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AST424 Final Report: Two Topics in Physics Education Literature

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ABSTRACT

In the research field of education, it is well established that measures of teacher quality are highly correlated to student outcomes (Darling-Hammond (2000)). As such, this report summarizes research findings that address the topic of effective teaching practices in the physics and astronomy classroom, so that they may be understood and applied by myself and educators. This report finds that the use of Interactive Engagement (IE) methods in the classroom including lecture demos, simulation demos, and modeling assignments are significantly better for student development of physics concepts and beliefs than classes that do not make use of IE. Moreover, classrooms that made use of a composite of IE methods were found to be more effective than individual IE methods by almost 100% and modeling based teaching methods were the deciding factor in shifting physics students' beliefs to more accurately reflect the discipline as a whole.

1. INTRODUCTION

What makes a great teacher? This is the fundamental question that motivates my research and is a question whose answer will be useful to my future endeavors. It's also a question with great breadth. The content, the methods, and the learning environment are just a few examples of starting points one can take in order to start tackling such a large topic, and for that reason my interests have had me looking into many areas. Arguably the most important area of research I have looked into is pedagogy. The role of the teacher effectiveness in student learning outcomes cannot be understated and, for that reason, knowing how to best teach the given content is worthy of investigation. In this report, I would like to present two areas of the literature that are particularly relevant to physics and astronomy educators while also being straightforward to act on.

1.1. *Engagement*

Having students engaged in lessons is necessary for learning, and with introductory physics being so relevant to everyday lives, attention in Physics Education Research (PER) has been brought to the study of student engagement in the physics classroom. In an important study which would become a branching-off point for future PER, physicist, R. R. Hake surveyed 62 physics classrooms across high schools, colleges, and universities to see the effect of student engagement on learning outcomes (Hake (1998a)). What he found - and later discussed here - was that classrooms where teachers made use of engaging pedagogy saw up to 80% learning gains over more traditional classrooms. Engaging pedagogy or “Interactive Engagement (IE)” includes practices like class demos, simulations, and group work while traditional classrooms fall under “chalk and talk”.

1.2. *Student Beliefs*

When did you first understand physics and astronomy as a discipline? Typical introductory physics courses involve mathematics primers, weekly problem sets, and perhaps dreaded pendulum labs, and while necessary for developing skills that physicists need, the average practicing physicist or astrophysicist likely does not relate to the same daily routine as a student. With this in mind, it falls upon the role of educators to guide students in developing correct beliefs about the field and what physicists and astrophysicists actually do: the scientific method. Moreover, for students taking only a single class/course in physics or astronomy (perhaps as a requirement) it is even more important that educators develop those beliefs effectively.

2. TESTING

Claiming that one method of teaching is more effective at improving conceptual understanding or improving student beliefs over another begs questions regarding how studies are conducted: what is effective teaching and how is it measured? While accessing the deep learning of a group of students would be insightful and lead to strong conclusions, it can be infeasible for education researchers to do this. Instead, in order to test a hypothesis in PER, an evaluation is done before and after an intervention so that a comparison can be made. For example, if researchers wanted to know how effective a particular pedagogy is over another when teaching Newton's laws, researchers would need to conduct a test on Newton's laws before and after a student's mechanics unit and measure how much students improved on said test. The significance of the results improve with larger sample sizes and it is important to make sure the test accurately reflects the ability you are measuring (test validity). With these factors in mind, a selection of standardized tests are frequently used in PER: those relevant to this literature review are the FCI, FCME, MPEX, and CLASS tests which will briefly be grouped and discussed. Since almost - if not all - introductory physics courses involve a mechanics unit, PER often focuses around mechanics content when evaluating student learning since it is fundamental to physics and there is a large sample size to survey. The Force Concept Inventory (FCI) and Force and Motion Concept Evaluation (FCME) are two multiple choice tests designed by physics education researchers to serve as a standard, reliable tools when evaluating student learning in PER. They're useful for studies across high school, college, and university physics since the test items don't involve computation as seen in Figure 1.

While the FCI and FCME are valuable for assessing student understanding of Newton's laws, physics education researchers are interested in other aspects of student understanding of physics too. The Maryland Physics Expectations Survey (MPEX) and the Colorado Learning Attitudes about Science Survey (CLASS) use Likert scaling to gauge student attitudes towards physics:

A potted plant falling from a patio roof on the top of a single story building:

(A) reaches a maximum speed quite soon after release and then falls at a constant speed thereafter.
(B) speeds up as it falls because the gravitational attraction gets considerably stronger as the plant gets closer to the earth.
(C) speeds up because of an almost constant force of gravity acting on it.
(D) falls because of the natural tendency of all objects to rest on the surface of the earth.
(E) falls because of the combined effects of the force of gravity pushing it downward and the force of the air pushing it downward.

Figure 1: An example question from the 2003 FCI. The question describes real phenomena, is completely conceptual, and assesses knowledge of Newton's laws. These elements make them useful for assessing students in a variety of physics courses.

25	Learning physics helps me understand situations in my everyday life.	1 2 3 4 5
26	When I solve most exam or homework problems, I explicitly think about the concepts that underlie the problem.	1 2 3 4 5
27	"Understanding" physics basically means being able to recall something you've read or been shown.	1 2 3 4 5
28	Spending a lot of time (half an hour or more) working on a problem is a waste of time. If I don't make progress quickly, I'd be better off asking someone who knows more than I do.	1 2 3 4 5
29	A significant problem in this course is being able to memorize all the information I need to know.	1 2 3 4 5

Figure 2: Questions 25-29 on the Version 4 MPEX. The Likert scaling is seen on the right were [1, 2, 3, 4, 5] correspond to [Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree].

Apart from being just a course survey, select questions in the MPEX and CLASS tests are designed to gauge the accuracy of student beliefs about physics (see Questions 25 and 27 in Figure 2.). Researchers decide on which beliefs align with physics experts in order to set a baseline for student evaluation.

Once tests are conducted before and after an intervention, researchers evaluate the differences in pre/post test score. One measure is exactly that, the difference of the post and pretest scores, known as the "learning gain":

$$g = Post\% - Pre\%. \qquad\qquad \langle g \rangle = \frac{g}{100\% - Pre\%}$$

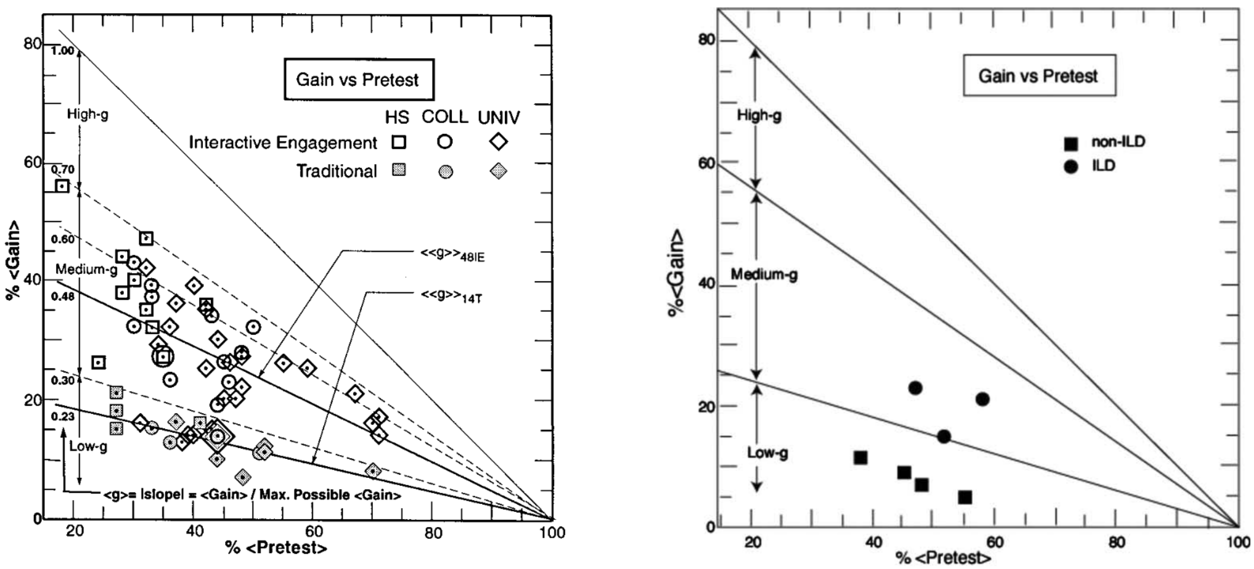
The normalized learning gain (NLG, ⟨g⟩) is just the learning gain over the maximum possible gain allowed by a student's pre-test score. If a student were to score a 40% on the pretest, the maximum possible learning gain they can attain on the post test is 60% (and NLG of 1). From the NLG there are a variety of ways to compare the effect sizes of the control and experimental groups and find statistical significance. For Likert scaling, number values can be assigned to each response (1 = strongly disagree, . . . , 5 = strongly agree) and total score for a test can be evaluated as the average value.

3. FINDINGS

R. R. Hake first demonstrated in 1998 that Interactive Engagement (IE) has significant positive effects on learning in the physics classroom (Hake (1998a)). IE as Hake defines it are "methods [that] are designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors". Though not strictly defined, a few examples of IE methods include: group work, lecture demos, simulations, and modeling projects (Hake (1998b)).

Promotion of conceptual understanding is a response to the disconnect that can occur between concepts in physics and their formulaic representations. Jacobsson and colleagues surveyed two physics classrooms in 2024 to investigate the role of mathematics in physics (Jacobsson et al. (2024)). Through a series of interviews, Swedish high school physics students admitted to habits such as jumping to solutions and using AI chat bots. On top of the interviews, PER researchers had students write a modified FCI in which half of the questions were made to be computational and found that students would, on average, score better on computational questions than those that were purely conceptual. The survey recognized the conceptual gap Hake addresses with IE, and with teachers sharing that they were concerned that students were doing "meaningless symbol manipulation", in regards to missing conceptual understanding.

When imagining 'engaging' physics we might consider hands-on activities like labs but Hake makes the distinction that IE methods must be "heads-on" too. By this, Hake is implying that interactive activities aren't necessarily engaging by their own virtue, and that thought must be put into making activities engaging, avoiding the pitfalls of "recipe-type" labs in the classroom. In 2010, Sharma and colleagues decided to replicate Hake's study but for specifically investigating the effect of Interactive Lecture Demos (IDLs), as opposed to a composite of IE methods (Sharma et al. (2010)). IDLs are physical demos performed by a course instructor in front of the class. At the University of Sydney, Sharma's team evaluated student learning gains over seven classes in introductory, university level physics; they found that students achieved higher learning gains when in the test group using IDLs. Learning gains saw an increase of up to 42% on the FCME: While significant, these results showed a more modest increase compared to Hake's upper limit of 80% for the composite measure of IEs with the FCI (seen in Figure 3.). All in all, Sharma found that IDLs did increase student learning gains over the students' mechanics unit, but with an important distinction. Through interviews with the seven course instructors, the researchers found that IDLs done poorly did not see the same student engagement as those done well. Run-down equipment, live demo failures, and set-up difficulties were among the problems that instructors listed in regard to student engagement, emphasizing the need for and reliance on designated lab technicians.



(a) Hake's 1998 Composite of IE Findings

(b) Sharma's 2010 IDL Findings

Figure 3: The x-axis represents the average pretest score for a class and the y-axis is the average learning gain after the posttest. Each sloped line indicates an NLG. In Hake's study, shaded markers indicate 'traditional' courses and unshaded represent those using a composite of IE. In Sharma's study, squares indicate 'traditional' courses and circles indicate those using ILDs.

Modeling and working with models are at the heart of what physicists and astrophysicists do, so as no surprise, modeling is important to developing correct beliefs about physics and astronomy. In 2015, Madsen and colleagues conducted a meta analysis of 24 studies to determine the effect that instruction had on developing student beliefs about physics (Madsen et al. (2015)). They compared studies involving courses from algebra based, calculus based, AP, and even primary teacher education courses in physics. They also compared teaching methods regarded as more traditional to those involving modeling and research. To synthesize their results Madsen chose studies which made use of MPEX and CLASS assessments only and uncovered a collection of interesting findings. First, students of physics courses that were not designed for physics majors, like those designed for primary school teachers, saw the largest positive shift in beliefs, while AP and calculus-based courses saw more conflicting results. Second: courses which focussed on modeling saw positive shifts in beliefs across all levels of physics. That is, the conflicting results for AP and calculus-based courses in shifting beliefs were differentiated by instructional methods, as seen in Figures 4 & 5. Lastly, smaller class sizes saw greater positive shifts in beliefs about physics.

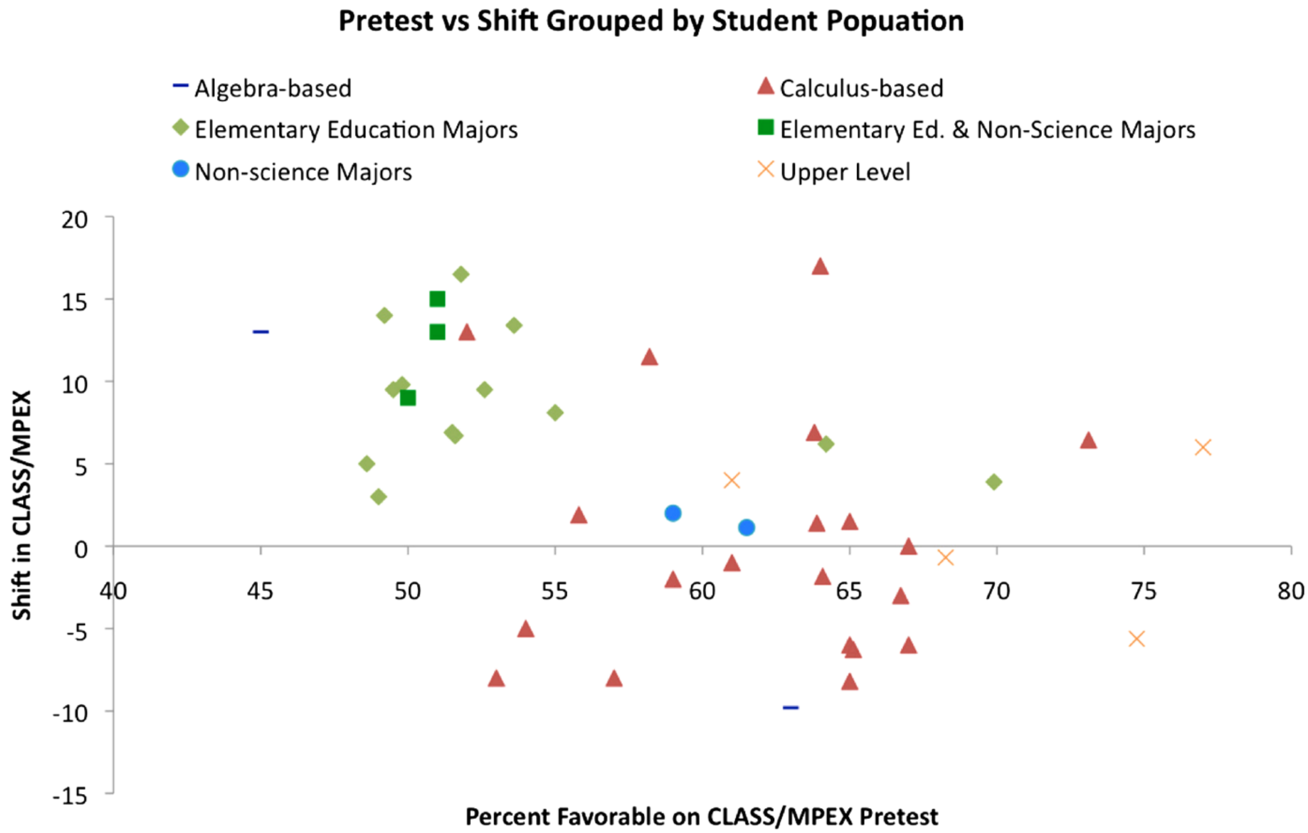


Figure 4: Graph of the average shift in beliefs of a class based on class population. The y-axis represents the direction of the shift after the posttest, whether student beliefs improved. The x-axis represents how closely a class's beliefs aligned with experts on the pretest: It makes sense here that university ("Upper Level") students already have more sophisticated beliefs about physics than Non-science Majors.

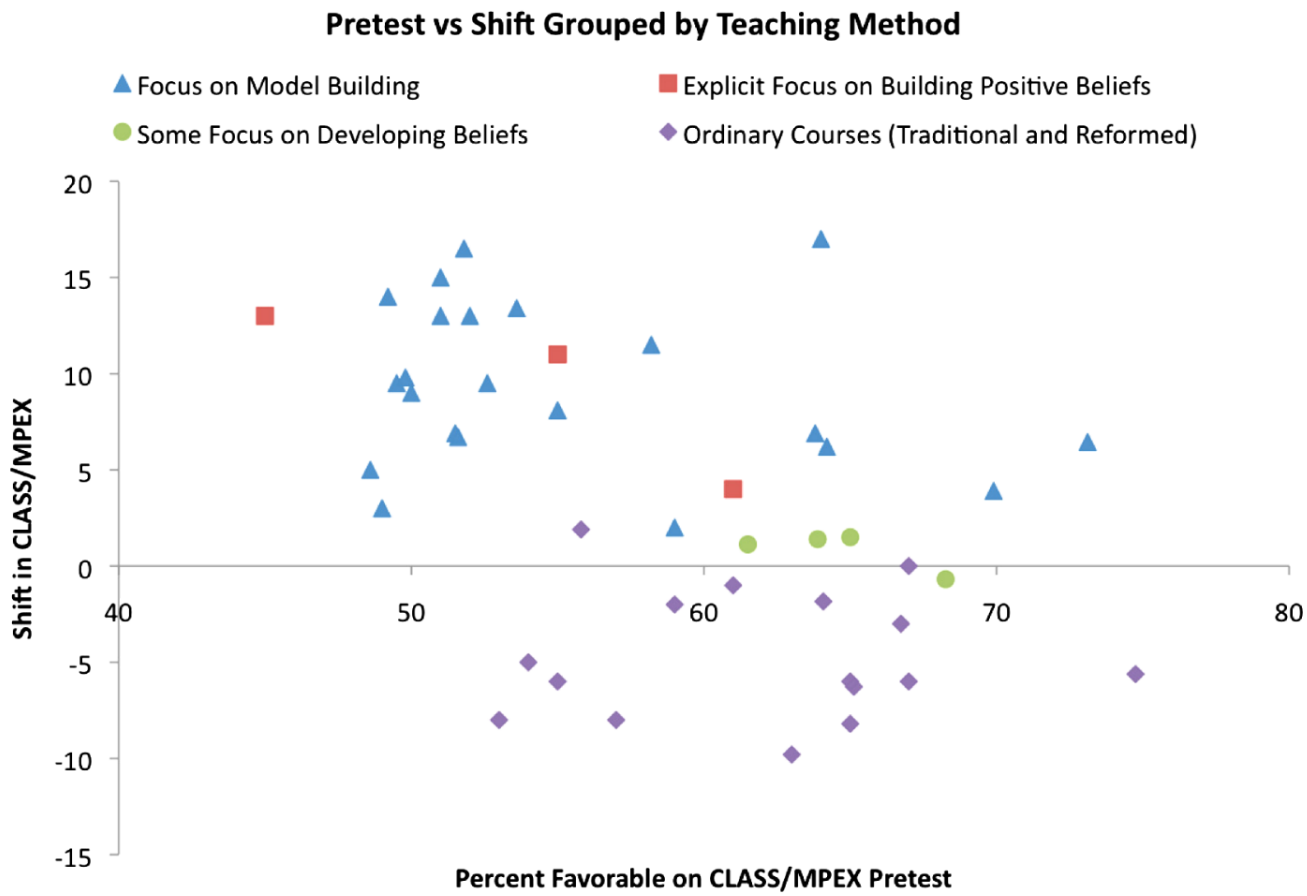


Figure 5: A recreation of Figure 4. but categorized by teaching method. Model Building and Ordinary Courses are the two largest categories with two categories that put specific focus on building positive beliefs about physics. Teaching method could not be categorized for a few classes and so this figure is missing data points that are on Figure 4.

4. DISCUSSION

4.1. *The Relationship Between IE and Building Positive Beliefs*

The effects of IE methods on student learning gains with FCI/FCME conceptual tests support the idea that IE methods are a valuable tool for any physics or astronomy classroom. Moreover, the results suggest that while individual IE methods such as IDLs are beneficial to student learning, a composite of IE methods including (but not limited to) simulations, peer instruction, group work, and IDLs are even more effective. Physics and astronomy educators should make use of all the options available to them in regards to IE in order to increase student conceptual understanding.

When discussing student beliefs about physics, it is not too surprising that those with less expert-like beliefs initially have the most room to improve them. What is notable is that the deciding factor between whether a calculus-based physics course saw positive or negative shifts in student beliefs was whether the course made use of model building. Model building, which is reflective of the physics and astronomy disciplines at the research level, falls under Hake's umbrella of IE. In this way, support for IE is not only based in improving student understanding of physics concepts but also building accurate physics beliefs.

Directing the topic to Jacobsson's findings regarding student conceptual understanding often lagging behind computational ability, IE methods play an important role in making sure students understand the concepts behind the math and formulas that they manipulate. Madsen proposes a possible explanation for why the traditionally-taught, calculus-based courses see negative shifts in student beliefs: their math-heavy focus and coursework shroud the underlying physics principles they represent. Students interviewed in Jacobsson's study similarly reported negative beliefs with a focus on searching for- and plugging in formulas, emphasizing the relationship between having conceptual understanding and accurate beliefs about physics.

4.2. *Limitations*

This choice of research area and results come with limitations. The discussion regarding IE and its benefits to student conceptual understanding is just that: a benefit to conceptual understanding. The

FCI and FCME are designed to measure conceptual understanding of Newton's laws (seen in Figure 1.) and do not assess the skills of computation and how they relate to conceptual understanding. Though touched on briefly to contrast conceptual understanding, computational ability in physics and astronomy is its own important topic.

Another limitation is that while it is easy to suggest making use of IE methods in the classroom, as university course instructors recognized when using IDLs, IE as a resource is not always accessible and has the potential to be done poorly. While a university instructor may have a designated lab technician to assemble a demo or lab stations, a high school teacher may not. IE methods done right require resources and time which vary from situation to situation and suggest that more resource-accessible classrooms benefit more from IE. Additionally it is worth mentioning that not all subjects lend themselves to the same IE methods. Astronomy and Astrophysics instructors often rely on simulations instead of IDLs, meaning that IE looks different for different classes and is not a catch-all.

5. CONCLUSION

What makes a great teacher? While it's a broad question, this research helps clarify what physics teachers can do: Engage their students and nurture their beliefs about what they're learning.

IE methods are useful tools that increase student understanding of physics concepts. Though they have their limitations, a composite of IE methods in the physics classrooms sees students better understanding the underlying mechanisms of the physics they learn as well as developing accurate beliefs about physics as a field. The role of the educator in developing accurate beliefs about a technical field like physics in their students is an important responsibility. Having students model and doing research with the physics they are learning gives students the "heads-on, hands-on" experience of an actual physics researcher, developing their beliefs through doing.

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