations and interviews were used as data. Among the findings are the teacher's practice can be delineated into two modes, a classroom mode and a laboratory mode. Students in the classroom mode are expected to mentally reason as they are guided by the teacher. In the laboratory mode, the teacher did not hand out detailed instructions for performing labs as he expects students to develop procedures for themselves. The teacher treats Newton's laws of motion as unquestionable givens. (PR)

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"EMOTIONAL DISTRESS" IN TEACHING FORCE AND ENERGY:

A PHYSICS TEACHER'S STORY

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The research reported in this article was supported by a grant from the National Science Foundation (Grant No. MDR-8954668) and by the Wisconsin Center for Education Research, School of Education, University of Wisconsin-Madison. Any opinions, findings, or conclusions are those of the authors and do not necessarily reflect the views of the supporting agencies.

Presented at the Annual Meeting of the American Education Research Association, Atlanta, GA, April 1993.

SE 053 940

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Introduction

The thoughts that teachers have about the content and students they are to teach influences the way in which they will teach. This idea, which accords with common sense and common experience and is also supported by a growing body of research, lies at the heart of our research, of which the study reported here is a part. Our argument is as follows: if we want to improve science teaching (and national reports are calling for just that) and science teaching depends on teacher thinking, then research on experienced science teachers is needed to inform the goals of science teacher certification and professional development programs. The goals of our research project, Project DISTIL, are to (a) describe the nature of the conceptions of teaching science, including disciplinary knowledge, held by a sample of experienced high school biology, chemistry, and physics teachers (to be reported elsewhere at this conference), and (b) identify relationships between these teachers' conceptions of teaching science and their knowledge-in-action.

This paper focuses on one of twelve teachers studied in Project DISTIL. Mr. Dodgson teaches high school physics. He, like the other teachers in the project, deals with the commonalities of curriculum, students, and teachers in a uniquely individual manner. In particular, he has a deep understanding of the qualitative aspects of physics and their essential role in the interpretation and use of physics formulas. Thus, for him, what are fundamental to physics are not the equations or problem solutions so explicitly a part of most physics curricula, but the ideas, the concepts that provide meaning to mathematics. The essence of a physics problem, for him, is working at the interface of theory and experiment where decisions of subtlety and complexity need constantly to be made to ensure the validity of any conclusions drawn.

After outlining the theoretical basis and the methodology of the research, we present an overview of Mr. Dodgson's classroom, and we analyze in detail a few significant events as evidence for assertions we make about his practice.

Theoretical Basis

This paper draws upon data gathered as part of Project DISTIL, an NSF funded project designed to investigate the relationships among disciplinary knowledge, conceptions of teaching science, and student learning in high school biology, chemistry, and physics (Hewson & Hollon, 1989). The general approach adopted in the project is a variation of a constructivist perspective (Magoon 1977, Wittrock 1985, Fosnot 1989, von Glasersfeld 1989, Wheatley 1991). This assumes that humans construct their own knowledge, using their existing knowledge in order to do so. This construction of knowledge takes place within a context of social interaction and agreement. In the process of construction, people develop relatively stable patterns of belief. They construct knowledge in ways that to them are coherent and useful. Since the construction process, however, is influenced by a variety of social experiences, the knowledge constructed by each individual is not normally completely personal and idiosyncratic. Existing knowledge and social agreements about meaning limit not only how new experiences are interpreted, but also determine what is perceived in any situation. Thus, two individuals exposed to the same events may perceive and interpret them in very different ways, depending on their individual underlying knowledge and beliefs, within the contexts of the norms around them.

From a constructivist point of view, then, we can argue that teachers build conceptual structures in which they incorporate classroom events, instructional concepts, socially approved behaviors, and explanatory patterns. In this project we have distinguished between two aspects of a teacher's knowledge. On one hand, there is the general, formalized propositional knowledge that a person may possess (Schön, 1987, p. 40). In the present study we see this knowledge as including the set of ideas, understandings, and interpretations of experience concerning the nature and content of science, the nature of learners and learning, and the nature of instruction and teaching that the teacher uses in thinking about teaching science. We describe this as a science teacher's conception of teaching science (Hewson & Hewson, 1989).

On the other hand, there is a teacher's knowledge-in-action: that form of knowing inherent in a teacher's actions in the context of daily teaching activities (Schön, 1983, 1987). Knowledge-in-action is partly conscious and partly implicit in actions, and may be accessible through reflection on particular events. We do not view knowledge-in-action as synonymous with a conception of teaching science; for example, it is highly contextualized and partly implicit. At the same time we do not claim that it is discrete from it. The relationship between a teacher's knowledge-in-action and conception of teaching science remains for us an open question.

Design and procedures

In this article we focus on one teacher in the study--Mr. Dodgson, a high school physics teacher--and we describe and analyze one component of his knowledge--his knowledge-in-action. In doing so, we do not imply that his conception of teaching science or the knowledge of other teachers in the study are of less interest. On the contrary, some of these aspects are reported in companion articles (Lyons & Freitag, 1993; Hewson & Kerby, 1993). We do, however, recognize that it is necessary to present sufficient detail so that a reader can make his or her own judgments about assertions we make. We also believe that Dodgson, like other teachers, is a unique professional whose story is worth recounting. Thus the research question addressed in this article is:

What is Dodgson's knowledge-in-action?

Teacher Selection

The criteria for inclusion in the project were that teachers should have a minimum of five years teaching experience and a willingness to contribute to the profession. For practical purposes they also needed to be within about 30 miles of the research site. Of the twelve project teachers, we selected

Mr. Dodgson as the focus of this article for different reasons. Pragmatically we wanted a teacher we had both observed; this restricted us to two physics teachers. Of these two, we chose Dodgson because from the outset there were aspects of his practice that had struck us as unusual. In particular, he strongly emphasized the qualitative aspects of physics, in contrast to a more mathematical, quantitative, equation-using approach. We describe his approach below in some detail. In choosing Dodgson, however, we do not wish to imply that other physics teachers in the study were less interesting. We will analyze them in the future.

Dodgson has taught for more than 20 years at a large suburban high school in the Midwest. He has run many workshops for local elementary, middle school, and high school teachers; he has presented at regional, state, and national conferences; and he has participated in a federally funded project aimed at upgrading physics in the upper elementary and middle grades.

Determination and analysis of knowledge-in-action

The knowledge-in-action of the participant teachers was determined by combining data obtained from intensive observation and multiple interviews. First, the observations of a teacher's classroom during the teaching of relatively self-contained topics describe each topic as enacted by the teacher and experienced by the students. Second, post-topic interviews (or PTI), designed to probe the reasoning behind instructional decisions made while teaching the topic, were conducted after each of three topic observations. These observations and interviews help us to develop insights into the practice of experienced high school science teachers in developing and carrying out instruction. In other words, the combined analysis of observations and post-topic interviews provides a representation of the teacher's knowledge-in-action.

Observations. The observations of a teacher's lessons were recorded in different ways: in writing and on videotape. The data collected on a daily basis thus ideally included written observation notes, a written summary of the lesson, written comments made by the observer of particularly interesting features in the lesson, the videotape of the lesson, and the coding of the observation for modes of instruction, levels of discourse, cognitive demand of students, and content development.

The categories mentioned above (modes, discourse, cognitive demand, and content) were used to generate descriptions of patterns of practice and identify significant and representative events in each topic. Representative events were identified using primarily the topic summary and coding outcomes. They were events that were typical or characteristic of the class, e.g., one teacher regularly circulated through the class after posing some problems and guided students' practice by asking further questions rather than telling them the answer. Significant events tended to be unique and out of the ordinary and were probably first addressed in the comments file. We have found events to be out of the ordinary in two ways; first, with respect to that individual's practice, i.e., they are significant because they are unrepresentative; and second, with respect to the practice of other teachers, i.e., some events in a particular teacher's classroom could be both representative of his or her practice and significant. Since it was from the observer's perspective that they were seen as being significant in both cases, there is a measure of idiosyncracy in their choice. This is a consequence of the methodology that we understand to be more a strength than a weakness.

Post-topic interview. The post-topic interview (or PTI), conducted with each teacher after each topic, was constructed around representative and significant events that had occurred in the teaching of the topic in order to understand why the teacher taught as he or she did. We found that the PTI was very useful in gaining insights into a teacher's rationale for instruction and his/her basis for making reasoned decisions.

Analysis Procedures. The analysis of teacher-topics was centered on different, overlapping issues that arose from both data and theory, e.g., from the representative and significant events used in the post-topic interview, from the conceptual and methodological structure of the project, and from the ongoing process of analysis. The process of analysis was cyclical as we returned to different data repeatedly in a constant comparative cycle to generate grounded assertions about teachers' beliefs about science, learning, instruction, and teaching science. We sought to balance a priori analysis frameworks with emergent data frameworks. The origin of an analysis issue, i.e., theory-based or data-based, was thus of less consequence than its ability to provide understanding and explanation of a particular teacher-topic. The different origins do, however, explain the combination of unique and common issues in a teacher-topic analysis. Several outlines for analyses were developed and continue to change as each analysis lends its uniqueness to the study. By maintaining the complete teacher-topic as the unit of study, i.e., as a context for looking at teacher decision making, instructional strategies, transformations of concepts, and expectations for student learning, we hope to illuminate differences and similarities between teachers, between topics, and between science disciplines.

Presentation of outcomes. We present the outcomes of our analysis of Dodgson in seven different segments. For the most part these segments are based on particular episodes that we describe in some detail. We believe that contextualizing them with this level of detail adds greatly to the meaning and the power of our interpretations of Dodgson's practice.

The segments were chosen with different criteria in mind. These are listed in Table 1. First, we have chosen segments that are representative of Dodgson's practice. The first segment in particular sets the context of his classroom for later segments by describing his normal modes of instruction, and the fourth through seventh segments describe patterns with respect to his understanding and use of equations (segments 4 & 5), his monitoring of students' comprehension (segment 6), and the concerns he believes his students have with the content (segment 7). The second criterion we have used derives from the need to consider the fundamental components of teaching science: the nature of science, the nature of learning and learners, and the nature of instruction. While each of these components is present in each segment, the focus of the second, third and fourth segments is physics content; of the fifth segment: instruction; and of the sixth and seventh segments: learning and learners.

Table 1 about here

The third criterion for selection of segments was significance. We chose events that seemed to us to be unusual and out of the ordinary. While we recognize that this obviously depends on our personal opinion, we have tried to be explicit about the basis of our choices. This criterion has influenced our choice of all except the first and sixth segments. The remaining segments are significant in different ways: the third segment seems unrepresentative of his practice, and the remainder (segments 2, 4, 5, & 7) appeared significant to us in comparison with the practice of other physics teachers.

In this article, all stated or implied comparisons of Dodgson's practices are with those of physics teachers outside of the current project. While we intend to draw comparisons with other teachers in the project in the future, the interim state of our analysis precludes us from doing that in this article.

Description and Interpretation

The first of the seven segments sets the context of Dodgson's classroom for later segments by describing his normal modes of instruction. The remaining six segments are labelled with a key phrase or sentence spoken by Dodgson that, for us, epitomizes the segment.

We start those segments that deal with a localized set of events by listing the assertions that we make about Dodgson's knowledge-in-action arising from the events presented in the section. Next we provide a description of these events that includes extracts from classroom dialog and post-topic interviews. This is followed by our interpretations of those events, expressed in part in the assertions listed at the start of the section. The assertions are printed in *italics*.

The analysis is based on the observation of two topics and subsequent post-topic interviews (or PTI). The first topic on Newton's Second Law (or N2) lasted for 12 days, and the second on Energy (or EN) lasted for 15 days. Quotes from the classroom are referenced thus--N2 d5--meaning Newton's Second Law topic, day 5; and from the post-topic interview thus--PTI EN 659--meaning the Energy topic, post-topic interview transcript line 659.

The Context: Dodgson's Classroom

Dodgson's room is made for physics. Light-colored walls and long vertical windows keep the room bright. The classroom space is divided into two areas, one for 'lecture' and the other for lab. Nine physics tables with electrical outlets occupy the lab area. Around the outside of the room are shelves, cupboards and counters, most of them filled with stacks of equipment and boxes. The activities one can observe within the room on different occasions are likely to be of two very different kinds:

> *Dodgson's practice can be delineated into two modes, a classroom mode and a laboratory mode.*

During the laboratory mode, responsibility for deciding how to proceed has been transferred to the students. Pointedly, Dodgson does not provide any written lists of procedures for the students to follow during labs. Rather, the students generate and write their own procedures to fulfill simple goal statements, such as, "Use cart with spring, predict how far up an incline the cart will coast."

During the two units observed, students worked on lab exercises that varied from using simple apparatus to explore the meaning of Newton's Second Law lab to using observations they made on a field trip to the Great America amusement park. To enable students to be successful given the paucity of procedural instructions, Dodgson supports the transition from classroom mode by focusing on the qualitative aspects of the experiments. He knows that students will "flounder" when beginning their labs but expects that they will learn by thinking through procedures for themselves. He outlined what he would say:

> [L]et's do a real experiment, let's have you do something, [decide what] you want to find out, how do you do it, what physics do you know, what is the theory, what are the other elements of doing the lab, and then let's write about it. (PTI N2 781)

Carrying out experiments this way required a lot of time. For example, three days of student work was devoted to the Newton's Second Law lab. The Great America lab was preceded by a day of independent student planning and followed by two days of writing it up.

During the classroom mode, Dodgson does most of the talking. Student answers and questions are usually brief and he elaborates on physics ideas at length. He makes the decisions of how to proceed during class. He tends to stay out in front of the long demonstration table to talk, question, gesticulate, and enjoin the students in a running exploration of physics ideas, events, and relationships. He only goes behind the front table when he needs to write on the board or carry out a demonstration so that the students can see from their loose rows of desks. He talks with a deliberate and thoughtful intensity about the subject at hand and that, most definitely, is physics. He expects the students to listen, observe and think carefully about what takes place during the class.

During the classroom mode, students are expected to mentally reason along with Dodgson as he guides them through an exploration of the ideas of physics.

The following discourse illustrates how he acts to guide and anticipate the students' thinking.

> T: A couple of days ago I approached it this way, look at the Second Law. What's got that acceleration? Whatever this is? [Points to formula on board] However much inertia that is. How much inertia is that? Say it.
> S: Two kilograms
> T: Two kilograms. Why didn't you ask about my arm? Isn't that accelerating upward too? The answer is, I didn't ask about my arm. I didn't ask what the tension was in my muscles. I asked about the force I was exerting on the brick. And you caught it just like that. Remember in a couple of days how easy that was.
> T: [Points to board] This is not the acceleration of anything you want to think about, it's the acceleration of what I specifically asked about. Therefore the mass is that object's inertia, the thing you're thinking about, not the whole world or even other things attached. Of course now you might ask about the masking tape and the polyethylene [around the brick]. So see, that would be a good question, you'd have me . . . for our purposes there are only two forces. [T writes on board--Points to board] Somebody say what you have for this force.
> S: [Inaudible]
> T: Ok. Thank you. The weight of the brick. Now I've got to be careful here. (N2 d10)

"Keeping control"

In introducing the central laboratory activities of the topic on Newton's 2nd law, Dodgson departed from the common pre-lab practice of focusing on procedural details to that outlined in the following assertions:

> *Dodgson does not hand out detailed instructions for performing labs; he expects students to develop procedures for themselves.*
>
> *Dodgson extensively models the qualitative analysis involved in using physics theory to perform a valid empirical investigation.*

Description. The major lab activities of this topic were two related labs in which students were asked to find out how the acceleration of a dynamics trolley depended on a) the force with which the trolley was pulled and b) the mass of the trolley. Dodgson set the scene as follows:

> It's been a long time since we've done a real honest-to-goodness experiment, as a class. We've fooled around some, we've done some testing and stuff, done some self-correcting problems, but now we've got a real honest-to-goodness lab. An experiment: there's an independent variable, there's a dependent variable. Which means all those other things come into play, like don't lose control: when you are changing the force to see how it affects acceleration, you can't change anything else. You haven't thought about this for twenty years like I have. There are some things that might change kind of accidentally. Be alert for changing conditions. When you write the procedure, make it clear to the reader what you did to maintain control. You will look at this, and some things will occur to you as being a good idea.
>
> "Let's do it this way, not that way."
> "If you do it this way it's not going to work."
> "No, this look, let me show you, you have to go like this."
>
> Why and what you were thinking about: that goes in the procedure.
>
> "We accelerated some carts."
>
> That's useless. I have no idea what you did. Get it in the procedure. What did you do special to make sure it would work? (N2 d3)

After introducing the laboratory--by briefly reviewing Newton's Second Law and outlining the experimental tasks mentioned above--Dodgson spent about 30 minutes talking about the physics involved in making measurements. He did not give out a set of procedural steps to be followed. Instead he explained how the formal equations to be used imposed constraints on what could be counted as valid experimentation. It was thus the explicit task of the experimenters to ensure that the procedures they used did not violate these constraints. To exemplify this, much of his discussion focused on measuring a dynamics cart's acceleration (the dependent variable in both labs) by measuring time and distance, and using the formula

s = v(0)t + 1/2at**2

If the initial velocity v(0) was 0, one could solve for a in terms of s and t. So much for the mathematics; what of the physics? Dodgson said:

> Will it [initial velocity] automatically be zero? No! You have to make it be zero, folks. When must it be zero? When you start the stopwatch. You start the motion when you start the watch. It's not obvious. Be cautious! (N2 d3)

He went on to consider (1) that the acceleration needed to be constant to use the above formula, and (2) what had to be done in the lab to achieve it. As with a zero initial velocity, constant acceleration doesn't happen automatically: students had to make it happen.

Once the students had started the lab, Dodgson circulated among the groups while quietly watching their work. Virtually all of Dodgson's comments to students related to their need to maintain the physical conditions required for a valid application of the formula. For example:

> You're not keeping the force constant . . you'll have to get better at it in a way you're not even thinking of.
> If you saw Steve doing something wrong, you'd let him know, wouldn't you?
> I don't know whether it's an accident but you're the first group I've seen doing something right . . (N2 d3)

The following day, Dodgson spent another 20 minutes recapping the previous day's discussion and explaining what he saw students "doing . . wrong" in the lab. The students then returned to the lab a second time and essentially repeated the experiment all over again, though this time with a much greater sense of purpose and efficiency.

Interpretation. The lab was the basis of two related assertions, the first of which is:

Dodgson does not hand out detailed instructions for performing labs; he expects students to develop procedures for themselves.

In other words, Dodgson did not tell students the lab procedures (in terms of specific physical actions); rather he expected them to work these out for themselves and write down in great detail (in their lab reports) what they did. This pattern is consistent across all laboratories done in both topics. The second assertion is:

Dodgson extensively models the qualitative analysis involved in using physics theory to perform a valid empirical investigation.

Dodgson, in spending a great deal of time modelling the arguments that link a mathematical formula to a particular experiment, demonstrated the full extent of meaning tucked into the minimalist nature of the mathematical symbolism. This, in our view, represents a major departure from common practice and is significant because of the amount of time Dodgson gave to it: 20% of the unit on Newton's Second Law. Dodgson stated his reasons for doing this as follows:

> [From my earlier teaching experience, when students] formed some portion of the procedure, they were doing something that made sense to them. Whether it was right, was not the point I guess, and it usually was, but they were doing something which when I asked them why they were doing that, they could tell me. And, it didn't take long after that before I quit giving instructions for labs as much as possible, and instead adopted the process of trying to make sure that they understood what the question was that they were trying to find out, and help them see some of the elements of finding out about that question, but leave the essential procedure to them. This adds a lot of time to doing the lab. Some labs that you ought to be able to do in a period, will sometimes take two or three. And very often the first day is a very slow miserable day for the students. (PTI N2 496)

"The connection is the idea"

On two occasions during the topic on Newton's second law, Dodgson introduced Newton's third law into the discussion. The first of these was enigmatic; he gave no reason for introducing it, he raised a problem in interpreting it, and he left it without resolution in an equally unexplained, abrupt manner. This we found problematic: what connected this interlude to what preceded and followed it? While at no point did Dodgson outline his reasons for this juxtaposition of events either in class or in the post-topic interview, the interpretation we develop below is that his purpose was to help his students see that each particular component of his physics class drew its meaning from its connections to the body of physics. The assertions we draw from this section are:

Dodgson treats Newton's laws of motion as unquestionable givens.

Dodgson sees physics as interconnected, as a coherent discipline.

Description. Dodgson had been working on an example to demonstrate an application of Newton's second law. Without any linking comments, he introduced Newton's third law by referring to a poster that showed Garfield (the cartoon cat) hitting a tennis ball that rebounded against his head, with the caption "For every action there is an equal and opposite reaction." Dodgson posed the question: "What's wrong with that statement?" After a minor interchange with one student Dodgson ended the segment with no hint of an answer, or a connection to what followed: the episode remained unresolved and the transition was abrupt.

Dodgson moved on by introducing a new idea, seemingly unconnected to Newton III, through two further examples that he used to raise the issue of how an inanimate object produces a force when in contact with a second object, e.g., a window broken by a stone or a desk top supporting a stapler. After considering both examples in some detail, he posed the question: "How does [the window, the desk top] know [to exert a force] if there is nobody in there adjusting things?" Dodgson then answered the question in a short interlude by providing a causal explanation: he spoke about the electrical nature of matter and how atoms resisted compression through electrostatic repulsion.

At this point Dodgson returned to the Garfield poster, unlike the previous transition with a connecting comment: "What's wrong with that poster has something to do with this," i.e., with objects "knowing" how much to push. He introduced an alternative formulation of the third law: whenever one object exerts a force on another object, the other exerts an equal and opposite force on the one. He considered in turn each part of the restated law in two ways: by stressing it directly and by considering alternative interpretations. He considered the central concept in the law. "That's not in the poster. What was the word? You can say it in this class. Force." He considered the simultaneity in the law, contrasting this with the poster in which action preceded reaction.

> This kind of thinking [in the poster] explains wars . . every action--you fly over my border--there's an equal and opposite reaction--if I can manage it: Bang! (N2 d10)

He considered an object exerting a force on another object: "what the heck could it exert the force on except something else?" He acknowledged that "some people think things exert forces on themselves" but argued the inconsistency of this view with measured data. He considered the precision and universality of the law: the forces are exactly equal and precisely opposite **always**, without exception. He then reinterpreted the Garfield poster: the reaction to "racquet hits ball" is not "ball hits cat" but "ball hits racquet." He finally considered the reciprocal action on different bodies condition of the law. As he discussed in a subsequent interview:

> . . and what's missing a lot from the Third Law is the fact that the objects push on each other; that the Third Law doesn't just say whenever there is a force, there is going to be an equal force in the opposite direction, but that's what students hear. (PTI N2 1158)

He addressed this issue by posing a dilemma that suggested motion is impossible:

> "If I push on the brick with some force and if there is an equal and opposite reaction force, how can the acceleration be anything but zero?" (N2 d11)

This he resolved by pointing out that action and reaction forces act reciprocally on different bodies and not on the same one as suggested in the dilemma.

Interpretation. The sandwiching of the two segments on Newton III around the question of how inanimate objects "know" how much force to exert still requires an explanation. The only explicit reference Dodgson made about this arrangement was that quoted above, viz., "What's wrong with [the Garfield] poster has something to do with this," i.e., with objects "knowing" how much to push. Yet at no point did he outline the "something" connecting the two.

Both the "knowing" objects and Newton III segments seem to be self-contained. Dodgson did not explicitly use either one to explain or support the other. With respect to the former, he provided a causal mechanism to explain how an object can exert forces on another object with which it comes into contact. He made no attempt in this example to develop an implication of reciprocal and equal forces, i.e., to provide an explanation of Newton III. With respect to the latter his prime intention seemed to be to clarify its various aspects in some detail; the Garfield poster representing but one among several alternative interpretations of the law.

The possibility that these segments were sandwiched together by chance or whim seems small in light of Dodgson's comment that they had "something to do with" each other. Another reason to believe they were connected emerged in the interview he gave after teaching the topic. There he spoke at length about the difficulties students commonly have with Newton III. In particular, as his quote above points out, they neglect the condition that action-reaction force pairs act on different bodies. In addressing this problem, his primary strategy is to pose the dilemma about the impossibility of motion mentioned above:

> And one of the things I do is to say, so here is an object sitting on the table, and I intend to push on it, and I am going to use Newton's [second] law to prove to you that it cannot accelerate. (PTI N2 1158)

Thus in dealing with a difficulty students have with Newton III, he turns without hesitation to Newton II. In other words he sees a very close relationship between Newton's different laws.

What connections, in particular, could Dodgson have seen between these segments? There appear to be at least two possibilities. The first would be to use Newton III to provide a second explanation of how objects "know" when to exert a force, Dodgson having already provided a causal mechanism for the process. But Newton III could provide a different kind of explanation: the table pushing up being a logical consequence of combining Newton III with the unproblematic fact of an object exerting a downward force on the table, particularly if it's heavy. The second possible connection reverses the first: it uses the table segment to provide a mechanism to explain Newton III by developing from the causal mechanism Dodgson had introduced an implication of reciprocal and equal forces. As we noted above neither of these was done explicitly.

Both of these possibilities seem reasonable when considered in the context of Dodgson's views on physics. First, *Dodgson treats Newton's laws of motion as unquestionable givens*; his task as a teacher was not to question or verify, or validate these laws, but explain what they meant. As he commented about the lab the students did on Newton's Second Law:

> Is the point of this to see if Newton was right? Well, how presumptuous of us. I mean this was done two hundred, four hundred years ago, people continue to do it, it's in all the textbooks, there's absolutely no reason to do this . . (PTI N2 767)

Second, *Dodgson sees physics as interconnected, as a coherent discipline.* As he said in an interview:

> [I] try to convince my students that all of these things [are] interrelated . . . when you turn to the chapter on impulse and momentum, that's not new, that's a variation on a theme. (PTI N2 2212)

In another interview he said:

> And when I was a student, I was much more wound up in making sure I had my homework done than [making sure] that anything really made sense. And it was a long time before things started to make sense. I didn't see connections. And that's why. The connection is the idea. (PTI EN 583)

In light of these views it is easy to imagine that Dodgson's purpose in sequencing instruction as he did was to help his students see that each particular component of his physics class drew its meaning from its connections to the body of physics. In other words, interpretations of these segments of his teaching depend greatly on Dodgson's understanding of physics as a coherent discipline.

"Learning equations gets you in trouble, learning the fundamentals gets you out"

The "fundamentals" are a term that Dodgson uses for the ideas he wants to illuminate in the minds of his students. The discourse in the classroom makes it clear that his understanding of physics is both deep and broad. What is not, however, as apparent is how he expects the students to reason along with him through his extended development of ideas. What factors does he expect to be present so that the students are able to be mentally engaged in his qualitative analysis of physics ideas?

First, Dodgson believes he is able to speak to the knowledge students already have, and anticipate the questions they have about a physics topic. By constructing an argument based on the laws of physics that appeals to reasoning and observations the students can carry out, he works to persuade the students that the physics view is instrumental and meaningful for them.

Dodgson extensively models the reasoning process of comparing phenomena with the accepted body of coherent physics knowledge and laws.

This is closely related to the earlier assertion that in lab, Dodgson models the qualitative analysis involved in using physics theory to perform a valid investigation. There the purpose of the task was to plan an investigation; here it is to understand a common phenomenon.

Description. This example comes from the first day of the Energy topic. After introducing his definition of work, Dodgson developed the idea by talking about a homework problem in which students had calculated the work done on a suitcase. Pointedly, he did not write out an exemplary solution for the problem. Rather, he used it as the example subject for the purpose of thinking about "work".

As shown in the transcript below, Dodgson took an ordinary phenomena and cajoled the students to think about it from a very particular point of view; one that contrasted with the everyday kinds of considerations one might give to moving a suitcase. From this perspective, carrying a suitcase is a very ordinary activity. When most people pick up a suitcase in 'real life' they may think about: where they are going to travel to with it, how to heft it into the trunk of the car, or question how it became so heavy; but not Dodgson. What he wanted the students to think about as he walked back and forth at the front of the classroom with an imaginary suitcase, follows:

> You know the words, whenever the energy you're looking at changes from one form to another, use that as the definition of when work has been done. (Dodgson pretends to pick up a suitcase and carry it.)
> Here's the suitcase. I pick it up, I carry it over here, and I set it down. And you want to think about how much work has been done, and you start looking at forces, you have to admit to a negative work, in setting it down. You have to. Because of the real definition of work.
> Look at the suitcase, there it is . . here it is, did I do work, forget about force, how do you know I did work? Or if I drop it on my foot? It's got a kind of energy, called gravitational potential energy, that it didn't have, or it's got more of it. I mean if the force should give way, it obviously has some gravitational potential energy here, [we're] not at the center of the earth, after all. So I do work to lift it, force times distance, weight times this distance we lifted it, so far so good.
> Now watch, I speed it up, did I do any work? Yes, so force and distance make sense? Force, some little distance to get it going, what kind of energy did the thing gain? Kinetic, can you calculate how much that is? What's the equation? It's got the one half in it. Huh, you've got to know that.

> So I get it over here now I stop, that kinetic energy that I gave it, where is it now? Well I don't know, but the suitcase doesn't have it. It's still got the gravitational potential energy I gave it by lifting it, now I set it down, look at the sentence. How much did the sum of all the energies of that suitcase change, from there to there? Is it hotter, is it moving faster, is it farther from the center of the earth, have I compressed or stretched a spring or a rubber band or anything, have I given it some nuclear energy it didn't have before, have I changed it's chemical substance in any way? Have I done any work on that suitcase by the time I'm done? What do you have to say? No. Did I do some work along the way? Yes.
> How can you do some work, and wind up having done none, without having somewhere in there having the negative? This negative work doesn't have to feel good, it has to allow you some way to predict what's going to happen if I drop the suitcase on my foot. Or if I get in front of it, does it have kinetic energy, is it going to run me down? (EN d1)

Interpretation. The lengthy segment above, necessary to demonstrate an intact block of Dodgson's qualitative analysis, illustrates the number of relationships that are called upon to link the topic with the knowledge that is expected of the students. To exemplify this, we see that throughout the segment Dodgson referred to the common language aspects of the suitcase example, viz., picking it up, carrying it over, setting it down, speeding it up, etc. In a parallel conversation, he talked about each of these actions in the language of physics, i.e., in terms of work, force, distance, energy, etc., and of gaining energy, doing work on the suitcase, summing all energies, etc. But the segment is about more than specific connections between physics concepts and an everyday event: Dodgson was also intent on showing how physics pulls all aspects of the example into a coherent whole, with the power of being able to predict the outcome of this and other events. In other words, it also shows the exhaustive attention that Dodgson gives to an argument.

Thus, the referent body of knowledge that students are expected to build their understanding around is the carefully stated definitions and relationships of Newtonian Physics. The physics is not open to dispute; one of the goals is not for students to develop or discover physics ideas. Rather, the goal of Dodgson's classroom modeling is for the students to interpret and analyze events and experiences of the world around them using a physics perspective.

In some sense, physicists may see equations as very concise expressions of ideas and relationships in physics. Dodgson sees an algorithmic manipulation of equations by students as too easily misconstrued as an understanding of physics. In his practice, he is very deliberate in distinguishing between equations and ideas. The following segment represents one of many instances where he emphasized how a naive application of an equation can lead to conflict with the correct physics:

> How can a force that isn't zero, multiplied by a distance that isn't zero, give you an answer of zero? If you got zero and felt good about it then you probably know the definition of work better than [the textbook author] does. You know it in a useful way, a way that is going to allow you to predict what's going to happen. Somebody suggest how I should change this equation so that for your problem, problem five, the answer will be zero, which it is. (EN d1)

A student raised the need to consider the angle between force and displacement in doing the calculation. Dodgson then described how thinking in terms of the force parallel to the displacement is more useful:

> Now you can figure out whether that's sine, cosine, or tangent of this angle, you don't need [the text author] to tell you. And if you figure it out, then if the question changes just a little bit you're not going to be suckered into using cosine when you should be using sine.
> Watch out for equations. An equation made by somebody else is made for something that person has in mind. Which might not be the same way you are going to need it. That's why you should learn some trigonometry, some definitions, like that one, force parallel to displacement, and not learn equations. Learning equations gets you in trouble, learning the fundamentals, gets you out. (EN d1)

"Should you bring the equations or should I?"

> Students in chorus: "You should!" (EN d10: Exam Review for Energy Unit)

Like other teachers in our study, Dodgson acts on his awareness that while a competence in using equations can be indicative of some understanding of physics, it is not equivalent to it. For Dodgson, there is a tension in his teaching between facilitating the students' capacity to solve textbook problems and enjoining them to make sense of the world around them with physics ideas.

Dodgson works hard to help students reconcile the goal of using physics to explain the world with that of merely using equations to calculate problem solutions.

Description. The possibility exists that as much as Dodgson resisted it, the students saw the two goals as made up of separate rather than integrated activities.

> Part of the way physics works for you is knowing how to choose the best way that will work for you [to solve a problem] on an exam. This will mean the most efficient way. (EN d10)

Dodgson made the argument that a broad understanding of physics will enable the students to be efficient in using the equations of physics, and that manipulating equations is just a subset of the whole practice of physics. Yet Dodgson was also concerned that the students may have held a conception that manipulating equations can serve as an effective measure of their physics understanding.

> [Using graphs] suddenly helped me to see relationships that I had missed in all of my education. ... That was one of the things that I latched on to as being very, very helpful. But then it wasn't until later that I started to worry about the fact that what students were doing to learn physics was to learn to use equations, pure and simple. (PTI EN 659)

An interchange with some students about the Energy exam reinforced Dodgson's belief that this is a difficult conception for students to discard.

> Do you know what happened on the final exam? ... I gave out a sheet of equations . . . and some students actually came to me and said, "now you said you would give us all of the equations." And I said yes. And they said, "Well, I need an equation for conservation of energy." And I said, "That's not an equation, that's an idea." And they said, "But we had an equation which had that stuff in it" and I said "Yes we did, we did have it but here are the [equations for the] energies." [I asked them], "You want me to write out the equation for conservation of energy?" and they said, "Yeah". So I wrote down, total energy before, and I put before in quotes, equals total energy after."
> And they were profoundly unhappy with me. What does that tell you? They don't see that conservation of energy is anything except some equation to solve. And if you write it out [in the long form with the other equations included in it], they could [solve the problem]. They didn't know to take those two energies and add them together for crying out loud. (PTI EN 788)

Interpretation. Dodgson believes that he will continually need to wrestle with the students' thinking about equations and physics. The experiences he has had with students over the years as they use equations continue to reinforce this belief. He continued talking about the conservation of energy as follows:

> And you know why? Because I didn't do it right this time. As much as I tried to show that that's what conservation of energy was, the sum of all of the energies before, and I did some [work with that idea] on the board, <I: Yea, yea> I didn't make them do it. (PTI EN 855)

His practice of having the students graph relationships is consistent with emphasizing the connections of physics as being critical for a real understanding of physics. In one sense, his value for graphing may come from his perceiving them to be a mathematical bridge between equations and ideas. Making students graph is one way that Dodgson's attempts to reconcile equations and ideas are manifested in his actions in the classroom.

> I: How did you come about, um, thinking about these things in terms of a graph or the value of the graph?
> R: How did I come to it? . . In one of the textbooks I used, I'm pretty sure it was way, way back in PSSC stuff, that yes, I have it. There's a, ah, there's even a movie in the PSSC series that has a, ah, car driving on a deserted stretch of highway and carrying a chart recorder that runs off of the wheel, they drag along behind. And they, they make a big deal about the, the area and the slope and tieing it together. And I don't remember that I ever learned that. So I stopped when I was teaching and here was the book. I came to the school and the book was laying on my desk, handed out, and come to that page and you start doing it. It, it suddenly helped me to see relationships that I had missed in all of my education. (PTI EN 636)

"That startles, I can see it in their eyes"

As observers sitting in the back of the classroom, we were not able to infer when the students were passively reasoning along with Dodgson. We do know that he felt confident in assessing when 'they were with him' even as he continued to dominate classroom discourse.

Dodgson says things and creates events in the classroom to attract the attention of the students.

Dodgson believes that he is able to interpret subtle non-verbal cues from the students that indicate when they are with him.

During the interview after the Energy unit, the researcher asked about an instance when Dodgson stopped a videotape to question the students.

> I: And you asked them, "Why did the puck on the table not move in a straight line?" then sat there...
> R: ... I honestly don't know but it wouldn't surprise me if I waited too short a time to get an answer and, and moved it ahead. I'm not sure I wanted an answer so much as I wanted to leave, ah, leave the impression that this looked like something going against the rules of the universe that we had learned earlier. Things do go in straight lines and here's something that doesn't. (PTI EN 1088)

He went on to explain that his question about the puck was:

> . . kind of a rhetorical question. Maybe exactly a rhetorical question. I believe that people learn things better if at least some point along the line they're surprised. I think it wakes you up. Sets you up to deal with new information because you need it. We've got a discrepant event here. (PTI EN 1126)

When Dodgson was asked to talk about how he comes to asking demanding questions during the Newton's Second Law post topic interview, part of his response was as follows:

> And one of the things I do is to say, so here is an object setting on the table, and I intend to push on it, and I am going to use Newton's law to prove to you that it cannot accelerate. Now you know it can, so listen closely. ... Most of them look at the ceiling or look at each other like I've fallen off of some other planet or something. But the hope is that somebody is really thinking and will realize what is missing. And to the extent that that comes easily, that's good, and if it doesn't then I try to help it along by asking, asking leading questions. And one of the leading questions is: let's talk about it, maybe this is an exception. Let's talk about exceptions. (PTI N2 1202)

Later in the interview, the interviewer asked how Dodgson how much he relied on information like facial expressions to inform where to go next in the class, he said:

> R: A lot. I think I rely on it pretty heavily. I do watch their expressions. When somebody on one side of the room is answering a question, I'm watching people over on the other side. (PTI N2 1600)

Dodgson also brought up his intent to engage the students' thinking when asked to explain:

> I: What do you think happens with the students when you say "I'm unhappy with this definition [of work]?"
> R: I think they don't have very many teachers who take on the book and say the book's wrong and I'm right. That startles, I can see it in their eyes. ... [I]n the back of the room you couldn't see expressions and [that is one example] of how I use clues that he couldn't have recorded. ... It's an attention getting device.

Dodgson goes on to say:

> I have lots of evidence that this is a surprise to students and they want to hear more about it. (PTI EN 906)

We continue to work at understanding how Dodgson uses non-verbal cues to inform his classroom discourse. The goals of his teaching methodology are predicated on the degree to which the students think intensively about the concepts he raises in class. While he did elicit occasional verbal responses from the students, the long segments of class time where he was reasoning aloud about physics seemed organized around what became, for a lack of more vocal student response, rhetorical questions.

> I don't generally plan my questioning technique the day before, or before coming into class. I, ah, you know, some little subtle thing will prompt me to do it one way or the other. (PTI N2 1680)

"It's going to cause emotional distress"

On a number of occasions across both topics Dodgson explicitly demonstrated that he thought about the difficulties his students would have in learning physics, with respect to both their reactions to accepted physics and the alternative explanations they offered of different phenomena. These are encapsulated in two assertions, the first of which is:

> *Dodgson tells students that many physics ideas will be counter-intuitive for them, i.e., that they just don't feel right.*

There were several examples in Dodgson's teaching to support this assertion. On the first day of the Newton's second law topic, he sketched a daunting path for his students:

> [T]he stuff that you are about to begin now is counter intuitive. Apparently human brains are still wired the way Aristotle's was. What made sense to him--and it made sense to him, and made sense to people for a couple of thousand years--makes sense to you intuitively. Some of what you're going to have to learn here, I think you're not going to like. It's going to cause emotional distress, right about here. [patting his stomach] Be ready for that, be ready to accept it. (N2 d1)

He continued:

> Galileo and Newton came up with some wonderful ideas, that absolutely everybody who has studied this stuff and tried to do things with it, like hit the moon with a rocket, now knows is right. Newton nailed it, Galileo nailed it first. Some of that is not the way you think the world operates. (N2 d1)

A further example of physics not feeling right came later in the same unit with a preview of what lay ahead:

> Please listen to me, when we get started on this circular motion stuff, you are going to find certain aspects of that bewildering . . . it's easier for straight line motion, but it's not different for circular motion. It seems to be, and my job is to convince you its not. Don't panic. Yeah, it's different. No, it feels funny. All right, too bad. (N2 d11)

The pattern of referring to physics not feeling right continued in Dodgson's teaching with the second topic of Energy. After talking for some time about the concept of work, he continued:

> How can you do some work, and wind up having done none, without having somewhere in there having the negative? This negative work doesn't have to feel good. It has to allow you some way to predict what's going to happen if I drop the suitcase on my foot. Or if I get in front of it, does it have kinetic energy, is it going to run me down? . . . You are constrained

> to adopt terminology that suits definitions, and not your visceral sense of the way the world works. (EN d1)

In other words, Dodgson's consistent message was that while the physics they would do wouldn't feel right, they were not to use this discomfort as a guide to what was right. In his mind there was no question that Newtonian physics was right; as such it needed to be judged by a different criterion than: Does it feel right? This criterion is: Does it work? Can it be used to make correct predictions?

The second assertion we make in this segment is:

During class sessions, at times Dodgson outlines and contrasts opposing points of view, one representing the canonical view (that students may find counter-intuitive) and the other an intuitive view that "feels right," i.e., that makes sense to the students.

On several occasions Dodgson provided specific examples of both intuitive and accepted ways of thinking about a common phenomenon. As was outlined above, this strategy was central to Dodgson's teaching of Newton's 3rd law. Another example occurred at the start of the Newton's second law unit:

> People didn't used to think about [rolling a ball across a table]. They thought basically about the things sitting on the top shelf over there . . . which indicated that things wanted to be at rest. That was the natural way. And if you wanted something to move, the only way it would move very far was if you keep pushing on it. Soon as you stop, it stops. But Galileo said, yeah but things are different . . . he could imagine something that he didn't live to see: frictionless motion. (N2 d1)

Dodgson outlined contrasting interpretations again later in the unit when he considered what it was that a force acted on:

> Whenever there's a force, now how can there be a force if something doesn't push on something else, may I ask? Or pull? . . whenever one object exerts a force on another, well what the heck could it exert the force on except something else? (N2 d11)

He then acknowledged a different formulation:

> Some people think things exert forces on themselves. They think that's what keeps projectiles going. I throw something up, it keeps going up because the force that I gave it is continuing to push . . . you remember maybe thinking that once perhaps weeks and weeks ago when we started projectiles? (N2 d11)

We assume that Dodgson contrasts opposing points of view because he believes it will help students learn physics better, i.e., he predicates the acceptance of his development of ideas, or the persuasiveness of his argument on the expectation that students will experience dissatisfaction with their ideas when they do not fit with systematic physics concepts and relationships. Dodgson models the criterion of consistency of physics ideas in his explicit vocalization of dissatisfaction with concepts that do not meet this criterion. As he commented:

> You asked me what I do when it's hard [for students to learn a physics topic]. Well, I guess I look for lots of ways to try to show that such and such is the correct way to go about it because it works, it's cohesive, it, it sets. And I do things like pointing out that perhaps the problem is that you learned it differently some time and now you not only need to believe this but you need to unbelieve something else. So I work at that." (PTI EN 1899)

Conclusions

Dodgson's knowledge-in-action, as represented in the analysis presented above, includes two very strong focal points. The first is his rich, detailed view of physics. The second is his sense of what is entailed when his students learn physics. Both of these exert a strong influence on the nature of his instruction. What, however, remains something of an enigma to us is how he sees his instruction serving the purpose of helping his students come to understand physics as he sees it.

With respect to the first focal point, the segments we have detailed above provide a rich account of physics as Dodgson sees it. To gain perspective on this account, we find it useful to contrast it with what, in our view, is a typical physicist's point of view. This is that the quantitative nature of physics is of the essence. Physics uses the language of mathematics, and its central ideas are expressed in the form of equations that are models of precision, efficiency, and utility. When these theories are applied to the natural world, quantitative measurement is the hallmark of success. As Kelvin is reputed to have said: "If you cannot measure a quantity, you do not understand it." When a viewpoint such as this is translated into the classroom, it is likely to manifest itself as an emphasis on activities such as quantitative problem-solving and laboratories that emphasize the gathering and mathematical analysis of quantitative data.

This physicist's view does not, however, guide the course of events in Dodgson's classroom. While he does not eschew mathematical formulas, quantitative data gathering, or numerical problem solving, these are not the prime focus of his classroom. On the contrary, as demonstrated in several of the segments presented above, Dodgson is greatly concerned about the physical meaning that is hidden by terse mathematical symbolism. He recognizes very clearly indeed that mathematical manipulation is not akin to physical interpretation. Two quotes that clearly epitomize this are "Learning equations gets you in trouble, learning the fundamentals gets you out" and "[Conservation of energy] is not an equation, that's an idea." Further, the "Keeping control" segment is, in our view, preeminently about the qualitative, conceptual difficulty of applying physics theory to natural objects and events. In summary, Dodgson sees the theory of physics as unquestionable, the application of physics theory to the natural world as complex and neither self evident nor automatic, and qualitative reasoning as an essential component of the practice of physics. In our experience of physics teachers in general, this emphasis is unusual. We see him translating these convictions into his teaching in two ways. He spends a considerable proportion of class time on the qualitative reasoning and analysis he regards as an essential component of physics. He also expects that his students will mentally reason along with him as he guides them through an exploration of the ideas of physics.

With respect to the second focal point mentioned above, the analysis of Dodgson's knowledge-in-action reveals something of his thinking about his students and their understanding of physics. First, he recognizes that students bring a range of common perceptions to class that make sense to them but are often contradicted by Newtonian ideas. Second, because of the views his students hold, he doesn't expect them to find the learning of Newtonian theory a comfortable experience. He is very clear that even if students accept that these ideas are what they should use in doing physics and can do so effectively, they will still find them counter-intuitive. As reported above he said: "[T]he stuff that you are about to begin now is counter intuitive. Apparently human brains are still wired the way Aristotle's was." Later he said: "Yeah, it's different; no, it feels funny; all right, too bad."

Thus he sees a need to address different points of view in his teaching. On a number of occasions he deliberately outlines opposing perspectives--the common sense view and the physics view--in class. We suspect that by doing so Dodgson wants to convey the message that learning physics is not as simple as it may at first seem; that when students have difficulty they are not alone, i.e., that they shouldn't opt out of the struggle too soon; and that they should look for other criteria to decide if they are right than their "visceral sense of the way the world works." It also seems clear that for Dodgson the validity and utility of Newtonian mechanics is not open to question; rather his goal in teaching is to show how this abstract, difficult, counter-intuitive theory applies to events and objects in the natural world as represented by the laboratory, an amusement park, etc.

In summary then, we see that Dodgson's knowledge-in-action includes two strong focal points that serve to integrate his views on physics and on student learning with his instruction. There is, however, a question that remains for us. To look at the students and classroom from Dodgson's perspective requires a leap of faith. That leap requires us to share in Dodgson's confidence that he has a good idea of what his students already know and that he can direct their thinking about physics concepts along a web of pathways during class. In his own words:

"I want for my students to see that these ideas tie together." (PTI EN 471)

In a general sense, we would agree. But at a more detailed level, we are uncertain. Apart from asking for an occasional show of hands on a question, Dodgson made no systematic attempts to elicit the conceptions of all his students. While he asked questions that demanded thought, he did not use this as an opportunity to generate classroom discussion within the classroom mode: student talk was almost exclusively directed back to him. And, as a proportion of total time spent in the classroom mode, there is not much student talk. A metaphor for Dodgson's instructional practice that seems

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appropriate is that of a naturalist guide. The guide's knowledge of his or her field is encyclopedic. S/he also knows from long experience the difficulties his or her students will have. So the guide decides ahead of time which path to follow. As s/he comes to a plant or insect along the way, s/he will expound on the resonance of its lifestyle with respect to its niche in the natural world. The students follow along, occasionally asking questions. Physically they are present, but who is to say whether their thoughts are on a termite nest at hand or personal topics far away?

In conclusion we see this study of Dodgson being valuable for at least two reasons. First, we have painted the picture of a teacher who has made a series of decisions about his teaching that grow out of his extensive knowledge of both the subject and the students he teaches. These decisions interact with each other in ways that are, for the most part, supportive of one another. In combination, they represent a teacher who is unique and who cannot be categorized with a simple label. In our view, this is an essential characteristic of being a professional teacher.

Dodgson is also of interest for a very different reason. While the findings that students hold a wide variety of conceptions of the natural world are increasingly familiar to classroom teachers, there is little knowledge of the ways in which teachers use this information in their classes. This study provides a description of one teacher's implementation of these findings, viz., Dodgson's very pointed recognition that his students may not feel that Newtonian physics is right and his comparison of different perspectives in his classroom. We have had several different reactions to this practice. One educator objected to "the confrontational nature of his teaching;" another felt that, while it might be appropriate for physics majors, it would only confuse other students who were struggling with physics. The power of examples such as this to generate interest and discussion is, we believe, of considerable value in both pre- and in-service science teacher education.

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Table 1: Criteria for choosing segments

Segments	Representative of practice?	Components of teaching science	Significant in comparison with:
1. The context	Yes: context	-	-
2. Keeping control	No	physics content	other teachers
3. The connection . .	No	physics content	his own practice
4. Learning eqns . .	Yes: equations	physics content	other teachers
5. . the equations .	Yes: equations	instruction	other teachers
6. That startles . .	Yes: monitoring Ss	learning & learners	-
7. . . emotional distress . .	Yes: S concerns	learning & learners	other teachers