Physics Classroom Engagement: constructing understanding in real time

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Abstract
The dismal results of standard physics teaching found in the research in physics education are explained and justified by the folk theory of physics teaching. Challenging this folk theory at its core results in far superior student learning. An example of an alternative practice called *student understanding-driven* instruction is described. Implications for the role of the teacher and for teacher preparation are drawn, as are challenges to engaging in this alternative physics teaching practice.

Keywords: Folk theory of physics teaching, *student understanding-driven* instruction, conceptions of real image formation.

Resumen
Los resultados lamentables de la enseñanza de la física estándar encontrados en la investigación en física educativa son explicados y justificados según la teoría popular de enseñanza de la física. El desafío de esta teoría popular en sus resultados básicos es muy superior en el aprendizaje de los estudiantes. Se describe un ejemplo de una práctica alternativa llamada instrucción de *entendimiento conducido del estudiante*. También, son descritas las implicaciones para el papel del profesor y la preparación del mismo, ya que son desafíos para la contratación en esta práctica alternativa de enseñanza de la física.

Palabras claves: Teoría popular de enseñanza de la física, instrucción de *entendimiento conducido del estudiante,* concepciones de formación de imagen real.

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I. INTRODUCTION

Physics learning today

It is well documented that most students leave instruction on physics topics with no significant change in their understanding of the phenomena studied. Mounting evidence to this effect has been published for at least 30 years. A bibliography containing this evidence is on-line [1]. The bibliography, just updated in February, 2007, now has 7,700 entries.

This evidence is apparently unknown to many in spite of the quantity of it published, shocking to some and rejected by others [2]. The prevailing folk theory of physics teaching explains this outcome. The folk theory of physics teaching can be defined in the following way:

Physics teaching is the presentation of the established canon by approved methods for the benefit of the deserving.

Very few students show evidence of receiving the canon presented to them as anything other than a kind of rote memorized catechism. This apparently is the general outcome regardless how skilled we are at the approved methods for presentation of our canon. Under the folk theory the elitist assumption is apparently very few students are deserving; that is, few students have the mental capacity and the diligence to get what is presented. This folk theory with its elitist view of people explains the results, exonerates teachers and students for poor performance, and boosts the egos of the "deserving." Of course, numbered among the deserving are teachers of physics, physicists, and a few students.

The folk theory goes unquestioned as if it is the natural order of things. Hence, many very intelligent, hard working and sincere instructors of physics have lived with these results all their careers without challenging them. In fact the results are aggressively defended [2].

Evidence to the contrary

If there were no evidence to the contrary, then the folk theory would be acceptable, because it fits the observations. Yet, there is evidence to the contrary. An alternative explanation for learning leads to a very different practice of physics teaching from which many students leave having made significant changes in understanding in significant numbers.

This different practice of physics teaching rests on a different explanation of the nature and origins of knowledge and a different relationship between knowers and this knowledge. This different view of knowing and knowers comes out of the work of the Swiss Genetic Epistemologist Jean Piaget and the Radical Constructivist Ernst von Glasersfeld [3, 4]. The result of experience in this physics teaching practice is most students do demonstrate evidence they have constructed new understanding of the phenomena studied in much greater numbers than students taught under the folk theory.[5]

Hence, we have evidence that generally students leave physics instruction without having changed their understandings of the phenomena studied. Out of their experiences in physics classes students also apparently generally form opinions (1) that they cannot understand physics, (2) only certain special people (the deserving) can really understand physics and (3) it is mostly just mathematics. Yet, we also have evidence that most students can indeed construct new, more powerful understandings of the phenomena for themselves. Such experiences do not support the ideas that most cannot really understand physics or that only a certain few are deserving. Thus, teaching practices consistent with the folk theory do unnecessary damage to most students and, thereby, to society. This damage is accomplished by 'teaching' most students who experience instruction on physics topics that they are inadequate when they are not. Corollary to this damage is the students are 'taught' to be dependent on others for truth. A society is weakened when its members are convinced they are inadequate and dependent on a few for the truth.

II. A DIFFERENT TEACHING PRACTICE

At the heart of this different physics teaching practice is Piaget's notion of equilibration. Human beings tend to adjust their understanding such that predictions based on this understanding fit experiences with the phenomenon the understanding explains. When the predictions or expectations do not fit experience with the phenomenon, a disequilibrated state is the response. People who have disequilibrated, either avoid the situation, sweeping it under the carpet, or they draw near the situation to develop modifications to existing understanding that would enable expectations that better fit the experience. Hence, in order to have students develop new understandings, they have to disequilibrate. It is the physics teachers' central role to establish situations in the classroom in response to which the students are likely to disequilibrate. This role is profoundly different than in the folk theory.

Piaget and his colleagues studied young people making sense of their world, both physical and social. Their interest was in development, not in schooling, so he did not focus on standard school learning. They found they could best explain their observations concerning development using the idea of equilibration of cognitive structures.

For the teacher the practical problem is how to induce disequilibration, when a.) only the students can disequilibrate themselves and b.) only the students can find a new equilibrium by constructing their own new understanding of the world to fit their experience. One approach is to engage students in eliciting their own conceptions by applying them to making predictions about some new experience. Then have them actually experience what happens when the prediction is tested. To induce disequilibration, their predictions should not match what actually happens. If the teacher has formulated a good working understanding of the students' understandings, then the students are likely to disequilibrate when they are surprised by the contrast between the actual outcome and their predictions.

How can a teacher know what the students' conceptions of the phenomena are likely to be? There are two major sources. One is the bibliography cited at the beginning of this paper and accumulating publications from physics education research [1]. The other is in the classroom working with the students. Most of the class time needs to be spent with students sharing their ideas about the phenomena. Obviously, this is a major departure from a folk theory driven classroom.

There are many venues and media that can be used to get students to make explicit their ideas both for themselves and teachers. The most commonly used modes are speaking and writing. The writing can be informal as in notes made in class, more public as in on-line discussions, or formal as in writing assignments. Another mode to encourage collaboration is group-designed posters to illustrate the ideas of the group. Such a poster can be found in Figure 1.

III. REAL IMAGE FORMATION

An example of disequilibration

Most people, trained in physics or not, seem to operate with the notion that an image comes as entity from luminous objects to a lens. In terms of rays, one ray comes from each point on the luminous object. The image is manipulated by the agency of the lens to appear clear and sharp on a screen. The image has a physical size all the way from the source to the screen where it appears, usually inverted, sharp and clear, as illustrated in Figure 1.

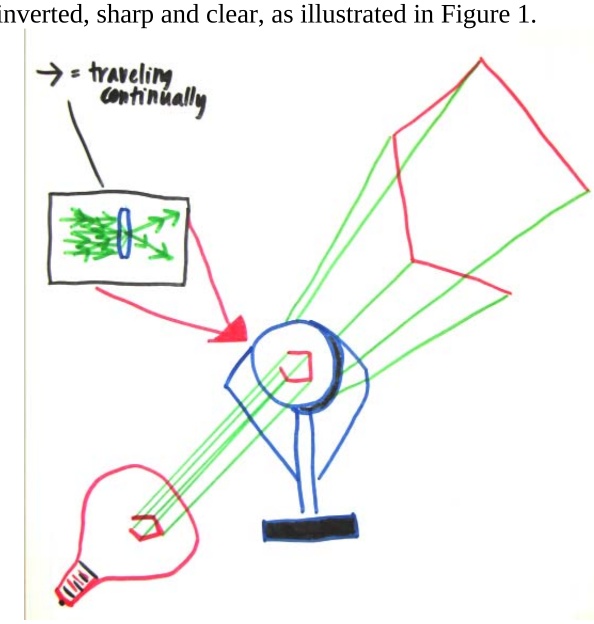

FIGURE 1. Image manipulation by a lens. This is a typical poster drawn by a group of four students when asked to use the idea of light rays to illustrate using light rays how they think the image comes to be on the screen.

This notion of image leads most people to predict that if we have a sharp image from a luminous source present on a screen, when we cover half the lens, we will only see one half of the image on the screen [6]. The other half will be blocked. Yet, when this is tried, the *whole* image remains! One can even use a card with 1.0 cm hole over the lens and move the hole around. The image will remain whole and fixed in location on the screen.

How is this example used to induce students to disequilibrate? The best way is to begin with the students attending to their own conceptions of images from lenses. We show them the luminous object, lens and screen placed so that a bright, sharp, clear image is apparent on the screen, but the students are admonished not to manipulate the apparatus [7]. We ask: what would happen on the screen, if we were to cover half the lens? First, students write and sketch their own ideas on this question with an emphasis on why their answer seems reasonable at this point in time. Next, the students are invited to share their answers to the questions with each other, again with an emphasis on their justifications for their answers. The point here is not the prediction, but to elicit their conceptions concerning this particular situation. The goal is to get students to be explicit about their own ideas, to share them with their peers, and to find out about the ideas of others. After this discussion, then the students are invited to try covering half the lens with an opaque card. Because of the level of commitment to their predictions, cultivated by their efforts to justify or explain their prediction, the fact that all of the image is still there and it does not matter which part or how much of the lens remains uncovered results for many, even trained physicists, in disequilibration.

The actual experience of disequilibration is far more than merely cognitive. It has an affective impact, too. When it is okay to have one's prediction not match what happens, then it is possible to draw near the experience and participate in discussion about the implications of this outcome for the explanations that supported the original predictions. Under the folk theory, the focus is on accurate reproduction of the canon. The teacher immediately corrects any departure from the canon. As such there is a premium on accurate predictions. In folk theory driven instruction students quickly learn not to predict from their own understanding, but to guess what the teacher wants.

When students are freed to make predictions from their own understanding, they are free to revise their understanding when they find their predictions do not match the outcomes. In the context of a ray model of light, it is typical that students decide there must be more than one ray coming from each particular point on the luminous source. The multiple rays from any one point must be hitting all the points on the lens. How else could leaving any arbitrary portion of the lens uncovered result in the whole image on the screen? The notion that the image leaves the source as an entity is discredited. The notion that there is a single ray from any given point on the source is also discredited. At this point in the students' minds there is a viable alternative to the issue of single rays from points on luminous objects, but there is yet to be developed a viable alternative to the notion of the image leaving the source as an entity.

This example is but one glimpse of the process in the classroom. By stringing together a number of such examples, a teacher can engage a class of students in constructing for themselves multifaceted explanatory theories of a phenomenon that fit experience quite closely. Once students have constructed such a theory, they can answer questions about possibilities that go far beyond what they have directly experienced. Because students developed and tested the theories themselves, they develop skill at constructing theories. Importantly, they do not have to rationalize why they did not get what was presented. Knowledge is no longer handed down from the deserving for the deserving neophytes. Students are no longer dependent on the deserving for the truth. Everyone constructs knowledge and has the responsibility for their own constructions. Instead of leaving the instructional experienced damaged and dependent, students leave the experience empowered and with deeper understandings of the phenomena studied.

IV. DISTINCTLY DIFFERENT INSTRUCTION

The teacher faces a completely different set of issues and challenges in this practice than the teacher using the folk theory of physics teaching. Because teaching is not about transmitting the canon to the deserving, the teacher becomes dependent on students, as students are the only ones who can change their own understandings. In spite of this dependence there are things that the teacher can do which have profound effects on the students. To carry out the kind of examples above, the teacher needs to have constructed personal understanding, not just satisfied the normal content course requirements for teacher candidates in the folk theory of physics teaching. In addition, the teacher must develop a personal understanding of the ways *students* typically think about the phenomena—"to see the development of physical theory in … students' minds" [8]. This comes first from consulting the research literature on student conceptions, but much more comes from listening to and observing the students as they talk about their ideas of the phenomena and make predictions.

The very issues attended to in instruction are different. Under the folk theory of physics teaching, the canon is spelled out in textbooks. The texts determine the sequence, quantity and level of the canon presented. In lab, the experiments are all designed to show elements of this canon. On the other hand, using this different practice of physics teaching, the experiments are chosen for their potential to be experiences over which students are likely to disequilibrate. Because the canon and its organization are a distilled, streamlined and hierarchical organization of topics and examples, the canon bears no relationship to how such knowledge might be developed.

The example in geometric optics illustrates the canon is worse than useless as a guide when real change in understanding is the goal. In the standard, textbook-driven treatment of geometric optics, the students would be marched through the 'law of reflection' and Snell's 'law.' Then they would be shown the technique of drawing special rays and given the thin lens equation and asked to perform special ray constructions and do thin lens calculations. Throughout definitions of terms would be given as if the students should be able to understand and know the meanings merely because they have been told or shown. Yet, when the students' understandings are probed after such instruction, as did Goldberg and McDermott [6], we find after this instruction the students' notions of real images are essentially unchanged.

Neither the details of the 'law' of reflection, Snell's 'law,' special rays nor the thin lens equation play *any* role even in the larger more complete unit of *student understanding-driven* instruction of which the example is a part. The canon as described by the standard table of contents of a physics book is *essentially useless* when change in student understanding is the goal.

Implications for physics teacher preparation

The central challenge to the physics teacher, then, is how to establish the conditions under which students are likely to disequilibrate. Clearly, this task cannot be accomplished if the teacher does not know how the students think about the phenomenon to be studied. It also cannot be accomplished if the teacher does not know the experiences possible with the phenomenon to be studied.

These two capacities are sadly lacking in most people who teach physics at any level. *This inadequate state of affairs is not due to shortcomings of the teachers of physics, themselves.* Instead it is due to shortcomings in their preparation and training to teach physics.

Teacher preparation is generally driven by the folk theory. For example, in the U. S. physics teacher preparation consists of presenting the canon to the teacher candidates, generally via two of the accepted methods: lecture and scripted laboratory activities. Then the teacher candidates are shown the accepted methods of presentation and given some supervised practice in a real classroom. This basic description has not changed even under the influence of the No Child Left Behind Act, imposed by the U. S. federal government. In countries where there are formal teacher preparation programs, the training is similar. In countries where there is little or no formal training to teach, the main criterion for teacher selection is evidence of being in possession of the canon, usually via a degree in the subject.

As Niedderer has written: "...a physics major has to be trained to use today's physics whereas a physics teacher has to be trained to see a development of physical theories in his students' minds"[8]. Sadly, the folk theory driven standard preparation does not focus the attention of the teacher candidates on the development of physical theories in the students' minds. It does not even focus the teacher candidates on the development of physical theory in their *own* minds. So, while the standard preparation does expose teacher candidates to some of the possible experiences to be had with the phenomena, the necessary component of focus on the development of understanding is simply not there at all in their training. Thus, it is not a surprise that the result of folk theory driven training is folk theory teaching. The consequence is damage to students and society, weakening both the students and the society to which they belong.

Resistance to change from the folk theory

The cognitive and affective processes relied upon in this alternative teaching practice are believed to be explanatory of natural human functioning. These natural human functions are suppressed quite effectively by years of standard instruction under the folk theory, which is employed in the teaching of every subject. Just as they come to us with well-established conceptions of physical phenomena, students come to us with well entrenched personal explanatory theories of schooling which entail the roles and obligations of both student and teacher. This alternative practice does not fit these standard notions of schooling well at all. As a result, another issue the teacher using the alternative practice must deal with is engaging students in rethinking learning and the consequences of this different notion of learning for both the students and teachers. Hence, engaging in disequilibration over physical phenomena must occur against the background of coming to grips with reconceptualization of the learning culture of the classroom.

The teacher who desires conceptual change for the students faces resistance from students, colleagues and administrators. The whole educational enterprise is driven by the folk theory of teaching. The preparation of teachers is determined by the folk theory. The evaluation of teaching for purposes of teacher advancement and salary are also dominated by the folk theory.

Students are indoctrinated into a debilitating world-view through instruction driven by the folk theory. Emilia Ferreiro's field is not physics, but early acquisition of reading by young children. Nonetheless, she captures the challenges very well in the following passage:

"Instead of asking about the method employed, it is more useful to look at the *practices* used to introduce the child [student] to reading [knowledge], and how this object [knowledge] is presented in the classroom. There are practices that lead children [students] to think that knowledge is something that *others* possess and that they must turn therefore to *others* to obtain it without ever participating in the construction of such knowledge [themselves]. There are also practices that make them think that "what has to be known" is given once and for all, as if it were a closed, sacred, and immutable set of elements that are to be transmitted but not modified. Yet other practices place the child [student] "outside" the knowledge, making them passive spectators or mechanical receivers who can never find the answers to the whys and wherefores that they don't even dare to formulate aloud.

"There is no neutral pedagogical practice. Every single one is based on a given conception of the learning process and of the object of such a process. Most probably, those practices more than the methods themselves are exerting the greatest effects in the domain of literacy [or science], as in any field of knowledge. Certain practices may appear "normal" and others "aberrant" depending upon how the relation between subject and the object of knowledge is understood and how both terms of this relation are characterized. It is at this point that psychopedagogical considerations must be supported by epistemological reflections." (*Emphasis* in the original) [9].

We see from the evidence in the bibliography that the folk theory-driven methods of physics instruction have little effect on students' understandings of the phenomena studied. On the other hand, it is clear from the response of many students that they come to our classrooms expecting, even demanding, to be "mechanical receivers" of "a closed, sacred, and immutable set" of truths. They do not expect that they could ever "participate in the construction of such knowledge" themselves. Administrators and many parents insist on preserving this status quo by their action. Yet, the wisdom of Ferreiro's words in our own classroom experience is clear. Resistance and road-blocks to *student understanding-driven* instructional practices are great, but it is nonetheless possible to employ such practices with success as demonstrated by the evidence cited above [5].

VI. CONCLUSIONS

Physics teaching based on the folk theory by teachers trained to teach according to the folk theory is a spectacular failure at engaging students in developing new understanding of the phenomena. An alternative, *student understanding-driven* practice has been demonstrated to result in most students developing new understandings of the phenomena. Piaget's equilibration plays a central role in this alternative instruction. The teacher's role in the practice is markedly different than under the folk theory. Necessary pedagogical content knowledge for the teacher in this alternative practice is described and an example of the practice in geometric optics has been illustrated. Resistances to the alternative teaching practice are acknowledged.

All students can develop new, deep and powerful understandings of the phenomena, if engaged in doing so properly. We have an obligation to the students, society and our profession to so engage the students when we teach. To accomplish this we have to question the folk theory of teaching and its consequences. Then, we need to change both the preparation of teachers and the evaluation of their work, so that we do not perpetuate the folk theory of teaching.

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