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Three Active Learning Strategies to Address Mixed Student Epistemologies and Promote Conceptual Change

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Novice science learners or introductory science students vary greatly in their understanding of the nature of science. For example, many students do not conceive of scientific knowledge as a highly ordered, coherent, knowledge structure that contains a set of interrelated ideas. Such a framework enables the learner to relate new material to prior knowledge and, if warranted, assimilate the new material within the framework. Many students have strong beliefs that knowledge is conveyed by authorities, such as the instructor and the textbook. Also many student's own knowledge structure is fragmented or "in pieces," as described by diSessa. Fortunately, this portrayal is not valid for all students. Many other students enter the classroom with productive intellectual values and possess, or can quickly develop with little prompting, alternative, and coherent conceptions that conflict with target ideas. These students are able to relate new material to prior knowledge and, if warranted, assimilate new material into pre-existing conceptions. The challenge of contemporary science education reform is therefore to address the diverse needs of a "mixed student epistemology" classroom. In this paper we review three instructional strategies that show promise to address this challenge in the context of an introductory physics classroom: (1) the Reflective Writing and Labatorial interventions of Kalman et al. (2) the Conceptual Conflict Collaborative Group and Critique approaches of Kalman and Rohar, and (3) the integrated Elicit-and-Challenge and Bridging Technique strategies of Lattery. Each approach stresses the need for students to critically examine their own ideas in relation to target course ideas and discuss their ideas with peers. The second and third approaches emphasize the important role of the history and philosophy of science in science teaching. The aim of such efforts is not only to convey subject-matter content knowledge, but also to shape the student mindset, metacognitive practice, and understanding of the nature of science.

Keywords: reflective writing, critical thinking, knowledge in pieces, coherent theory, student's epistemological beliefs, cognitive dissonance theory, principle of counter induction, model-centered instruction

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INTRODUCTION

An ongoing debate in the science-education community exists between those who believe that students enter the classroom with stable and coherent ideas about the natural world that differ from those presented in science textbooks and by their science teachers, and others who claim that student knowledge consists of isolated structures called phenomenological primitives (p-prims). The former view is referred to as the "Theory Theory" (TT; e.g., Posner et al., 1982; Vosniadou et al., 2008). An exemplar was the idea that students begin their studies with stable and coherent conceptions or theories about force and motion similar to the theories that were held by ancient philosophers and scientists (Wandersee et al., 1994). The second view is referred to as "Knowledge in Pieces" (KiP) and emerged in the 1990's as a dominant alternative to TT. Each view has important and different implications for the goals and methods of instruction that lead to productive changes in the student's knowledge structure (conceptual change).

Naturally, a student's scientific knowledge structure reflects their view of science learning. Students who see science learning as a passive activity believe that scientific knowledge is received knowledge, while students whose knowledge structure is highly fragmented see scientific knowledge as an enormous body of unrelated "bits" or trivia to be memorized. This private and usually implicit student epistemology can be characterized as "problem driven"; i.e., scientific knowledge consists of isolated structures, such as the equations, "cherry picked" from a chapter summary to solve problems related to specific situations. In this view, equations are not abstract representations of general ideas or principles, but merely instruments to calculate things. Conventional science instruction often exacerbates the problem. For example, inattention to the interplay of theory and experiment, or competing theories, leaves the student with the false impression that scientific progress is due entirely to experimentation. The modern scientific classroom must therefore be designed to address the diverse needs of a mixed student epistemology classroom.

Reflecting on his theory of student intuitive knowledge, diSessa (1996) writes: Do ordinary people have anything like theories of the physical world? It seems the most plausible a priori position is "no." Theories are things that belong to formal science (p. 711). Recently, however, Lattery (2017) presented detailed counter evidence for this claim. His research shows that many introductory physics students can and do think theoretically and even generate their own theories that differ from those found in their textbooks. The context of these observations is a university introductory physics classroom. Lattery's work provides evidence to support the claim "that students are authentic and creative scientific modelers" (p. 109), and asserts that, the "student view of force and motion does not appear to be incoherent or fragmented, but driven by [a] rule…" (p. 142). This observation suggests not only that many students enter the classroom with semi-coherent and stable conceptions about how the world works, but also an instinct for the nature of science or scientific knowledge (e.g., scientific knowledge must be coherent). Lattery's findings are consistent with the "theory theory" view of student knowledge that was previously dominant in the field.

The question then is, what might we make of these different perspectives? Given the possible epistemological diversity of our introductory science classrooms, we propose instructional strategies that help students build a formal understanding of science from productive "pieces" of knowledge *and* through a carefully guided analysis of their alternative conceptions. Key to combining these strategies is a learning environment that allows students to discuss their ideas with their peers and the instructor. Before describing these strategies in detail, we discuss (1) research that begins to evaluate the scope of the challenge presented by epistemological diversity in science education, (2) a concept critical to understanding learning environments that seek to address this challenge (*incommensurability*), and (3) a set of five research questions to guide the improvement of these learning environments.

OVERVIEW OF STUDENTS' VIEWS ON THE NATURE OF SCIENCE

Kalman (2002, 2010) demonstrates that student understanding of the nature of science can be advanced through direct study of the philosophy of science. In these research studies, university students are placed in small groups and assigned a philosopher of science to study throughout the course (e.g., Kuhn, 1962/1970; Popper, 1963; Lakatos, 1970; Feyerabend, 1993). Significant time (60 min a week or 60 min every second week or five 75 min sessions) is devoted to group presentations. The groups report periodically to the entire class. In addition to sharing these ideas in class the students hand in a written work. Only the latter is marked.

With respect to the theory-pieces debate, about half of the students in the experiment described by Kalman (2002, 2010), who held views of science consistent with Popper on the first day, view scientific knowledge as coherent and interrelated. At the end of the course, only three students (all categorized as "other") had a view of science that could be categorized as "knowledge in pieces" (KiP). All students who initially identified as Baconian and KiP had sharpened their viewpoint and showed evidence of a coherent view of the nature of science. It is now generally understood that the nature of a naïve student intuitive knowledge (whether coherent or fragmented) depends on the specific experiences and cognitive development of the student (Kalman, 2010). This knowledge is almost certainly correlated to the student's understanding of the scientific-thinking process itself.

INCOMMENSURABILITY AND SCIENCE LEARNING

Student conceptions in science are found to be *incommensurate* with accepted scientific theories (Chi, 2013), much as ancient

Greek ideas of force and motion are incommensurate to those of Newtonian mechanics. An idea is said to be incommensurate with another idea when there is no, or a very limited, basis of comparison between the two ideas. Kuhn (1962/1970) and Feyerabend (1962) independently introduced the idea of incommensurability to the philosophy of science. Kuhn used *incommensurability* to illustrate the holistic nature of the changes that take place in a scientific revolution; for example, Kuhn claims that many scholars initially rejected Newton's theory because it did not explain the attractive forces between matter, something required of any mechanics according to Aristotle, Descartes, and their followers (Kuhn, 1962/1970). In later publications such as Kuhn (1981/2000) he continued to emphasize the difference between normal, cumulative growth that is in accord with existing concepts and revolutionary discoveries that could not have been made wholly on the basis of previously known concepts such as the discovery of Newton's theory. Such new discoveries require replacing known concepts with new concepts that are incommensurable with antecedent ideas. The implications of these observations for classroom learning are just beginning to be explored.

In *Against Method*, Feyerabend states (p. 212): "In 1962, I called theories such as those containing 'impetus' and 'momentum' incommensurable theories." Feyerabend's incommensurability corresponds to questions that have meaning only in a particular theory. As Kalman (2009) notes, if an overlap between successive theories exists (i.e., shared ideas and/or concepts exist), then there can be interesting questions that are meaningful in the context of both theories. Thus within the context of both the wave and particle theories of light we can ask whether or not diffraction takes place. However, if there is no overlap, questions exist that have meaning only in the context of one theory, but not the other. As such, a question on the nature of the Ether makes sense in the context of the wave-ether theory, but has no meaning in the context of Einstein's special theory of relativity.

FIVE QUESTIONS OF SCIENCE INSTRUCTION

Addressing student ideas that differ in key respects to accepted (target) scientific knowledge is a significant challenge for science education. Kalman (2017) presents research questions in science educational research in that are examined in depth throughout his book. In the context of the design of science instruction, we consider five of these basic and local questions:

1. What is the nature of student knowledge: knowledge-in-pieces or a coherent theory.

The question of the nature of student knowledge has important implications for instruction. If student knowledge is fragmented and disorganized, instruction should build scientific concepts from the relevant "pieces" as done in the Bridging Technique (Clement and Rea-Ramirez, 2008). However, if student knowledge exhibits coherence (e.g., the student places increasing value on explanatory consistency in their modeling activities), instruction should confront student ideas, as done in the Elicit-and Challenge approach. Lattery (2017) presents evidence to justify an integration of these two approaches.

2. What is the stage of the students' intellectual development?

McKinnon and Renner (1971) state the hypothesis: "The majority of entering college freshmen do not come to college with adequate skills to argue logically about the importance of a given principle when the context in which it is used is slightly altered." In this context, Renner and Paske (1977) found that "approximately 50% of entering college freshmen are concrete operational." This itself is a gross simplification. Vygotsky (1978) critiqued the assumption that a student's developmental level is entirely given by a battery of tests of varying difficulties. In his opinion, what the student can do "with the assistance of others might be in some sense even more indicative of their mental development than what they can do alone" (p. 85). The role of the instructor is therefore to provide the necessary scaffolding (Wood et al., 1976) for students to progress through stages of development.

3. What are the student's epistemological beliefs or approaches to learning?

Elby (2001) notes "students' epistemological beliefs—their view about the nature of knowledge and learning affect their mindset, metacognitive practice, and study habits in a physics course." Another issue to consider is the views students have about the Nature of Science (NOS). Students generally start out with a Baconian perspective that scientific ideas develop by induction from experiment (Kalman, 2010). Clough (2006) points out that students' conceptions about the NOS are based upon "Teachers' language, cookbook activities, textbooks that report the end products of science without addressing how the knowledge was developed" (p. 467). Instruction should then focus also on students' views of the NOS, emphasizing the interaction of theory and experimentation as a method for adjudicating and refining theories.

4. What instructional supports are necessary for students to examine and develop their own ideas and compare them to the ideas presented by peers, the textbook, and the instructor??

Feyerabend (1993, p. 33) points out that critical evaluation of one's own ideas requires the consideration of an alternative, competing idea. This is the principle of counter induction, stated alternatively as changes in theories occur only when one theory is compared with another. In order to maximize empirical content, a scientist will compare theories with other theories rather than with experience, data, or facts. This pluralistic approach has often been used in the past. For example Newton did not try to prove, in advance of experimental evidence, that the assumptions he made in his theory of gravity were axiomatic or valid. His approach was to use them as working assumptions which would be accepted hypothetically only as long as their consequences threw light, in exact detail, on hitherto-unexplained phenomena. Thus, he made a practice of critiquing *theory qua theory*. Students, whose goal is solving problems alone, will have difficulty seeing the value of this approach. What would a student make of Newton's discovery that inertial mass and gravitational mass are the same? "It [mass] can also be known from a body's weight, for—by making very accurate experiments with pendulums—I have found it to be proportional to the weight..." (Newton, 1686, Opening paragraph of the *Principia*)." Instruction should then be designed to support such methods of comparing and contrasting theories.

5. How does the student deal with cognitive conflict or cognitive dissonance?

Cognitive dissonance theory (Festinger, 1957) continues to be the subject of new research; for reviews see Cooper (2007) and Harmon-Jones and Harmon-Jones (2007). Psychological discomfort, or dissonance is produced when relevant and inconsistent cognitions occur. Linenberger and Bretz (2012) discovered that cognitive dissonance occurring in interviews provides important information about how students understand enzyme substrate interactions. The student is convinced by experience with everyday phenomenon that their intuitive ideas about the natural world are correct (e.g., "motion implies force"). The natural student response to cognitive dissonance is to assimilate (in a Piagetian sense) scientific knowledge from the textbook or teacher into a pre-existing knowledge framework. Put in a different way, cognitive dissonance leads students to misread the textbook and mishear the teacher.

Our own individual and joint work has three instructional strategies that address the teaching and learning issues raised by these questions. We present these below. In each case, a combination of approaches is employed to meet the needs of a mixed student epistemology classroom. These active learning strategies engage the learner in scaffolded tasks and take them through one of the identified processes described above.

STRATEGY 1. REFLECTIVE WRITING AND LABATORIALS

Madsen et al. (2015) performed a meta-analysis synthesizing 24 studies and found that in typical physics classes students' beliefs are less expert-like at the end of the course than they were at the beginning. Kalman et al. (2015) considered the hypothesis that students' epistemological beliefs could become more expert-like with a combination of appropriate instructional activities: (a) pre-class reading with metacognitive reflection (Reflective Writing), and (b) in-class active learning (Labatorials) that produce cognitive conflict/dissonance, and (ideally) a transition to more productive ideas. Below we describe both Reflective Writing and Labatorials, as well as briefly report on the impact of a combined approach.

Reflective Writing

For many years, Kalman et al. designed new and innovative pedagogical tools to meet these instructional challenges: The Reflective Writing (RW) tool (Kalman and Rohar, 2010; Kalman, 2011; Huang and Kalman, 2012; El-Helou and Kalman, 2018) is a metacognitive activity, that prompts students to examine textual material, before coming to the classroom or laboratory in the manner of a hermeneutic circle (Gadamer, 1975/1960). The student begins an examination of a textual extract with preconceptions (misconceptions). The key quintessential experience occurs when the student is pulled up short by the textual extract. "Either it does not yield any meaning or its meaning is not compatible with what we had expected" (Gadamer, 1975/1960, p. 23). The metacognitive reflection begins when they question their understanding of the text within the entire "horizon" (Kalman, 2011, p. 163). Gadamer (1975/1960) expanded the notion of horizon that originated with "Heidegger (1962)". Gadamer takes the term "horizon" to be all that one can see defined by your pre-understandings. In reading a text, one encounters the horizon of the text and self-examination will produce a new horizon.

While reflective writing can be used as a tool for self-awareness it has also been employed as an assignment assessment with the aid of rubrics (Khanam and Kalman, 2017). This instructional strategy has been used in Grade 11 and across many post-secondary subject areas. One drawback to this approach is that it doesn't work well with younger students (El-Helou and Kalman, 2018); the authors speculate that this result is due to the stage of the students' intellectual development.

Labatorials (Laboratory + Tutorials)

The development of Labatorials at the University of Calgary (Ahrensmeier, 2013) was motivated by the introductory physics tutorial system used at the University of Washington (McDermott and Shaffer, 2001). Students are given a worksheet that contains instructions for experiments, calculation problems, computer simulations, and conceptual questions. At the onset, students are assigned to groups of 3 or 4 members and provided with conceptual questions and asked to make predictions. Each lab section has one lab instructor assigned to a maximum of 16 students. Each group completes a Labatorial worksheet that usually contains 3–6 checkpoints. On completing each checkpoint, the group reviews the answers with the lab instructor. If the answer to a question is incorrect the lab instructor will help the students to find the correct answer through exploration and discussion of alternative ideas. The worksheets are developed in such a manner that students who arrive on time and concentrate on the material can finish all checkpoints in the time allotted. Evidence suggest that Labatorials are useful to both instructors and students (Sobhanzadeh et al., 2017). Students identify their strengths and weaknesses and identify areas of their understanding that need to be strengthened. At the same time, instructors can recognize and address problems immediately.

A Combined Approach

Kalman et al. (2015) show that students' epistemological beliefs become more expert-like with a combination of (a) pre-class metacognitive reflection (Reflective Writing), and (b) in-class active learning (Labatorials) that produce cognitive dissonance. This research examined: an experimental group of 8 sections (110 students) and a control group of 7 sections (102 students) of an introductory physics course. Both groups performed Labatorials, however, the experimental group performed Reflective Writing while the control group performed summary writing.

To assess changes in students' epistemological beliefs, this study used Hofer's discipline-focused epistemological beliefs questionnaire (DFEBQ) (Hofer, 2000). A pre-test was administered in the Fall, and a post-test was administered after two semesters. All students performed Labatorials. Students who had taken Reflective Writing in the first semester continued with Reflective Writing in the subsequent semester; students who had taken summary writing in the first semester similarly continued in this mode. Results showed that the students' epistemological beliefs in the experimental group (Reflective Writing) become more expert-like in their thinking compared to the control group.

The strength of this combined approach is its emphasis on developing conceptual knowledge through writing and metacognition. Students/peers are also challenged to compare their ideas with accepted scientific views. Reflective Writing is done by students at home and does not require additional class time. Indeed, since students have read the textual material before coming to class, the instructor should cut back on the material that is presented and use the saved class time for "flipped classroom" activities such as those described in Strategy 2 below.

Summary of Strategy 1

Sobhanzadeh et al. (2017) found that Strategy 1 is useful to help students to explore the relationship among various physics concepts. Students improved their understanding of concepts, problem solving skills, engagement, and performance in the lab. However, the approach was not designed to produce profound and sustained learning, which (as we explain below) requires a thorough peer-centered discussion of both prior and target ideas.

We are currently testing Strategy 1 in high school physics classrooms. Preliminary results indicate that it works well in such a setting. The main challenge of implementing this approach is that Strategy 1 requires a complete redesign of conventional laboratories as described by Sobhanzadeh et al. (2017).

STRATEGY 2. CONCEPTUAL CONFLICT COLLABORATIVE GROUP AND CRITIQUE EXERCISE

Kalman and Lattery have each argued that deep science learning in the science classroom is not generally possible unless students have an opportunity to sort out their ideas with peers and consider alternative or competing ideas. Below we describe three approaches that show promise for generating these deeper levels of reflection, comparison and confrontation of opposing theories. These consist of the Conceptual Conflict Collaborative Group, the Critique Exercise, and lastly, the Combined Approach; each has been the subject of research by one of the current authors.

Conceptual Conflict Collaborative Group

In a university course (Kalman and Aulls, 2003) students considered two alternative frameworks: pre-Galilean Physics and Newtonian Physics. The idea of the course design is for students at first to view the frameworks almost in a theatrical sense involving a conflict of actors (Aristotle, Galileo, Newton, and others) in the history of science. The study showed some students gradually identify with the conceptual positions taken by the proponents of the alternative frameworks and become themselves a part of the action.

During the course, students gradually realize that the positions defended by the actors are connected to concepts from different parts of the course. Armed with this knowledge, students evaluate the two competing, alternative frameworks through the Conceptual Conflict Collaborate Group (CG) exercise (Kalman et al., 1999) and through an argumentative essay (*critique*) (Kalman et al., 2004). Three to four students are assigned to a collaborative group. Within each group students take on roles such as scribe, reporter, critic, or timekeeper. Although students remain in the same group throughout the semester, students are given the option to change roles in each activity.

For each exercise, students are asked to discuss for a fixed time limit a demonstration or qualitative problem. Time limits are set so that none of the groups need to wait for other groups to complete the task. The lesson impresses on the student that there are at least two ways of looking at the problem. Having two groups with different concepts report to the class produces the desired conceptual conflict. Then, representatives of each group debate the issue between themselves. Afterwards, the rest of the class is invited to present questions to these representatives. (The use of personal scientific conceptions by an "expert" did not appear to have negative connotations, an issue examined by presenting qualitative essay questions on the final exam).

To underscore that two conflicting concepts have been presented, the class is asked to vote on which concept resolves the demonstration or qualitative problem. Voting is essential because students due to cognitive dissonance students often misinterpret what they hear or read. Due to the vote, students are anxious to find out which point of view is correct. The professor resolves the conflict by using demonstrations.

To evaluate this approach, Kalman et al. (1999) studied two sections of the same calculus-based mechanics course taught by the same instructor. Four concepts were examined. In one section concepts A and C were examined using the collaborative group method while concepts B and D were taught by conventional methods. In the other section, the procedure was reversed: concepts B and D were examined using the collaborative group method while concepts A and C were taught by conventional methods. Pre- to post-test gains for question sets based on an enhanced version of the force concept inventory (FCI; Hestenes et al., 1992), showed that the group that used the collaborative group method was more successful in making a conceptual change than the group taught by conventional methods (Kalman et al., 1999).

Kalman et al. (2010) also compared the above approach with Peer Instruction (PI) (Mazur, 1997; Crouch and Mazur, 2001; Lasry et al., 2008). This experiment made use of two equally experienced instructors teaching an introductory first year physics course for science majors at a large public university. Students were randomly allotted to the two sections of the course. Both teachers had often used PI with clickers to cover other concepts than those covered in this paper. The Force Concept Inventory (FCI) was used as a pre- and post-test to compare the two classes.

A comparison of CG and PI for two classes and three tasks are as follows: For the first task, the collaborative group (CG) method produced a statistically significant higher score ($p = 0.017$). There was no statistically significant difference between the methods for the second task, even though the CG method produced a slightly higher result. For the third task, the class using CG produced a higher score with virtually no overlap within the statistical error. Overall, the CG method seems to be more effective than the PI method.

Critique Exercise

The critique activity was introduced to promote critical examination of the alternatives produced in the collaborative group exercise. Essentially the critique activity is an argumentative essay. Students have to produce as many possible arguments that favor all of the conceptual ideas raised in class and then indicate which viewpoint is in accord with the experimental evidence. The critiques are designed to encourage the students to undergo a "critical discussion to decide which natural interpretations can be kept and which must be replaced" (Nelson, 1994). To write critiques, students had to clearly contrast two perceptions of physics principles, specifically students must provide convincing arguments both for an explanation arising from the Newtonian viewpoint and an alternative explanation. Furthermore, they must clearly state which viewpoint is "correct" based on experimental results.

A Combined Approach

The Conceptual Conflict Collaborate Group exercise was used in conjunction with the critique exercise by Kalman et al. (2004). Students were presented with two scenarios drawn from an earlier conceptual-conflict collaborative-group activity. One scenario corresponded to an explanation that does not have experimental validity and the other to the Galileo-Newtonian framework. Both scenarios were generated by students in the classroom. All in all, three conflict exercises were used in conjunction with the critique activity. Comparison was made with students who had in a previous year used the CG exercise alone. Analysis was done using only those students in the second year who took both the pre- and post-tests, who were present at all three conflict exercises and additionally who wrote all three critiques. The addition of the critique produced a statistically significant improvement for those students exposed to both the Conceptual Conflict Collaborate Group exercise and the Critique exercise compared with those students exposed to collaborative groups alone.

The strength of this combined use of peer conflict and writing (argumentative essay) is the depth of critical analysis it produces. Students quickly become invested in their positions through peer interactions (oral and written); and they see a stake in defending their ideas and evaluating others. The effects of this immersive experience of scientific communication are stable learning outcomes. The approach is most helpful to students who entered the classroom with a view of scientific knowledge as coherent and highly ordered—a necessity for instructional strategies that place importance on experiment and logical consistency to induce conceptual change. A limitation of this approach is that the competing/ideas (i.e., those of Aristotle, Galileo, Newton, and others) considered by students are presented from the beginning, rather than uncovered through their own experimental work and logical reasoning.

As discussed at the end of Strategy 1, RW is done by students at home and does not require additional class time. Indeed, since students have read the textual material before coming to class, the instructor should cut back on the material that is presented and use the saved class time for "flipped classroom" activities such as those described in Strategy 2. Typically to implement Strategy 2, we have students do Reflective Writing so that time is available for the Conceptual Conflict Collaborative Group activity, as well as other activities.

STRATEGY 3. THE ELICIT-AND-CHALLENGE APPROACH AND THE BRIDGING TECHNIQUE

The third and final strategy involves the use of an Elicit-and-Challenge approach along with a Bridging Technique. This method starts with the assumption of a mixed epistemology and is implemented within a "model-centered" physics classroom. Instead of conflicting explanations, students build models that need to be explained. As with the Reflective Writing (RW) and conceptual conflict techniques and the joint Labatorial-RW interventions, these strategies draw on the history and philosophy of science for both inspiration and implementation.

Elicit-and-Challenge Approach

The Elicit-and-Challenge approach begins with a set of hands-on activities to expose students to common set of concepts, ideas, and skills for the lesson unit. Then, students are placed in small groups to complete a modeling task. A consensus model is developed and shared with the entire class. Students articulate and defend their models before peers and the instructor.

For example, in Lattery (2017) students are asked to develop and present dynamical models of fan-cart phenomena based on their understanding of statics, the concept of net force, and numerous motion detector activities. Two primary cases are considered: the one-way trip of the fan cart (the mechanical analog of the vertical ball drop) and the two-way trip of the fan cart (the mechanical analog of the vertical ball toss). The ultimate goal of such activities is for students to acquire a classical (Newtonian) force concept through an extended and carefully guided process of model building.

As students struggle to respond to new information (contrary experimental evidence, logic arguments, and resources from related physical system), new models are generated. After multiple competing models are thoroughly considered, students write a paper on their ideas, receive a peer review, and provide a rebuttal. In the above example, students are observed to generate only four basic pre-Newtonian models of the one- and two-way trips of the fan cart; these models map onto those generated by ancient philosophers and scientists for the analogous cases of the vertical ball drop and toss.

As a cumulative activity, students "teach and defend" their model to others using a whiteboard presentation—a key technique used in the Modeling Method of Instruction (Jackson et al., 2008). The goal of this Elicit-and-Challenge approach is not necessarily to alter the student's alternative conceptions or epistemologies, but to give students space to explore the limits and exhaust the defense of their models. This often-regressive process highlights the distinct weakness of student's prior ideas, and challenges students to evaluate their assumptions. In short, the process primes them for target ideas.

In the above implementation, the history of science is incorporated in two ways. First, the instructor employs detailed arguments for/against competing models of the vertical ball drop and toss to probe student's views of the associated fan-cart phenomena. This can be done either in large-group class discussions or through anonymous peer reviews. Second, the instructor revisits the historical connections at the end of the unit to validate the students modeling efforts ("great minds think alike") and highlight the nature of the scientific modeling process (e.g., models are tentative, models to specific phenomena provide the key means to evaluate ideas, and multiple competing models are the norm in frontline science).

The use of a peer-review process to explicate and evaluate student competing models is very similar to the Critique Exercise previously described. In either case, the teaching principle is the same: for deep and sustained learning to occur, students must be given the opportunity to consider multiple competing models—whether generated through the student modeling process (Lattery, 2017) or through comparison of theories proposed by different groups (Kalman et al., 2004; Kalman and Rohar, 2010).

The primary challenge of the Elicit-and-Challenge approach is teacher training; in order to negotiate/challenge the various student models presented, teachers must have a sound understanding of the subject-matter content *and* a strong technical knowledge of how students think and learn in the domain. Additionally, this approach does not always end in a "tidy" resolution—the attainment of the intended learning objective. After "exploring the limits and exhausting the defenses," a student may be unable to make the intellectual leap to target ideas. This can be frustrating to the student. The purpose of the Bridging Technique in the next section is to marshal a set of resources (prior to or in parallel with the Elicit-and-Challenge process) so that the students can, with teacher guidance, discover target ideas.

Bridging Technique

In the Bridging Technique "students are guided by the instructor through a chain or network of related modeling tasks intended to bridge the student's prior knowledge with target knowledge." (Lattery, 2017, p. 254). For example, in the above activity, a network of cases involving a double fan cart is used to bridge the student's intuitive understanding of the one-way trip to a classical understanding of the two-way trip. The Bridging Technique is implemented either after or in parallel with the Elicit-and-Challenge tasks, although students do not generally recognize the bridging tasks as relevant to those tasks.

In contrast to Elicit-and-Challenge activities, bridging activities:

> do not challenge student alternative conceptions, but develop the capacity of students to recognize knowledge drawn from one physical case as relevant (literally similar or analogous) to another, and extend the range of applicability of a single unifying idea ("things go back to their original shape" or "net force steps produce velocity kinks") over a range of related physical cases (p. 255).

The Bridging Technique relies on the ability of students to extend prior knowledge (commonsense intuitions, folk science, anchoring intuitions, p-prims, etc.) to new domains through formal literal similarity and analogical comparisons. It should be noted that the Bridging Technique used in isolation, does not lead to sustainable learning outcomes because "it circumvents the student's initial high-priority ideas" (p. 255). In other words, in the above example, the student may be able to follow the "Newtonian agenda" of the bridging sequence, but not acquire the specific tools to understand why previous commonsense ideas fail. As a result, these less-productive ways of thinking remain central to the student's thinking and tend to resurface in new contexts.

A Combined Approach

Science learning gains achieved by combining the above approaches are documented through several detailed case studies in an introductory physics classroom (Lattery, 2017). A combined approach reflects openness to the question of student knowledge. In other words, it accepts the possibility that student knowledge consists of either "knowledge-in-pieces," for which the Bridging Technique is appropriate; or, more coherent structures, for which the elicit-and-challenge approach is suitable. A strength of this approach is that the competing ideas of the students flow naturally from their own experimental work and scientific reasoning; resolution of conflicts is guided by peer and instructor questioning—the latter inspired by the detailed analysis of model justifications in the history of science.

Strategy 3 requires a classroom learning environment that immerses students in the scientific modeling process, such as the Modeling Method of Instruction (Jackson et al., 2008). This strategy has been used successfully in a university-level physics course for non-science majors seeking general education credit. Future studies are being planned to evaluate this approach in middle and high school classrooms (grades 6–12).

SUMMARY

Contemporary science education reform must address the diverse needs of a "mixed epistemology" classroom. In this article, we presented three strategies that show promise to address these complex issues: Labatorials and Reflective Writing of Kalman et al. (2015); Conceptual Concept Collaborative Group and Critique essays of Kalman and Rohar (2010); and the Elicit-and-Challenge and Bridging Technique described by Lattery (2017).

Common to these approaches is an emphasis on the nature of science, subject matter content, and the role of the history of science in science education. Also common are activities that enable students to think through multiple competing ideas of the same phenomena with peers. Sorting through the strengths and weaknesses of multiple competing ideas enables students to understand not only why target conceptions succeed, but also why initial conceptions fail; both types of understanding are essential for deep learning in science (Lattery, 2017). Note that while the above three dual or combined instructional approaches target the same level of students, these interventions are sophisticated and not designed to be implemented all in one course. For a complete discussion of issues that teachers should take into consideration in employing these strategies, please consult the sources and references therein.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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