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Výuka fyziky a rozvoj myšlení

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Abstrakt

Piagetova teorie kognitivní rovnováhy a jeho výzkumné metody podnítily současnou éru výzkumu v oblasti fyzikálního vzdělávání v USA a dalších zemích. V příspěvku je stručně popsána historie počátků vývoje vědecké komunity v této oblasti výzkumu. Piaget a jeho kolegové shrnuli asi 60 let sběru dat o myšlení dětí do teorie popisující řadu stádií ve vývoji myšlení. V článku je popsána pedagogika založená na teorii kognitivní rovnováhy a Glasersfeldově radikálním konstruktivismu. Důkazy, že i lidé s vysokoškolským vzděláním neužívají ve svých úvahách formální myšlenkové operace, jsou výzvou, kterou je třeba přijmout v zájmu efektivního fungování demokratických společností. Jestliže víme, jak povzbudit více studentů k dalšímu rozvoji jejich myšlenkových schopností, nemělo by to být důležitým úkolem našich vzdělávacích systémů? Je v pořádku, když na středních a vysokých školách produkujeme absolventy, kteří neprokazují formálně-operační úroveň myšlení?

Klíčová slova: Piaget, myšlení, kognitivní rovnováha, radikální konstruktivismus, fyzika, pohyb a síla.

Physics Teaching and the Development of Reasoning

Abstract

Piaget's theory of cognitive equilibration and research methods sparked the current era in physics education research in the U. S. and other countries. Some of the history of the early development of the physics education research community is described. Essential features of the theory of cognitive equilibration are explained. Piaget and colleagues summarize some 60 years of data collection on children's reasoning as a series of stages in the development of reasoning. A pedagogy based on the theory of cognitive equilibration and Glasersfeld's radical constructivism is described. Evidence that people do not make use of formal operations in their reasoning even though college educated is raised as a challenge to the effective function of democratic societies. If it is known how to influence more students to develop further in their reasoning abilities, should this not be an important effort in our educational systems? Should we graduate students from schools and colleges who show no evidence of formal-operational reasoning?

Key words: Piaget, Reasoning, Cognitive Equilibration, Radical Constructivism, Physics, Motion and Force.

1 History and Background

1.1 In the "beginning"...

Robert Karplus, John Renner and others encountered the work of the Swiss Genetic Epistemologist, Jean Piaget (1896–1980), and his colleagues during the funded development of elementary school science curriculum projects in the 1960's. They in turn introduced Piaget to the English-speaking science education community. In the US, these projects, such as the Science Curriculum Improvement Study (SCIS) (Karplus, 1964), the Elementary Science Study (ESS) (Duckworth, Nichols, 1964) and Science — A Process Approach (SAPA) (Livermore, 1964), involved scientists, science educators and early childhood educators working together to develop curriculum and teacher training. Some of these early childhood educators, such as Eleanor Duckworth, had studied with Piaget and otherwise knew his work.

The findings of those working at the Center for Genetic Epistemology with Piaget include a development-based, phenomenological description of evidence of reasoning by many children about many specific examples over nearly 60 years. This description is presented as stages in the development of reasoning. Piaget's theory of cognitive equilibration explains the observed development of reasoning and understanding in their experimental subjects.

Robert Karplus, a physicist at the University of California, Berkeley was a principal investigator in the SCIS project. His exposure to Piaget's findings and ideas not only strongly influenced his work on the SCIS project, but also led him to begin conducting research to investigate students' development of reasoning.[1] For the SCIS project an instructional design strategy, now known as the Learning Cycle, was developed. Karplus' efforts extended to sharing Piaget's ideas and the Learning Cycle with the science teaching community, including the American Association of Physics Teachers (AAPT). In 1975 a workshop titled: Physics Teaching and the Development of Reasoning was first offered at a national AAPT meeting. Working through the Lawrence Hall of Science at UC Berkeley, a series of workshop manuals was developed based on the AAPT workshop design for Biology, Chemistry, Earth Science, etc. teachers.

1.2 Origins of the Physics Education Research (PER) community

Piaget's work has two things to offer to those interested in physics learning. First is a theory that explains and predicts changes in understanding of the physical world. Second is a research interview strategy to bring out evidence of children's understanding and reasoning about physical examples. For physics instructors interested in their students' understanding, both of these are of great value.

By the late 1970's Karplus was organizing sessions at AAPT national meetings on Piaget-influenced work examining physics learning. For those whose appetites were whet in the workshops, these single sessions alone were enough to draw them to AAPT meetings. The followers of these sessions began to try their own hands at the research in their own classrooms. This research revealed the nature of students' conceptions of the phenomena we study in physics and evidence of the circumstances under which these conceptions might change.

[1] One of the collaborators in this research was Elizabeth Karplus, an elementary educator and Robert's wife.

All of this interest led to the formation of a permanent committee of AAPT known as the Committee on Research in Physics Education. Interest and activity in research in physics learning has grown to the point that in 2011 in every time slot for parallel sessions of the AAPT national meetings there are multiple sessions involving some aspect or application of PER research. There are now groups in Physics Departments doing PER and Ph.D.'s in physics are being awarded in the field.

Not everyone or every group in the PER community would claim to be working in some Piagetian paradigm now. Nonetheless, it seems clear that the introduction of Piaget's findings, the theory of cognitive equilibration, and his research approach are the springboards from which the PER community developed. The Piagetian influence marked a shift from a behaviorist focus on teacher and student behavior and what is to be presented to a cognitivist focus on the student as epistemic subject which characterizes much of the work in PER today. Yet, sadly still, most students who take physics experience very little influence from this PER work in their own classrooms.

1.3 Theory and findings

1.3.1 Cognitive Equilibration

The theory of cognitive equilibration includes the basic premise that human beings function by constructing schemes for knowing or understanding the world of their experience. (Piaget, 1985) They are comfortable with their understandings of the world of their experiences when the experiences are consistent with or fit these schemes for understanding the world. There is a kind of equilibrium between their schemes for understanding and their experiences. This understanding is also supported by the fact that these schemes are found to successfully predict new experiences.

Human beings form expectations of future experiences using these schemes. Experiences, which fit their schemes, are said to be assimilated when encountered. When a person realizes that an experience does not fit personal existing schemes for understanding the world, then that person recognizes a disequilibration between personal schemes for understanding the world and this new experience with the world. This disequilibration might be major or extremely minor.

In general there are three possible responses to a perceived disequilibration. The first type of response is to ignore it, 'sweep it under the carpet', or avoid the experience. In which case there is no change in existing schemes or reasoning patterns.

The second type of response to disequilibration involves a small accommodation of existing schemes. For example, imagine you are served coffee in a unique ceramic mug. You have a well-used scheme for picking up a coffee mug to take a drink. Normally you find a "handle", some sort of a loop, which you wrap your fingers around to lift the mug. This mug instead has instead a figure of a knight in armor merely protrudes from the side of the mug with no gap between it and the side of the mug. You are surprised, but you grab the knight and pick up the mug. You have accommodated your "pick up a mug to drink" scheme because your existing one does not quite fit the new situation. This type of accommodation to an existing scheme, we do almost without realizing it.

The third type of response to disequilibration happens when no quick and easy accommodation to existing explanatory schemes is available. Instead of hoping it does not happen again, we draw near the experience, repeat it, examine it, try variations on it in an effort to formulate an explanation for the 'offending' experience. In so doing, a person enters into a process of constructing and testing revised or new schemes with which to explain or understand the experience. This process is called self-regulation. The resulting scheme or schemes also need to fit previous experiences. The result is a much more substantial accommodation in one's explanatory system. With such major accommodations, there may begin a series of accommodations in the explanatory system as incompatibilities are noted between newly accommodated schemes and previously existing ones.

In Piaget's theory of cognitive equilibration, people strive to gain a new equilibrium between their cognitive schemes and their experiences in response to this third type of response to disequilibration. The realization of a disequilibration in this case drives a self-regulation process to find an accommodation of explanatory schemes to experience. Each equilibration is a new relationship between cognitive explanatory schemes and experiences, because both the cognitive schemes have been changed and the body of experiences has changed. Not only will the body of experiences have changed due to the addition of one or more experiences, but also the status and relationship of the experiences to the cognitive schemes, that is, the meanings of the experiences change.

In Piaget's picture of development there are several factors that lead to cognitive development.[2] One is maturation. As one physically matures, one's ability to experience and manipulate the world increases. This influences another factor, experience. Experiences can be categorized into three types. One kind of experience is physical, experience with the physical world. Another kind of experience is social, experiences of social interactions in conjunction with physical experiences. A third kind of experience is with one's own thinking in response to and conjunction with the other two kinds of experiences. The third factor in cognitive development is equilibration. Without the drive for equilibrium between experience and cognitive schemes, cognitive or intellectual development would not occur. In this theory all three factors, maturation, experience, and equilibration, are necessary for this development.

There have been those who have challenged all or part of the theory of cognitive equilibration. As Lorenço and Machado point out these appear to be due to misunderstandings of various aspects of the theory, including the fact that the position taken by Piaget on the nature of knowledge is not realist or objectivist. (Lorenço, Machado, 1996)

1.3.2 Evidence of the development of reasoning

Piaget, with his colleagues, was exploring the genesis in human beings of reasoning and understanding of their worlds. This work, Piaget called genetic epistemology. Piaget was an experimental philosopher in epistemology. In the effort to uncover evidence of the thinking of children, Piaget watched them interact with their world and each other. He asked children when old enough to speak about their world to tell him their thoughts about situations to which he directed their attentions.[3] The actions of children who were pre-verbal in response to various stimuli were observed in great detail to discern evidence of their reasoning.

[2] It is important to remember that changes in the cognitive domain are not independent of the affective and physical domains in a person. These cognitive changes go hand-in-hand with affective and physical changes for a person.

[3] The best summary and explanation of Piaget's work in English is by Chapman (1988).

Piaget and his colleagues found they could characterize the very large quantity of examples recorded over many decades in what can be called stages, which describe a developmental sequence. It is developmental because each successive stage grows out of the previous one. The rate of progression through these stages of reasoning may vary, but the sequence appears not to vary.[4] What is being characterized is the observable behavior taken as evidence of the reasoning of the children in the experimental situations.

This stage description of the development of reasoning includes four stages.[5] (Fuller, et al., 2009) The first stage, which is pre-verbal, is called sensory-motor. During this stage children appear to be working out co-ordinations between their sensations and their physical and mental activity among other things. One such co-ordination is between vision and their limbs. The very young child works out that objects that can be seen might be manipulated by reaching out with a hand or foot.[6] Before this coordination the action of the hands and the orientation of attention evidenced by the eyes have little or no regular relationship with each other. Once language begins to develop, language becomes an experience and a mediator in this process of co-ordinations. With language the sensory-motor stage develops into the next stage in the development of reasoning named, pre-operational. In the pre-operational stage, language is used to describe and represent elements of experience. For example, a child might explain the wind as being caused by the leaves of trees waving back and forth.

This pre-operational reasoning evolves into evidence of specific reasoning patterns. First to develop seem to be class inclusion, conservation and serial ordering. In class inclusion classifications and generalizations are used. For example, all flowers are plants, but only some plants are flowers. Using conservation reasoning, if nothing is added or taken away, then an extrinsic property such as amount, number, length, weight, etc. is unchanged, in spite of changes in appearance.[7] Using serial ordering reasoning, the child can arrange objects, say sticks of different lengths, in a serial order and establish one-to-one correspondences, for example, younger children are not as tall. This cluster of reasoning patterns in evidence in a child's language and behavior is referred to as the stage of concrete operations.

This concrete-operational reasoning enables a variety of successes dealing with one's world. Using concrete operations a person can combine concepts and elementary ideas to explain experiences with familiar actions and objects, follow sets of instructions such as recipes, and can relate one's own viewpoint to that of another. But, these reasoning patterns are not up to other challenges such as: isolation and control of variables, anticipating all possible combinations in a situation, construction of new solutions to problems not encountered before, being aware of one's own reasoning and reasoning about hypothetical situations and objects.

To comfortably and competently deal with these latter challenges, an additional set of reasoning patterns has to be developed by the person. This additional set of

[4] A frequent misunderstanding of Piaget's findings is that these stages of the development of reasoning must occur in certain age ranges. Lorenço & Machado give a thorough response to this and other misunderstandings of Piaget's work. (1996)

[5] These stages describe reasoning patterns used by interviewees, and do not describe the interviewees, themselves.

[6] This necessarily involves a number of earlier developing schemes such as the notion of an object, the notion of a coordination of visual and kinesthetic experiences into the notion of a limb, which can be controlled, etc.

[7] Evidence of the conservation of all things conservable does not appear all at once. Certain conservations seem to appear before others.

reasoning patterns is called formal operations. These additional reasoning schemes are combinatorial reasoning, proportional reasoning, probabilistic reasoning, correlational reasoning, the separation and control of variables and reasoning with hypotheticals. These reasoning patterns or schemes enable one to systematically imagine all possible relations of factors, deduce the possible consequences of these relations, and test to find which of those consequences actually occur. Some of these reasoning schemes may appear earlier, but they are applied only in familiar situations and generally unsystematically.

Clearly, the formal operations are necessary to construct the depth and power of explanatory knowledge we wish for our students in science in high school and college. This kind of understanding is inaccessible to students whose reasoning has not developed beyond the stage of concrete-operational reasoning. Hence, for us as physics teachers, it matters what percentage of our students are still only displaying the concrete-operational stage of reasoning. Because human beings can develop through these stages of reasoning, when late adolescent to early adult students are not yet at the stage of formal operations, it becomes our responsibility to facilitate the continued development in their reasoning.

2 The challenge we face

For many in the physics teaching community in the U.S., the first introduction to Piaget's ideas was an article published in 1971 in the *American Journal of Physics.* (McKinnon, Renner, 1971). Many younger members of the physics teaching community might be surprised at several points made in the article so long ago. McKinnon and Renner concluded that:

> If colleges and universities do not try to solve the problem by assuming the responsibility for the intellectual development of their students, but continue to look at their primary purpose as the transmission of information about the several disciplines, the elementary and secondary schools will continue to fail in their mission of truly educating students. The needed changes, however, can come only through acceptance of inquiry by *all* of those who teach the teachers. — p. 1 052

This call for all who teach science to be engaged in learning science via inquiry has been repeated many times in subsequent years. To what extent is this an important part of the preparation of teacher candidates in science today?[8] It is still practically nonexistent in most teacher preparation programs in the U.S. At best lip service is paid to inquiry as one topic among very many in a "methods" course.

McKinnon and Renner establish that this is a problem by demonstrating that students entering college do not mostly demonstrate formal operations in their school work. Using Piagetian-based tasks completed by these students, McKinnon found that of these students 50 % only displayed concrete-operations in their reasoning and only 25 % displayed formal-operations in their reasoning on the tasks. The other 25 % displayed reasoning, which McKinnon labeled post-concrete-operational. Yet, in the samples of students Piaget and his colleagues studied students who began to develop and demonstrate formal-operational reasoning patterns between the ages of 11 & 15.

[8] To what extent is it present in the teacher preparation programs in other countries?

We know now there are noticeable differences in the ages of onset of formal-operational reasoning between the Swiss children Piaget studied and, for example, members of nomadic groups in the near East. But, should differences as large as McKinnon and Renner saw exist between the Swiss children and American children? In this question a key word is "should". On one hand, we believe things are as they are for explainable reasons. Hence, one might say that since the culture in which the Swiss students Piaget studied grew up is different than the culture in which American children grew up, then, yes, there should be a difference. On the other hand, we should keep in mind that the development Piaget describes is a property of human beings. In which case, we should be asking, if the Swiss children began developing formal-operational thought between the ages of 11–15, then why aren't our children in the U. S. developing this kind of reasoning at the same age and could they do it even earlier?[9]

McKinnon and Renner conclude that one major reason for this delay in development of reasoning is how teachers are prepared to teach by the universities.

> Who is teaching in the elementary and secondary schools? Teachers who have been educated in the existing colleges and universities. Those teachers have been subjected to four years of mainly *listening* experience [in college, following 12 years of essentially the same in primary and secondary school]. They have been lectured to, told to verify, given answers, and told how to teach. Lest you think the foregoing happens entirely in the colleges and/or departments of education, remind yourself that *all the content taken by a teacher* (which represents a substantially greater number of credit hours than do courses in education) *is taken outside the College of Education at a university.* Teachers are, in other words, not having the kinds of experiences with inquiry, which Piaget's theory of cognitive equilibration and the findings that support it suggests they must have in order to allow logical thought processes to develop.
>
> . . . The responsibility, then, for the small percentage of high school students attaining formal operations rests in part at the door of the institutions of higher education. They have assumed that their role is to tell. Future teachers, therefore, assume that telling is teaching and when they get their first class, they tell, tell, tell! All the while, very little, if any, intellectual development is going on. — *ibid*, p. 1 051
> (*emphasis* in the original)

Just a few years later Arons and Karplus point out that the evidence seemed on average to be that of the population ranging from 13 to 45 years of age only about a third demonstrate formal operations in their reasoning, a third only demonstrate concrete operations, and a third seem to be in transition in their reasoning. (Arons, Karplus, 1976) These proportions seemed to be relatively static in their reviews of the accumulating data. For them this suggests a conclusion and indictment against our educational systems.

> If it is indeed true that one-third of the school population is formal operational by the age of about 14 while one-third is still concrete and that these proportions do not change substantially from then on in spite of further schooling (including at least some university levels), then we face

[9] This question could probably be asked about other countries, too.

> the implication that our educational system is not contributing significantly to intellectual development (abstract logical reasoning). — p. 396

Arons and Karplus go on to point out that

> If perpetuation and advancement of a democratic society do indeed demand the broadest participation of a thinking-reasoning citizenry, if intelligent participation does involve abstract reasoning on matters such as, for example, what constitutes *enlightened* self interest, if more people must be counted on to engage in decision making when confronted with incomplete, "on the one hand . . . and on the other hand" evidence shorn of reliance on a "pat" answer from an ultimate "expert" . . . then we *must* gear our educational system to greater effectiveness in enhancing intellectual development than the incoming data show it to exert. — p. 396 (*emphasis* in the original)

3 Is the challenge still to be met?

3.1 In current classrooms

In the 1970's assessments of students' stages of development of reasoning were made by having students generate free-form responses to puzzles involving the reasoning schemes in concrete-operational and formal-operational thinking. These free-form responses were then individually judged for the presence or not of the reasoning schemes. Needless to say, this is a process too time intensive to be used with a large number of students by classroom teachers.

Various research groups generated a number of multiple-choice format diagnostics. Anthony Lawson, who had been a graduate student of John Renner's, developed one that is in use today. It is called the Classroom Test of Scientific Reasoning (CTSR). (Lawson, 1987) Coletta & Phillips compared results from the CTSR, the Force Concept Inventory (FCI)[10], and normalized gain over the semester on the FCI for college students taking physics. (Coletta, Phillips, 2005) They found a significant number of students whose performance on the CTSR did not reveal formal-operational reasoning.

The CTSR diagnostic has been used as a pre-diagnostic in a conceptual physics course on motion and force for non-science undergraduate majors at the university level. In the present work the diagnostic is being scored on a 0–24 scale. The high score indicates the presence of the appropriate formal-operational scheme in each pair of questions. The typical distribution of students in this course by level in college can be seen in Figure 1. There is a distribution across the levels, more freshmen than seniors, but still a noticeable presence of upper division students.

The distribution of pre-CTSR scores can be seen in Figure 2. In principle all of these students could have developed formal operations by the typical beginning college age of 17 or 18. The average age of these students is higher than that. The average of this set of pre-CTSR scores is 14.4. The median score is 14 and the mode of the distribution is 13. The design of the CTSR and its scoring suggest that for a student to display fully formal-operational reasoning the score would need to be 24 or nearly so. Only about 17 % scored 20 or higher. This is consistent with the kind

[10] The FCI also is used to study the efficacy of physics courses. (Hestenes, et al., 1992)

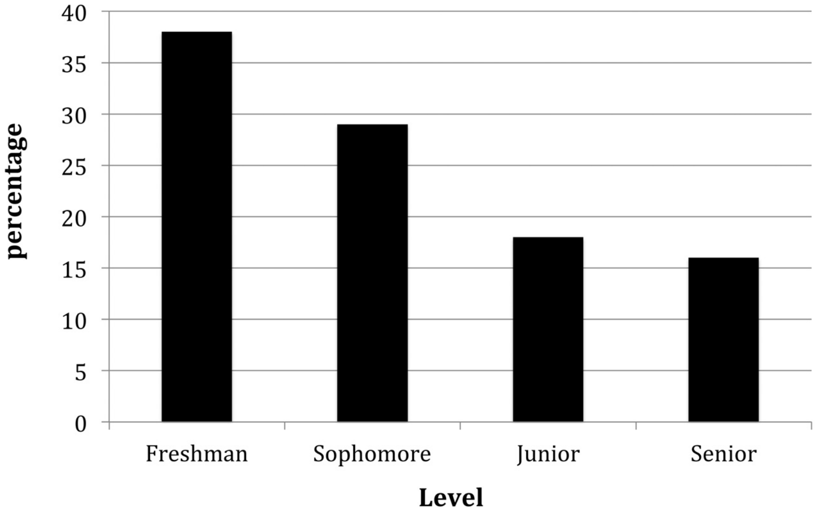

Figure 1: Distribution by level in college

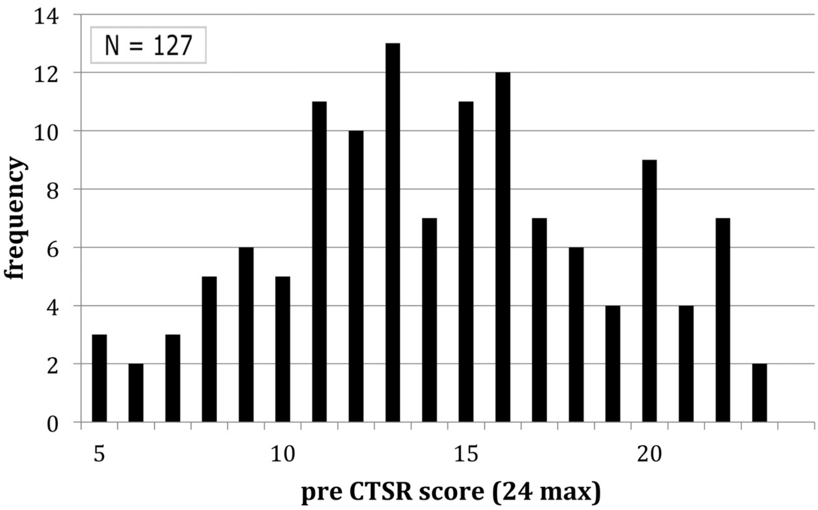

Figure 2: pre CTSR Scores-Motion & Force

of findings published in the 1970's. Few display all of the patterns of reasoning in the stage of formal operations.

3.2 A student understanding-driven pedagogy

The students represented in Figures 1, 2 were taking a course for which the folk-theory of teaching is abandoned. The folk-theory of teaching can be described in the following way.

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

It is called a folk-theory of teaching because it is...

- a belief about what teaching is,
- accepted by all, and
- generally unquestioned.

This folk-theory implies knowledge can be transmitted from one person to another, there are certain preferred methods, and only certain students are able to "get" what is being transmitted. It is one of a number of ways to interpret experience in classrooms and to explain the results of instruction.

Instead of a folk-theory pedagogy, these students experienced a student understanding-driven pedagogy, based on the theory of cognitive equilibration and a view of the nature of knowledge consistent with Piaget's and radical constructivism. (Chapman, 1988; Glasersfeld, 1995) This pedagogy is the result of a development effort by Dykstra starting in 1988 and described in some detail in a 2005 publication.[11] (Dykstra, 2005) In the view of the nature of knowledge employed in this pedagogy, explanatory knowledge has the status of stories we construct to explain experience and predict new ones. Of such knowledge, Piaget wrote:

> Knowledge is not a copy of reality. To know an object, to know an event, is not simply to look at it and make a mental copy or image of it. To know an object is to act on it. (Piaget, 1964)
>
> It is clear there is an undeniable role played by experience in cognitive development; however, the influence of experience has not resulted in a conception of knowledge as a simple copy of outside reality. (Piaget, 1972)

The canon ceases to be a guide to instruction in this student understanding-driven pedagogy. Instead the nature of the students' conceptions about the phenomena become the guide. The goal in this instruction is for students to make changes in their existing conceptions or understanding of the phenomena studied in the course. Necessarily then the objects of attention and manipulation are not apparatus in lab, the phenomena, or mathematics on paper, but instead the students' conceptions of the phenomena. The students are the only ones who can really know their own conceptions and they are the only ones who can change their own conceptions. This places the teacher in a profoundly different role than in the folk-theory of teaching. Instead of the students being outside looking in at a teacher in the folk-theory pedagogy, the students are "inside" looking at their own conceptions and their own experiences. The teacher's role then is to direct the students' attentions to experiences with a phenomenon that do not match their conceptions of the phenomenon, in other words, set the students up for disequilibration.

The theory of cognitive equilibration suggests that if there is to be change in such conceptions, then the students need to become aware of disequilibration between their conceptions of a phenomenon and their experiences with that phenomenon. The course runs in *elicit*, *compare*, *resolve*, *apply* cycles that merge one cycle to the next and sometimes nests cycles within other cycles. The *elicit* and *compare* steps are the main subjects of weekly laboratory sessions. Class time is primarily

[11] Three units of the American Association of Physics Teachers (AAPT) publication, Powerful Ideas in Physical Science (PIPS), written by the present author, make use of student understanding-driven pedagogy: Electricity (1995), Motion (2002) and Force (2002). More about PIPS can be found on the website for these AAPT materials for use at the college and other levels: http://www.aapt.org/publications/pips.cfm, last downloaded 2 Sept 2011. Numerous presentations on aspects of and learning results from this student understanding-driven pedagogy at AAPT national meetings have been given since 1989. Workshops involving this pedagogy have been given numerous times at AAPT national meetings: Image formation by lenses (starting in 1989), Powerful Ideas in Physical Science (starting in 1995) and the Piaget beyond "Piaget" (starting in 2006).

used for the *resolve* steps. Meetings of the full class are run like town-hall meetings to harness the power of many minds to the challenge of constructing or modifying conceptions to fit the phenomenon. Whatever has been decided so far about the phenomenon is *applied* in subsequent *elicitation* steps.

The process starts in the laboratory. For example, students studying light and optics might enter their lab session to find an unfrosted, shaped filament lamp turned on. One meter from the filament is a +30 cm lens. Beyond that is a small screen made from a manila file folder set so that a very sharp image of the filament is on it. Because the focus of attention is the students' conceptions about images, they are not allowed to manipulate the apparatus or interrupt the light between filament and image in any way at the beginning of an activity or cycle. Instead, they are asked: What do you think will happen if we were to cover the top half of the lens with an opaque card?[12]

The typical student conception here seems to be that the image leaves the lens as an entity, travels through space where it encounters the lens. The lens is an agent, which inverts the image and projects the sharpened or focused image on the screen. We work in a ray model of light, so they will typically draw horizontal rays from points on the filament to the lens. Rays from the top of the filament cross rays from the bottom of the filament after or in the lens as a result of the action of the lens on them. Where the crossing point is positioned differs. Some students have the rays cross in the center of the lens, others at the back face of the lens, still others in the region between the lens and the image. Essentially all of the students predict that half the image on the screen will be missing, because half the image (traveling as an entity from the filament) is blocked by the card. The differences in crossing point location result in different predictions about which half of the image will be missing, the top half or the bottom half. Everybody is convinced that half of the image will be blocked and now they have reasons to support their convictions.

To get to this point the students are asked to make the first two steps in a lab activity. First (step 1), answer on paper: What do you think will happen and why? Then (step 2), listen to the ideas of your lab partners (4 person lab groups) and try to understand what the members of the lab group think will happen. Record your group's ideas on paper. Then, and only then, the students are invited to make observations (step 3). They cover half the lens as they watch the image. They encounter a very surprising experience. When half the lens is covered, the whole image remains! Many experience disequilibration immediately. They try several times, both sides of the lens, top half-bottom half, left half, right half and then are invited to explore the question: How much of the lens can you cover and still see the whole image? The students are asked to make notes about the aspects of what actually happened which did not match anyone's predictions. In the last step (step 4) of the activity, they are asked to assess the situation. What are the implications for the reasons we had to support our predictions? What might be alternative ways of thinking about the images, which might have predicted what we actually experienced? Final, conclusions, well worked out explanations are not called for or typically even possible at this point in an activity. The goal of the lab is not closure, but its opposite through disequilibration. In each 2-hour lab period the students go through 2 to 4 of these activities. Most of the time is not spent manipulating

[12]The question is left intentionally ambiguous as to which side of the lens this card is placed on. When the students ask, the response is something like: If you think it matters, then give your explanation as to why. If you do not think it matters, then give your explanation as to why. The question comes from (Goldberg, McDermott, 1978).

apparatus. Instead, most of the time is spent with students eliciting their own ideas, comparing notes on each other's ideas, and considering the implications of observations that do not match predictions.

In the class meetings, gathering all of the members of all of the lab sections, the issues that arose due to the disequilibration experiences are the objects of attention, discussion and debate. The goal here is to pool the ideas in the class about what an explanation would need to be in order to have predicted the observations in lab. The possibilities that seem reasonable to the class become the basis for steps 1 in the lab activities the next week. While disequilibrations are resolved, new ones occur each week in lab. Eventually, the class constructs an explanatory scheme, which works well to explain the evidence encountered.

The students find themselves in possession of a theory of image formation by lenses in terms of light rays that they have constructed themselves.[13] The theory can be applied to new situations not studied or discussed in class, which is what students find themselves being asked to do in exam questions. Since the goal of the course is for students to have constructed a new explanatory system for themselves, the exam questions[14] are designed such that the responses are indicators of which understanding a student is using, the original one from before the beginning of class or the one the class constructed to fit the evidence so far.

Several units of study are in various states of development. These are on image formation by lenses, on electric circuits, on thermal phenomena, on color, on motion and on the nature of force.

The student understanding-driven pedagogy differs in certain respects from, but not totally incompatible with, other known approaches. Probably the best known, PER research-based approaches are by McDermott and colleagues at the University of Washington-Physics by Inquiry, Hestenes and colleagues at Arizona State University-modeling instruction, Etkina and colleagues at Rutgers University-investigative science learning environment (ISLE), and Karplus and colleagues at the University of California-the learning cycle.

This student understanding-driven pedagogy has been examined extensively in the motion and the force units using a diagnostic of students' conceptions of motion and force, named the Force and Motion Conceptual Evaluation (FMCE). (Thorton, Sokoloff, 1998) This work has been described elsewhere. (Dykstra, 2005) With the student understanding-driven pedagogy, the non-science/non-engineering majors, typically, show a shift in the class average on the FMCE from pre to post by 60 % of the total possible change. In physics courses for science and engineering majors taught using folk-theory pedagogy, this shift from the pre to post scores for the FMCE is typically 15 % of the possible change. The typical average pre scores are about 1 out of 15 and about 2 out of 15, for the non-science majors and the science & engineering majors, respectively.[15] What could the science & engineering majors

[13] This theory is not one familiar to most physicists because they have never been engaged in developing or even considering such a theory in their preparations or their own teaching. It also entails some relatively controversial conclusions, such as the converging lens has nothing to do with the inversion of the real image.

[14] Using Howard Gardner's suggestion that: "If, when the circumstances of testing are slightly altered, the sought-after competence can no longer be documented, then understanding-in any reasonable sense of the term-has simply not been achieved," the questions involve application to situations not encountered in class. (Gardner, 1991)

[15] It is important to note that in the U. S., nearly all of the students represented here have had folk-theory instruction on motion and force inflicted on them once in the middle grades. Many of the science & engineering majors have had a second round of folk-theory instruction on motion

do under the student understanding-driven pedagogy? If we know of at least one example such as this of a pedagogy that is so much more effective, then do we not have a responsibility to reconsider the wisdom of staying with the folk-theory of teaching? Don't we owe this to our students, professions and society?

While we see impressive results in change of students' conceptions concerning motion and force here, it is still important to note that the average shifts are still only 60 % of possible. An obvious step is to begin looking for another factor, which might be taking a role in the success or lack of success of some students. One such factor as suggested earlier in this piece is the development of reasoning of the students.

3.3 Is the development of reasoning a possible factor in this case?

One can ask: to what extent does the pre-CTSR score predict performance by the end of the semester? One way to judge this is to plot the percentage score on the final against the pre-CTSR score. We see the result in Figure 3. The data is for more than one semester of the course, but the final each semester is equivalent to previous semesters and it is not returned to the students. We see there is a fairly strong correlation of 0.6 with a slope of 3.0 on the best straight line through the data. It appears that a pre-CTSR score of 10 or less seriously diminishes the chances of earning a 70 % or higher on the final. Apparently, the CTSR does have some relevance for predicting student success on the final in this student understanding-driven instruction.

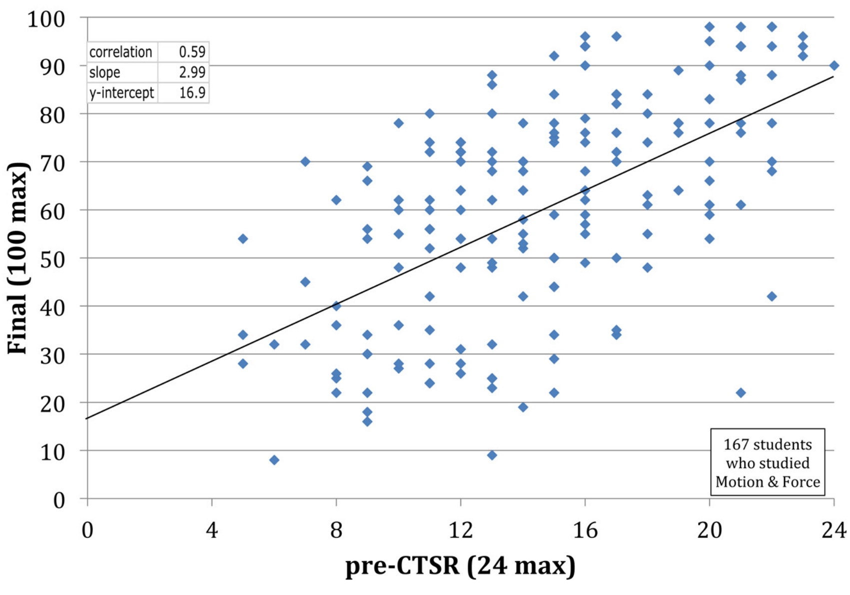

Figure 3: Final vs. pre-CTSR

Narrowing our attention to students not so successful in the course: Could one factor contributing to these students not thriving be their development of reasoning?[16] There are two pieces of evidence, which might support the conjec-

and force inflicted on them in what is called high school physics. Given the very low pre scores on the FMCE, what must not have been happening in the folk-theory instructional experience in physics?

[16]This question implies a conjecture namely that less successful student are less successful because their reasoning has not yet developed to formal-operational thought.

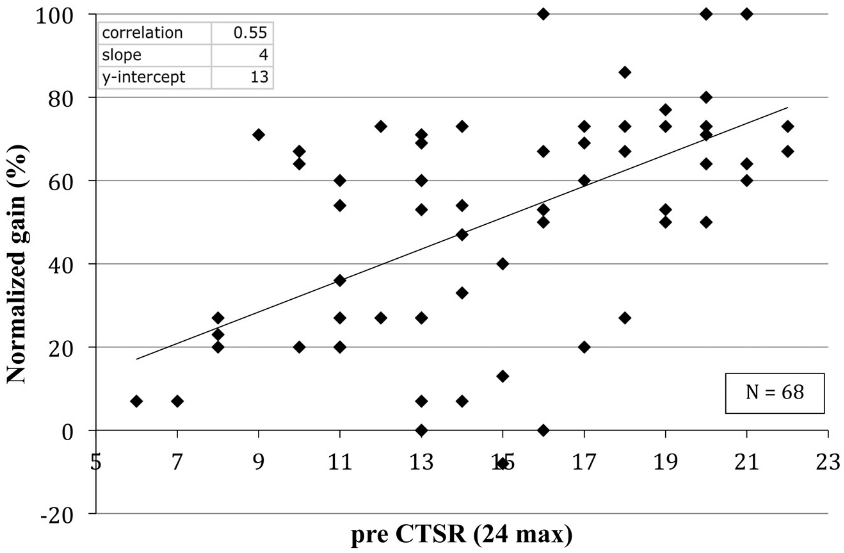

Figure 4: Normalized Gain vs. pre CTSR

ture implied in this question. One is that this instruction has been used with high school physics classes in which the FMCE was used pre and post. In this trial of a student understanding-driven pedagogy, the average gain of the two 25 student classes was about 6 standard deviations (Dykstra, 2005).[17] One could argue from this that even though the CTSR was not administered in this trial, the percentage of students likely to be displaying formal operations in high school physics might be fairly high. If one accepted this description as likely then there would be a basis for the conjecture contained in the question at the beginning of this paragraph.

The other piece of evidence supporting this conjecture is the data presented in Figure 4. In Figure 4, the percent of possible (normalized) gain from pre to post on the FMCE is plotted against the pre-CTSR scores of the same students. The scatter of points is not random. The correlation here is 0.55. It is not an extremely strong correlation, but also not an extremely weak correlation. From this data, it appears that as the pre-CTSR score drops below 12 out of 24, the average normalized gain on the FMCE drops off rather rapidly.

Another disturbing pattern in the data collected is the correlation between GPA[18] (grade point average over all college courses taken so far) and the pre-CTSR score. At the university from which this data was collected the maximum GPA is 4.0, which is earned on the credits for a course in which a student earns the grade of A. Should we expect there to be a correlation between a student's pre-CTSR score and GPA? If the exhortations of McKinnon and Renner and of Arons and Karplus have been heeded, one would expect this answer to be yes. Figure 5 is a plot of GPA against pre-CTSR. The correlation between this measure of development of reasoning and the GPA of students ranging from freshman to senior levels at the university is essentially zero. Apparently, at least for this batch of students at this particular university, the exhortations of McKinnon, Renner, Arons and Karplus

[17] This evidence also suggests an answer to the question raised earlier concerning how science and engineering majors might perform as a result of student understanding-driven pedagogy.

[18] The students in this study are all non-science, non-engineering majors. Their GPAs are uninfluenced by standard physics teaching since they have not taken any other physics courses to contribute to their GPAs. Their GPAs are accumulated from courses not in science or engineering. Hence, this is a reflection of standard folk theory teaching in other subjects.

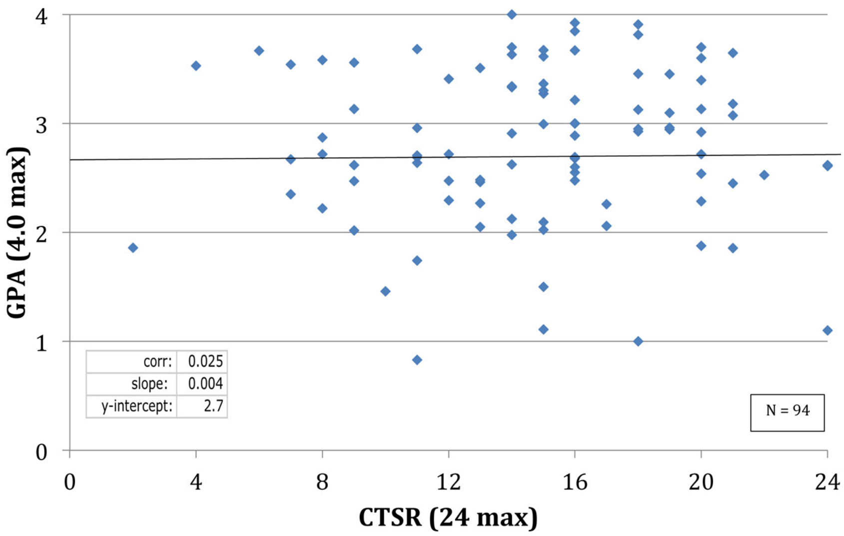

Figure 5: GPA vs. CTSR

are not being heeded.[19] The reader is invited to explore this issue at the reader's institution.

One question that arises here is: to what extent does the student-understanding driven pedagogy in these situations have an effect on the development of reasoning of the students. There is some data collected locally indicating the class average shift on the CTSR is in the right direction, but small. Two factors enter into the situation. First, in actual course settings, at the end of the semester when one would want to administer the post CTSR, students are not very interested in taking time in class or lab for something that is not on topic in the course, so post data on the CTSR is very hard to collect. Second, the specific details of the pedagogy are not designed to attend to making progress in the development of reasoning. They are designed to induce disequilibrations and support the subsequent self-regulation. Changes that might promote development of reasoning and still accomplish the existing changes in understanding are being considered.

4 In conclusion

One might argue that the CTSR looks too much like science, which might have an effect on the performance of non-science students. This might indeed be a factor for some students, but the CTSR does not actually require any previous knowledge in science. Indeed, it would be good to have a CTSR-like diagnostic that is more content neutral to avoid this possible effect, but such a diagnostic seems not to exist at present. Such a diagnostic could not be content free, but it could conceivably be more content neutral than the CTSR.

Apparently, formal-operational reasoning is not a necessary attribute for success in the undergraduate courses these students have experienced. But, then why

[19]Now one can argue that this is not a representative sample of college students in North America. Yet, in the now famous example of the FCI, many college faculty responded to the effect that these results are only for students at Arizona State — the students at my university are much better than that. (Hestenes, 1992) Eric Mazur at Harvard reacted this way. But, he was quite surprised when his students really did not do any better on the FCI. One can find this on YouTube if one searches there for: confessions of a converted lecturer. He came up with a way to interrupt lecture to engage students in actually making sense of the topics. It is clear to him that the changes in understanding happen because of these interruptions to lecture.

would development in reasoning be an expected outcome from folk-theory teaching as telling and assessment as regurgitation of what was told?

Sadly, it has been demonstrated that courses can be taught which do result in students advancing their development of reasoning. McKinnon and Renner described one such example. It has been demonstrated since then most clearly in the work of Shayer and Adey with Cognitive Acceleration (Adey, Shayer, 1994), the ADAPT Program at the University of Nebraska (Fuller, 1975) and the work of Reuven Feuerstein with Instrumental Enrichment (Feuerstein, 1985). *Isn't there an obligation on us implied by the fact it is known how to facilitate the development of reasoning in our students?*

With the evidence in Figure 5, as McKinnon and Renner pointed out, we are continuing to send teachers into the schools to *tell* students the canon, instead of develop in their reasoning and their understandings of the phenomena we study in science. As Arons and Karplus pointed out, when we deprive our teacher graduates of this opportunity to develop, we deprive their students of the same opportunity, and thereby our society, of the opportunity to develop to formal operations in order to make the society we live in better, more civil and more just. *Should college students develop formal-operational thought as a criterion for graduation? When we know how to make these necessary changes for our students, are we justified in continuing* ***not*** *to?*

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