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University of Northern Iowa

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Chapter 1: Introduction

AP Physics History

Every year, thousands of students across the country take the Advanced Placement (AP) Physics exams, a high-stakes achievement exam which has significant effects on their professional and educational futures (Stemler, Sternberg, Grigorenko, Jarvin, & Sharpes, 2009). In 2015, 171,000 students submitted their exams for scoring, up from 93,500 the year prior. This dramatic increase comes mostly from a change in the course programming. The previous single year-long AP Physics B course covered the content usually covered in two semesters of a college introductory physics course. The AP Physics B course split into two single year-long courses, AP Physics 1 and AP Physics 2, each covering the content of one semester of a college introductory physics course. Because of the change, many schools dropped a year-long prerequisite course mandated for their AP Physics B course and allowed students to enroll in AP Physics 1 with only a minimal mathematics course prerequisite. The striking effect of this was to open up AP Physics to a large number of previously excluded students to the course (Heitin, 2015).

Much research went into the design of the new courses including the reasoning behind making the change in the first place. Researchers found that the rapid pace with which AP Physics B teachers must go through the curriculum did not align to modern theories of student learning and cognitive processing. According to Stemler et al. (2009), the design of the AP Physics B course promoted memory and analytical skills, but not explanation comparison skills, data analysis skills, and synthesis of incongruent findings skills. Furthermore, AP Physics B students usually found it difficult to generate new theories, apply theoretical findings to authentic situations, and communicate findings to persuade others of the findings' value. Stemler et al. (2009) goes on to claim that, because students enrolled in AP Physics B are most probably among those who might go into physics as a professional discipline, the field as a whole suffers because it is potentially "dominated by individuals with a single profile of strengths, thereby inhibiting the capacity of the field to develop to its full potential" (p. 195). AP Physics B simply had to cover too many topics in a year and left no time for authentic scientific skill development. Students were only able to come to understand how to solve physics problems superficially.

On March 31, 1994, President Bill Clinton signed *The Goals 2000: Educate America Act*, which stated that the students in the United States would be first in the world in science and mathematics achievement by the year 2000. To assess this achievement, the United States Department of Education participated in the *Trends in International Mathematics and Science Study* (TIMSS), a large comprehensive and rigorous international study of student achievement (Gonzalez, O'Connor, & Miles, 2001). The study compared achievement on the TIMSS exam through categorization of students who have taken equivalent courses. For example, United States students were categorized as having taken an advanced mathematics course if these students had completed Pre-calculus, Calculus, or AP Calculus. Students from other countries were categorized as "having completed an advanced mathematics course" in similar ways. Students having taken one year of physics or AP Physics were categorized as having taken at least one year long physics course. The first exam was given in 1995, and the results showed that United States students were lagging behind most other modern countries, ranking 16th out of 21 in both mathematics and science literacy. Furthermore, US students ranked *last* in physics understanding and second to last in advanced mathematics understanding (Gonzalez et al., 2001).

The TIMSS physics exam questions are divided among three domains: knowing, applying, and reasoning. The knowing section comprises of classic physics recollection of facts, processes, relationships, and other broad-based factual knowledge, most commonly assessed through multiple choice style questions on the TIMSS. Applying domain questions task students with employing those factual relationships and processes to different contexts with which students are likely to be familiar because of their experiences in the physics classroom. This domain question style involves quantitative problems requiring numerical and algebraic solutions and written descriptive responses to qualitative problems. The reasoning domain tasks students with engagement in scientific analysis and applications of physics concepts in unfamiliar complicated contexts. This domain also involves hypothesis development and scientific experiment design. Again, we see both quantitative and written paragraph qualitative response type questions (Jones, Wheeler, & Centurino, 2015).

Because this was only the first year after the President's bill, many thought that the bill's actions simply had not had enough time to make an effect. The TIMSS exam was given again in the year 2000. Gonzalez et al. (2001) identified United States AP Physics Students as a separate group in the list of countries. Therefore, AP Physics students were compared to both United States' and all other participating countries' students who met the criteria for that categorization, having taken at least one year of general or advanced physics. Gonzalez et al. (2001) found that AP Physics students ranked 4th behind Norway, Sweden, and Russia, while the United States as a whole ranked 15th. The authors also note that US AP Physics students receiving a 3 or higher on the AP Physics exam (a passing grade on this exam), actually scored just over Norway's first place average score. Essentially, our AP physics program was effective for our highest achievers but remained ineffective for all other students relative to international achievement. Therefore, one reason behind the change from AP Physics B to AP Physics 1 and 2 was to include more students in the field of advanced high school physics.

In addition to mounting research similar to Stemler et al.'s (2009), College Board, the private company behind the AP exams, also considered data from this series of TIMSS international exams and subsequent research. Finally, the National Research Council's report on College Board's AP Physics B curriculum firmly established the need for a change. "AP Physics B is a gigantic course that is nearly impossible to cover properly in a single year. It encourages cursory treatment of very important topics in physics in a way this panel believes is inappropriate for an advanced high school course" (Gollub, Berthenthal, Labov, & Curtis, 2001, p. 420). The report strongly encouraged the development of a new course which focused more on conceptual understanding rather than mathematical manipulation. "It is much more important that students understand intuitively the consequences of shorting out a circuit element than that they able to solve numerous simultaneous linear equations obtained from Kirchhoff's Laws" (Gollub, Berthenthal, Labov, & Curtis, 2001, p. 420). The report's main conclusion is that colleges, physics professionals, and the physics field in general feel that the main objectives in advanced high school physics classes should not concern particular content topics, but rather should be focused on promoting physics dispositions and habits of mind.

"The AP Physics 1 course focuses on the big ideas typically included in the first semester of an algebra-based introductory college-level physics sequence and provide[s] students with enduring understandings and critical thinking and reasoning skills to support future advanced coursework in the sciences" (College Board, 2014, p. 5). For an Advanced Placement course, a comprehensive assessment measures these elements at the end of a calendar school year. The AP Physics 1 Exam presents students with physics problems from a wide range of physics domain subsets, also known as models. These models include kinematics, dynamics, work-energy, and impulse-momentum. One of the primary goals, then, of an AP Physics course is to promote student content knowledge and understanding and to develop student aptitude in solving problems in these models. Nonetheless, as has been shown, the primary focus of the AP Physics 1 course has become more than simply teaching these models and associated content. The primary objective for AP Physics teachers now is to promote understanding of how the models fit together under the big picture of the field of physics and to help students to develop problem-solving techniques and methods non-specific to model types, but generalized and conceptually based.

Consider the two example problems in **Appendix A**. The first is a free-response question from the old AP Physics B exam and was released in 2010. The second example comes from the 2017 AP Physics 1 Exam free-response section. Both questions generally assess similar ideas: energy conservation and/or two dimensional motion associated with a projectile. While the AP Physics B question tasks students with calculations and requires a numerical response, the AP Physics 1 question requires students to defend their response using argumentation supported by conservation of energy laws or two-dimensional motion principles. In essence, the students must be able to explain their ideas and justify predicted motion based on physics understanding. No longer can students just "be good at math" and score well. Students must be able to access and defend their entire understanding of the way motion occurs in our universe. It is important to note that students taking the AP Physics Exam are provided with an equation and constants sheet. Most of the equations in the field of basic mechanics which students might need are provided. Students are also allowed to use graphing calculators.

College Board published the objectives and standards that will be assessed on the AP Physics exams in 2014. While this document can be very helpful in terms of knowing what content and skills a teacher must teach in a single school year teach, “The AP Program unequivocally supports the principle that each school develops and implements its own curriculum that will enable students to develop the content knowledge and skills described” in that document (College Board, 2014, p. 5). While teachers may find the autonomy allowed by College Board a worthy privilege, it does mean that the teachers themselves, in individual departments, or in cross-district collaborations must figure out how to teach students physics in a big idea and conceptual way.

A student’s ability to employ a general method or approach to each physics model (kinematics, dynamics, work-energy, or impulse-momentum) on comprehensive exams questions largely determines his or her success on each question. Because the AP Physics exam is now a much more conceptually based exam, it tasks students with questions that permeate multiple models and arch over the entire field. If a student struggles to select a specific model pertinent to a certain problem, he or she also struggles to select the appropriate strategy and, therefore, struggles to successfully solve the problem. This paper aims to design and test a tool which measures and emboldens students’ abilities in model identification for purposes of successful achievement on the AP Physics 1 exam. The premise of this tool lies heavily in getting students to recognize and understand the relationships among physics models and to appreciate the purpose for each model. The tool provides students with the practice necessary to develop a physics intuition and learn a generalized strategy for approaching complex physics problems, both of which parallel the skills experts more readily employ.

Theoretical Framework

The aim of this study is to assess and facilitate students' developing conceptual understanding of the collection of topics in AP Physics 1 as a whole, rather than as discrete units. The implemented program will follow the pedagogical, curriculum, and assessment guidelines set out by the National Research Council in Gollub et al.'s (2001) report. The report cites that the analysis and critique of College Board's previous exams were based upon an earlier educational research and theory paper, *How People Learn: Brain, Mind, Experience, and School*, which was published in 2000. The main premise of the report focused on matching learning to how experts think and solve problems. The authors strongly emphasize the importance of teaching not a list of disconnected facts, but of teaching "useable knowledge which is connected and organized around important concepts and which is conditionalized to specify the contexts in which it is applicable" (Bransford, Brown, Cocking, Donovan, & Pellegrino, 2000, p. 9). The theory Bransford et al. (2000) presents is constructivist in nature, but heavily relies on two main components: prior knowledge (including social and cultural contexts of learning) and conditionalized knowledge. This paper will utilize the same theoretical framework.

Prior Knowledge. First, the human mind is goal directed and will actively seek information and understanding; it will try to make connections without much facilitation. Because students do not come into the physics classroom *tabula rasa* (they come with preexisting knowledge), their prior experiences and skills significantly influence their ability to organize and interpret their environment (Bransford et al., 2000). Learning is enriched when teachers can incorporate prior knowledge into their pedagogy and curriculum. Rather than denying the even partial accuracy or applicability of prior beliefs, teachers do better by helping students to unwind those beliefs and distinguish the accurate from the non-accurate. Students come to the classroom with ideas about how the world works. If these ideas are not engaged, students may learn new concepts and information for the purposes of an upcoming test, but revert to their preconceptions in other contexts (Bransford et al., 2000).

Next, the teacher needs to actually introduce some new information or facts that will serve as building blocks for deeper understanding. It remains the case that any analogies students will draw, explanations students can form, or connections students can make must be closely intertwined with factual knowledge (Bransford et al., 2000).

The main premise of Bransford et al. (2000) learning theory relies on students' ability to organize knowledge. "To develop competence in an area of inquiry, students must have a deep foundation or factual base, understand facts and ideas in the context of a conceptual framework, and organize knowledge in ways that facilitate retrieval and application" (p. 16). Experts are not just "smart people." Rather, they can plan a task, notice patterns, and draw analogies to other circumstances and problems. Experts have an ability to take in new information and transfer that new information to their existing organization.

Teachers also must teach students to become more sensitive to patterns so that they can better make those connections and linkages among facts, as well as recognize patterns quickly. While students will want to make their own "chunks," as it seems intuitive to do so (linking all the inclined plane problems together), part of the teacher's role must include facilitation of the development of the more effective and expert-like chunks. By teaching the correct chunks, students will in a better position to recognize the patterns of nature.

Conditionalized Knowledge. Experts seemingly recognize patterns easily and quickly because experts have organized their knowledge around core concepts such as conservation laws. When asked how to solve a certain problem, even competent beginners routinely described which equations they would like to use and then proceed to show how to manipulate those equations. Conversely, experts typically start by "mentioning a major principle(s) or law(s) that were applicable to the problem and how one could apply them" (Bransford et al., 2000, p. 37). Experts' knowledge is organized around big ideas and principles, while novices' knowledge is organized around memorized facts and equations and algebraic manipulation procedures. The fact that experts' knowledge is organized around big ideas and overarching concepts, so too must our physics curriculum be organized in a similar way. Students can begin to make those expert-like connections if they learn in this way.

Experts' knowledge is not only vast, but these individuals are also effective at relevant knowledge retrieval because the knowledge is "conditionalized, or it includes a specification of the contexts in which it is useful. Knowledge that is not conditionalized is often 'inert' because it is not activated, even though it is relevant" (Bransford et al., 2000, p. 43). Often, typical physics course assignments do not help students to "conditionalize" their knowledge. Bransford et al. (2000) showed that textbook or worksheet practice problems do not usually help students form conditionalized knowledge, because these sorts of problems are usually organized into very structured forms. A worksheet will probably only contain problems from one unit on it. Similarly, a textbook problem set only covers the chapter before, and "students who do well on such assignments believe that they are learning" (Bransford et al., 2000, p. 43). Those students find difficulty on comprehensive exams or when problems are presented randomly from somewhere in the entire course because the problems lack the structure or organization the students are used to with their assigned practice problems. Students never develop the skills to look for clues about the context of the problem.

Student difficulty on comprehensive exams comes from students' failure to conditionalize knowledge. They just always know which equations will apply to a given set of problems on worksheets or unit exams because that was the unit the course just covered; they know what concepts and formulas are going to be relevant. However, if teachers can design problem sets and assessments such that students can learn "when, where, and why to use the knowledge, they will learn to conditionalize that knowledge" (Bransford et al., 2000, p. 43). Nobel Laureate Herbert Simon stated that the definition of "knowing" has changed from remembering and repeating information to being able to retrieve and use information (Bransford et al., 2000).

The new AP Physics 1 Exam requires students be able to explain their decisions in problem solving; see the examples in **Appendix A.** Students need to be able to describe how they know what they know and support why their solution method makes sense. Therefore, understanding physics as a whole, as a big picture, encourages students to develop the skills necessary to evaluate their solutions and their problem solving course. Being able to answer questions such as "Why are you doing that?" and "How does it help you?" gives students mastery of their physics chunks and of their ability to dissect and solve a problem. Because students more readily recognize a problem under the umbrella of a chunk rather than simply as another problem to solve, they are prepared with a more effective solution method – they know how to start solving the problem. A more effective metacognitive structure gives students more control of the solution method and, therefore, a higher probability of correctly solving the problem (Malone, 2008). Furthermore, it gives students the wherewithal to analyze their solution method on the fly and, thus, to catch and correct more physics and mathematical errors. If a student can successfully predict how a solution should turn out, they are more readily able to notice when something isn't going according to plan, or according to the chunk.

Chapter 2: Literature Review

Background

Models. The task of teaching science concepts over the course of a school year necessitates a certain calendar or schedule of unit topics. Teachers rarely teach a scientific field, such as physics, all at once without any break-up of content into smaller components. These components of the physics field at large are known as *models*.

According to Etkina, Warren, & Gentile (2006), Rene Descartes was the first one to propose the idea of common or collaborative mental constructions which do not represent a single person's beliefs, but instead that from which one could deduce conclusions for comparisons to observations. However, the idea of using models or modeling in the classroom first really began with the work of David Hestenes and his colleagues. Hestenes defined a model as a "surrogate object, a conceptual representation of a real thing. The models in physics are mathematical models, which is to say that physical properties are represented by quantitative variables in the models" (Etkina et al., 2006, p. 15).

Hestenes and his colleagues called their curriculum Modeling Instruction, and they and their surrogates lead workshops and trainings around the globe introducing teachers to their methods. In Modeling Instruction, students are taught to organize the concepts in physics and their understanding around basic conceptual structures which they called models.

Hestenes further elaborated that a good model should be a simplified version of some system, one in which the scientist may decide what properties he or she can neglect. These models may be descriptive or explanatory and should function by analogy, or by connecting the system to more familiar systems or to prior experiences. Finally, a good model needs to have some predictive power about the evolution of and change in systems. However, the model always constrains the predictive power through some sort of limitations (Etkina et al., 2006).

In Modeling Instruction, the models are not simply taught to students. Instead, students develop them through constructivist-style learning opportunities. For example, students work on some lab and take data on the motion of the object in question. By plotting the data on a graph and analyzing the graph's properties (slope, y-intercept, and area under the curve), students literally derive the equations of motion themselves. For exmaple, a plot of velocity vs. time for a car rolling down a ramp is a diagonal line with a relatively constant slope. The slope turns out to be the acceleration, which students discover because the units of the slope of this graph have the same units as acceleration. Because the line has the form $y = mx + b$, the y variable is the velocity, the x variable is the time, and the slope is the acceleration. Thus, $v = a*t$.

After a few different similar experiments, the "acceleration" model is built up. Students begin to understand the different components and representations of accelerated motion, and they can also see how accelerated motion fits into the larger picture of physics – since all of the models are developed in similar ways. Then, the students practice using the model on worksheets and associated classwork. Finally, the students test the model in some sort of prediction lab. For example, students predict and test where a ball will land on the ground after it has rolled off of the table. This shows students that the models are not simply textbook equations which come out of nowhere. Instead, the models and associated equations actually represent their world and can be used to valid and accurate predictions of motion.

In doing physics like this, the different representations of motion (descriptive, algebraic, diagrammatic, and graphical) are developed by the students. In addition, students are taught how to solve problems in each model using the representations they developed. By developing the "physics knowledge in this way, "students are taught to appropriate solutions procedures to each model. This organization should allow students to easily identify classes of physics problems and to apply the associated solution procedures" (Malone, 2008, p. 1).

Modeling instruction serves to provide students with the conceptual knowledge and epistemological resources needed to develop a scientific understanding of nature. "Models are created with representational and mathematical tools, and their ranges of applicability and validity are established empiracally" (Brewe, 2002, p. 27). The models not only act as mental structures for physics knowledge, but the classroom development of the models help students to recognize and appreicate their relevance and utility.

To test the effectiveness of their curriculum, Hestenes and other science education researchers have utilized the Force Concept Inventory (FCI) as one measurement device. This short multiple choice physics assessment tests students' understanding of basic physics concepts in motion and forces. Hestenes explained that the FCI gives insight into "common sense theories," or physics conceptual understandings which people with no training in physics tend to hold. The FCI contains questions which concern commonly misunderstood systems and include possible multilpe choice answers that would be "correct" if a popular misconception were actually true. In essence, by giving a pre-test and post-test FCI in an physics course, teachers and researchers can measure the level of accurate physics knowledge and understanding gained by the student population. Students enrolled in Modeling Instruction physics courses routinely far outperform students not enrolled in such courses on the FCI. In other words, non-modeling students, even though they may learn how to solve physics problems and manipulate the algebraic formulas, tend to retain their incorrect assumptions and conceptions of the natural world (Brewe, 2002).

Education and physics experts like Hestenes have taken the recognized declarative and procedural understandings of physics (the content of physics) and organized it into helpful categories. These categories make the models which Hestenes and his colleagues conceived. Although different groups form these categories differently, this paper will follow the categories set out by the Massachusetts Institute of Technology Physics Department report on *Modeling Applied to Physics Solving*. This report breaks the field of Newtonian Mechanics up into skills and content hierarchies under five main categories, or models – kinematics and two-dimensional motion, dynamics, energy, momentum, and rotational motion (Pawl, Barrantes, & Pritchard, 2009). The MIT researchers included centripetal motion under the dynamics model, but this research will consider centripetal motion to be a separate model because students will need to identify centripetal motion as a separate model from rotational motion.

Each of these models serves to relate seemingly disparate facts and formulas into cognitive chunks for easier understanding and cognitive construction. Pawl et al. (2009) split Newtonian Mechanics into these models based on their relationship to the following hierarchal template.

Compatible Systems: Similar systems can be explained in similar ways. Therefore, systems can be grouped together. For example, some descriptions treat an object under consideration as a point particle, while other descriptions require a portrayal of a collection of rigid bodies.

Relevant Information: Because physical systems are usually described by interactions among objects and changes among objects' properties, compatible systems can be further classified by the types of interactions which serve as the agent of change. For example, some systems only require conservative interactions while others must include non-conservative interactions. Another example could be whether or not internal interactions such as atomic interactions will significantly affect the analysis of the system.

Law of Change: Each model comes with a set of laws or equations which demonstrate relationships among the models' primary variables (assuming the model holds). These laws can also be used to make predictions about the evolution of systems based on initial states.

In choosing a model to employ while solving a physics problem, students shall use the first two classifications of the template to identify and characterize the problem. Choosing the appropriate equation should remain the very last thing the student does. Pawl et al. (2009) recommend that students should use the type of interaction as their guide, as "only certain types of interactions function as agents of change for a given model. This associated a class of relevant interactions with each physics principle is the most important vehicle for the recognition and application of the principles with solving problems" (Pawl et al., 2009, p. 52). In this way, students learn to choose and employ specific equations and solution-methods by first learning to recognize patterns of nature. If students can start to see where one model might be successful where another might not, students may be able to perform more accurately and effectively on comprehensive exams like the AP Physics exam.

Problem Solving. This paper focuses primarily on the problem-solving aspect of the AP Physics 1 curriculum. Because the AP Physics 1 exam tasks students with problems from every unit of the AP Physics 1 curriculum, students need to be able to recognize and employ the appropriate model. Therefore, solving physics problems on comprehensive exams such as the AP exam requires a generalized approach to model identification. Thus, the definition of "problem solving" which this paper utilizes comes from Mayer & Wittrock (2006, p. 287): "Problem solving is cognitive processing directed at achieving a goal when no solution method is obvious to the problem solver." Problem solving, in the context of demonstrating understanding on the AP Physics 1 exam, rests first with the ability to employ a generalized model of approach. Students must be able to first see how a specific problem fits into the big picture of physics. They need to be able to first identify which model to employ before solving the problem.

When students took the energy unit exam during the academic year, they rightly assumed most of the problems on that exam would utilize the energy model. The same goes for the momentum unit exam, and the simple harmonic motion unit exam, etc. However, the comprehensive nature of the AP Physics 1 Exam makes no such demarcations. Problem 7 does not begin with a heading that says, "Use energy to solve this problem." Students need to be able to identify energy as the appropriate model before beginning to solve the problem.

Many research projects have implemented various techniques toward the aim of helping students to learn to solve problems. Historically, AP Physics B teachers and classical teaching physics pedagogy simply wanted students to find an answer to a problem, which is both "superficially and conceptually isomorphic to problems they have seen beforehand" (Marx & Cummings, 2010, p. 221). The student has seen this exact type of problem before, they recognize it, and then recall the solution method. However, this approach will no longer work in the new AP Physics 1. Furthermore, this method of learning physics does a disservice to learner, only providing a superfluous covering of the ideas as indicated by the research above. Instead, teachers must help students to develop their "capacity to fluidly and creatively tackle challenging and novel (to the students) problems" (Marx & Cummings, 2010, p. 221).

Past research attempting to improve student problem solving skills in terms of model-specific strategies has shown marginal improvements. Heller, Keith, & Anderson (1992) showed that better and more effective solution methods develop out of small cooperative group work when compared to the achievement of individuals working alone, especially in the context of qualitative analysis style problems. In effective groups, students share conceptual frames and promote each other's procedural knowledge. These groups also allow students to request clarification, justification, and elaboration from one another. Adams & Wieman (2015) demonstrated that students also produce better physics solutions when worked examples from an expert are available as reference. These references can be solutions prepared by the teacher or copied out of the textbook solutions manual. Students seem to do better when they can follow a guided strategy.

Nonetheless, these effects do not carry over to individual achievement. Students lose what gains they achieve from these resources when it comes time to work problems on semester or other comprehensive exams. Adams & Wieman (2015) indicate that these methods never actually help students to learn to solve problems on their own because they never learn to identify and employ the model structure of physics. The students develop strategies that rely on these resources and cannot transfer those strategies to new situations. The reason for this rests primarily upon students' novice abilities to see the big picture, to see how and why it all fits together, in line with the National Research Council's report recommendation to College Board. Because the students rely on these resources, they are never given the time nor shown how to begin to combine models into a single coherent concept. They still see each "new" strategy as separate and disparate. Solution methods are kept unconnected from one another.

According to Hammer (1989), much of students' difficulties comes out of their conception of physics as a collection of disconnected facts and formulas. They do not see the big picture or underlying reasoning behind a certain strategy not because they are unable to, but because they actually have a misconception about the purpose of physics in the first place.

> Many students are satisfied with learning physics as a set of relatively unrelated pieces, isolated from each other and from [their] everyday experience. Understanding remains incoherent and fragmented because it serves [students] comparatively well on problem sets and [unit] examinations. The disadvantage to this approach was that, although the techniques derive from a coherent theory, for [students, the techniques] were a collection of isolated formulas essentially divorced from physical meaning. [Students] cannot apply knowledge flexibly, because it is not well organized or integrated with intuition (Hammer, 1989, p. 664 and 669).

Singh (2002) describes the phenomenon by comparing the physics problem solving methods of experts to that of novices. Professional and experienced physics problem solvers such as physics professors see physical situations at a much more abstract level than do inexperienced problem solvers. The latter often concentrate on the superfluous items and get distracted by irrelevant details. For example, "students tend to group together all mechanics problems involving inclined planes, regardless of what type of physical principles are required for solving them" (Singh, 2002, p. 1103). In actuality, the fact that the object is on an inclined plane tells you basically nothing other than that the object will be moving in both the horizontal and vertical directions. By focusing on the fact that it is an "inclined plane" problem, students often lock themselves into certain memorized solution methods, which may not be the best approach for that particular problem.

It becomes clear why gains achieved by the resources mentioned above never stick and remain superficial. In the example of using teacher solutions as a guide, the teacher has already made the big picture connections among models. Therefore, this expert can identify and provide an effective strategy which the student can follow. However, the student might not necessarily understand why that strategy is ideal or useful. Adams & Wieman (2015) point out that small groups only seem effective because, usually, each group has at least one student who has made individual strides in understanding that other students have not. The latter students simply latch on to the strategies suggested by the more expert-like classmate and never actually make the connections themselves.

Ultimately, AP-level students may be able to perform well on any one unit exam throughout the course of the year, because they can follow the specific strategies to solve problems in individual models. They basically memorize a few of the common types of problems in a certain unit, know how to solve those precise problem types, and show proficiency on an individual unit. However, the primary difficulty resuscitates when it comes time for the semester exam or AP comprehensive exam. Many do not know how to select a strategy among many, because they do not see or understand the big picture of physics. They do not see how it all fits together. Difficulties “may be a result of misconceptions, not only of specific elements of physics knowledge, but of the general nature of what physics knowledge is, and of what reasoning and learning in physics involves” (Hammer, 1989, p. 668).

Therefore, students need to learn a strategy which can be employed on comprehensive exams, one in which physics principle or law selection directly follows a stepwise method. Students cannot rely on memorization of strategies specific to individual units or models, because selecting these strategies among many in the comprehensive exam setting has shown to be difficult. In addition to their regular content and skill studies in physics, students need to be taught and practiced in a model identification process.

Chunking and Model-Building. To teach students to identify and select appropriate models on comprehensive exams, students must first learn to recognize indicator clues and other pointers. These types of clues guide test takers to make an appropriate model selection. Once the correct model is selected, students can then go about solving the problem in their normal method: choosing an equation or multiple equations, rearranging some variables, and computing or solving for an answer. One of the difficulties in looking for the indicator clues associated with each model is that there are often multiple indicator clues. Larkin, Mcdermott, Simon, & Simon (1980a) proposed that each unit in a year-long physics course might contain 10 – 20 “things” which a student must learn. This would mean that, over the course of the year, physics students must learn and retain around 150 items and concepts. Students essentially have to know the entire AP Physics 1 curriculum to know each and every one of the clues. That would not be useful, because it defeats the purpose of a generalized strategy in the first place. Instead, the strategy should be aimed at getting students to begin to recognize models and model archetypes intuitively, not through memorization. The students should be able to recognize why the models are important and why/when to utilize the valuable properties of each model.

Singh (2009b) showed that many novice physics students attempt to solve problems using trivial clues and cues. Primarily, the problem lies with the physics teachers and traditional physics courses, as most physics courses rarely *explicitly* teach effective problem-solving strategies. Instructors often assume a certain prerequisite of problem solving abilities and presume students come into physics class with operational strategies of problem task analysis, planning, evaluation, and reflection. For example, any physics teacher can relay hundreds of stories about unrealistic student answers and ineffective student reflection. Common answers such as a car's velocity equaling 2000 m/s or the mass of a box equaling 10,000 kg support Singh's position. As outrageous as these reflection skills might be, many students lack the planning and analysis skills that high school and college physics requires. In addition to the content, teachers also need to make conscious efforts to teach metacognitive skills such as reflection, interpretation, mental organization and categorization, and relating new concepts to prior knowledge.

Singh (2009b) describes three important components of how people learn and solve problems: how the knowledge is acquired, how the knowledge is organized and saved, and how the knowledge is retrieved. Students are expected to retain a whole college semester's worth of physics content for the AP Physics 1 exam. How those items are encoded largely determine students' possible success. Singh (2009b) suggests teaching physics in the form of a hierarchical organization where the more fundamental concepts sit at the top of the hierarchy and the ancillary concepts sit below them. "Such indexing of knowledge in memory can be useful for accessing relevant knowledge while solving problems in diverse situations. It can also be useful for inferential recall when specific details may not be remembered" (Singh, 2009b, p. 183).

A narrower focus for indicator clues reduces the set of new concepts and terminology an individual student must know, allowing the content to be more easily learned, organized, and managed. Only a small set of indicators can guide students to pick the appropriate model. Thus, students can choose an equation out of the model, instead of out of the entire equation sheet. Much research has gone into a similar strategy useful in many domains, a strategy named "chunking."

According to Singh (2009b), people can generally hold only five to nine pieces of information in their working memory at any one time. If that is the case, then students cannot hope to "memorize" all of the equations, concepts, and strategies required for performing at the top level on the AP Physics exam. Singh (2009b) goes on to describe the process of "chunking," where expert physics problem solvers organize disparate bits into well-organized patterns. Thus, several pieces of knowledge can be accessed together as a chunk rather than as separate items.

This seems very intuitive, and students tend to do this automatically without much training. However, physics is a tricky subject where many of the ideas and concepts that may seem linked or connected to a layperson do not actually relate to one another. "The kind of physical reasoning and chunking that is usually learned and employed in everyday life is not systematic or rigorous. Although such hap-hazardous reasoning may have little measurable negative consequences in an individual's life, it is insufficient to deal with the complex chain of reasoning that is required for a rigorous scientific field" (Singh, 2009b, p. 187). The autonomous chunking people do in regular life does not reflect the type of chunking students need for performance on the AP exam. For example, an untrained physics student may try to chunk all the spring problems together or all of the ramp problems together, when physics contains many radically different types of spring and ramp problems.

Therefore, students need lessons in proper physics chunking. Furthermore, teachers need to teach students clues and cues associated with more expert-like problem-solving, rather than relying on the students themselves to construct the chunks. Research-based and professionally useful chunks may be more recognizable, and students may employ them more accurately and rapidly (Etkina et al., 2006).

"The perceived complexity of a problem not only depends on its inherent complexity but also on the experience, familiarity, and intuition we have built about a certain class of problems" (Singh, 2002, p. 1106). Singh (2002) asks us to consider the ballistic pendulum as an example problem. This problem requires the usage of both conservation of energy and conservation of momentum simultaneously. Because experienced physics problem solvers have built an intuition about when certain conservation laws might be useful, solving the problem appears "easy" when those solvers do it. However, students, who are much less experienced in physics, lack that intuition and find it difficult to even determine the appropriate model to employ and set-up a possible solution method.

Consider a person building a dog house. When the person came to the point in building the structure where he or she needed to nail two boards together, there is no question which tool to use. That person never had to "memorize" that a hammer goes with the task. The hammer is just the "right tool for the job," and it seems obvious to the person that the hammer applies to this task. Sure, at some point the person had to learn *how* to use the hammer effectively, and practice is required before the person becomes a proficient hammerer. Nonetheless, the familiarity of the task and the available tools leads the person, inevitably, to choosing the correct tool and applying the tool in a valid way.

Jackson, Dukerich, & Hestenes (2008) describe the model-building strategy akin to building a tool chest. Historically, physics teachers teach fragmented physics knowledge: each new unit is different and separate from the ones that came before and that will come after. Hestenes' and others' modeling theory proposes instead to organize physics content around scientific models, or coherent units of structured knowledge. Modeling requires a purposeful transfer away from the teacher playing the pivotal role as authority figure and towards the coach who facilitates the organization of knowledge and helps students to construct appropriate chunks. The students should be able to see a problem and, using their own structured knowledge, identify the appropriate tool to employ. The momentum model is the same thing as the hammer; they are both tools to solve a task.

Malone's (2008) study compared knowledge organization, the type and use of problem-solving and metacognitive skills, and the types of errors produced on exams between students enrolled in a Modeling Instruction-style course and students enrolled in a traditional course. She found that the modeling students outperformed the non-modeling students in that they utilized more expert-like knowledge structures, employed more effective metacognitive skills, and had fewer errors on assessment tasks. The non-modelers' knowledge tended to be framed around system surface features (such as an "inclined plane problem" as explained previously) while modelers' knowledge tended to be framed around scientific principles and laws. Malone (2008, pg. 1) also found that the modelers' structures and mental categories included "information about useful equations and diagrams and appropriate procedures for making relevant judgments." In essence, students were better at describing their solution methods and explaining the purpose behind steps taken (metacognition). Ultimately, her study demonstrated that students taught in a modeling-style classroom showed a 15% increase in problem-solving ability over non-modeling students.

Non-modeling students in Malone's (2008) study were still taught physics; they still learned energy and momentum content. However, students who were taught those topics as models and who were given the opportunity and capability necessary to cognitively organize those models performed overall 15% better on physics problem tasks like exams. By helping students to connect physics content, to develop a big picture, those students can improve their performance by significant amounts.

Proposed Physics Problem Solving Strategy

Ultimately, the idea behind teaching students to solve physics problems rests not with giving them loads of practice problems. As Byun & Lee (2014) discovered, there is no correlation between the number of physics problems solved in one's lifetime to physics academic achievement or understanding in physics. Instead, these researchers found that students who actually had a problem solving strategy and could effectively explain their strategy performed best on comprehensive physics exams.

Furthermore, Byun & Lee (2014) found that students who used a Knowledge-Development strategy performed better than those who employed a Means-End strategy. A Knowledge-Development strategy to solve physics problems first relies on utilizing equations and concepts related to the given physics variable in the problem. The problem solver writes down or considers some equations or concepts associated with the ***given*** variable, and continually "discovers" other relationships to the ***given*** variable and the equation until the problem is solved. Means-End strategies, also known as backwards strategies, seek first the physics equations associated with the ***objective*** or question variable. By first identifying the variable the solver seeks, he or she then works backward to find an equation which can get him/her there. Usually, Knowledge-Development strategies are used by expert-like problem solvers, while Means-End strategies are used by novices.

Malone (2008, pg. 2) states, "No studies have attempted to specifically analyze the cognitive structures developed by modeling students and how those structures might help during problem solving." While much research concerning the benefits of modeling on assessments exists, no studies have directly shown what those individual student cognitive structures look like, especially in an advanced physics setting. This research attempts to define archetypal model structures, facilitate the development of similar structures in individual students' conceptual understanding (teach students the models and how to use them), give those students practice using their structures in context, and examine possible correlations between the introduction of these structures and AP Physics 1 Exam performance.

The strategy this paper posits thus relies on, first, identifying the given variable, or **model**, as Byun & Lee (2014) recommend. Second, the problem-solver shall follow the set of steps and clues proposed by Pawl et al. (2009)'s models, Etkina et al. (2006)'s *Classifying Models* method, and Larkin, McDermott, Simon & Simon (1980b)'s *Knowledge of Physics and Algebra Strategy.* An outline of the strategy can be found in **Appendix B.** Students will learn physics content as a "story," a series of models, or chunks, such that they will use to identify a problem task's appropriate **model** using clue words and model properties. Students only have to know the seven models, seven "things," for the AP Physics 1 Exam, rather than the entirety of physics all at once. All physics content and solution-methods can thus be chunked and consequently identified by one familiar strategy: model identification. The strategy for implementing this program will be described in further detail in **Chapter 3: Methods** and in **Appendix B**.

Chapter 3: Methods

Formative Assessment Tool and Curriculum Changes

Introduction to Research. This paper aimed to design and test a tool which measured and emboldened students' abilities in model identification for purposes of successful achievement on the AP Physics 1 exam. The premise of this tool lay heavily in getting students to recognize and understand the relationships among physics models and to appreciate the purpose for each model. The tool provided students with the practice necessary to utilize the strategy presented by the teacher, employ the expert-like chunks introduced by the teacher, and develop a physics intuition when it comes to solving problems. The goal here was to help students to learn a generalized strategy for approaching complex physics problems, both of which parallel the skills experts more readily employ. Furthermore, the skill of model identification will help students to correctly recognize and classify system types on the AP Physics Exam. By developing this skill, students will be better suited to employ the correct problem-solving method, effectively set-up a system of equations and reference points, and, ultimately, successfully solve individual problems.

The formative assessment tool consisted of two parts: an innovative teaching practice and a series of quiz-like formative assessments. The innovative teaching practice is described briefly later in this chapter and in detail in **Appendix B.** The formative assessments are also described briefly in later in this chapter, and the formative assessments themselves can be found in **Appendix C.**

Pedagogical Model. As part of the experimental academic year, the instructor implemented an innovative teaching practice or pedagogical model. Throughout the academic year, the instructor continually referred to the "story of physics," graphical and unit analysis techniques, and implemented a model identification strategy which can all be viewed in detail in **Appendix B.** At the most basic level of the pedagogical method, the instructor was teaching students the "clue words" and other indicators helpful in recognizing model types on unfamiliar problems. For example, seeing the word "collision" meant students should be using the momentum model. Seeing a force vs. displacement graph meant students should be using the energy model. At first glance, one might assume the pedagogical method was simply designed around memorization of indicators.

However, the pedagogical model was actually designed to facilitate big picture learning rather than simply memorizing clue words and indicators. The instructor emphasized the necessity of each new model by incorporating "story of physics" lessons into the curriculum. For example (See **Appendix B** for a more involved discussion of this lesson), the instructor showed *why* we need to develop the new model of energy after completing the dynamics and centripetal motion units. The instructor presented a simple problem, which dynamics and centripetal motion can't solve. Thus, we decided as a large group that a new model was needed to solve problems where our previous models broke down.

The instructor facilitated routine large group discussions concerning questions on when the different models applied and *why* the different models are necessary. For example, "Why must we learn about energy <u>*and*</u> momentum? Why can't we just use energy to solve all of our problems?" Energy is a fantastic model, and it can solve a lot of problems. However, it isn't too great at solving collision problems because, although energy is conserved, much of it goes to non-usable containers like sound and thermal. Energy is hard to track during collisions. Therefore, we need a *new* model which we can track through collisions: momentum.

The instructor underscored the reasoning and usefulness behind each new model. In a sense, the word collision doesn't go with momentum because the student memorized it that way. Instead, the word collision goes with momentum because momentum is the most effective model to describe collisions. The pedagogical model taught students how all of the physics models fit together in the "story of physics." Where are each models' advantages and disadvantages, where do models break down or fail to predict motion, why does this or that model breakdown in this situation? The instructor honed on all of these questions and made sure that the students understood the answers.

Ultimately, the pedagogical model taught students *why* we have the physics models in the first place. In doing so, the instructor taught students to see the big picture of physics and to understand *how* motion can be described by the models, rather than simply that it can be. If all of motion could be described by kinematics, then why do we even teach the other units? Using this method, students begin to metacognitively understand the field of physics and, more importantly, how to describe the world around them. They can begin to think like a physicist, like an expert.

This story of physics pedagogical model follows the recommendations from **Chapter 2: Literature Review**. First, the model teaches students a generalized approach to solving problems. It gives students an effective method to solve most physics problems, rather than an infinite number of possible solution methods. It teaches students to use "model identification" first, before proceeding to solve the problem. Second, students begin to see physics as something bigger than disparate sets of facts and figures. Students see how physics ideas fit together and that each fact and formula has a role to play. They, hopefully, focus less on superfluous items such as “inclined plane problems” or “spring problems” as described previously. Instead, the pedagogical method teaches proper and effective chunking. Since the method only uses seven models (chunks), the human brains can remember all of the *things* at once. Finally, the generalized approach students employ is more expert-like, focusing on principles and laws first before choosing equations and setting up a problem. By teaching students *when* certain laws and principles pertain to a system, those students are better able to solve those systems because they are able to identify the appropriate ideas, concepts, and solution methods to the problem.

Formative Assessments. As part of this research, students completed a series of quiz-like formative assessments. The actual formative assessments can be found in **Appendix C.** Each of the three assessments presented students with a number of AP Exam level questions of varying topics. The assessments first tasked students with the identification of the model which would be best suited to solve each individual problem. In the data presented in Chapter 4, this information is represented by the phrase, **Model Identification.**

An explanation component accompanied every question: “why did you choose that model?” Students were expected to provide evidence for choosing that model among the others.

1. Correct model identification and correct answer scores were recorded and plotted over time.
2. Model identification and explanation were graded on a Likert Scale, as graded by the experimenter, as a 0, 1, or 2.
    a. 0: No evidence was given, evidence does not match chosen model, or evidence doesn’t make sense
    b. 1: Evidence is given and is logical, but the evidence does not fully support the chosen model or is insufficient at supporting chosen model
    c. 2: Evidence is given and is logical, and the evidence fully supports chosen model

Then, students were instructed to solve the problem. Students were also graded on whether or not they correctly answered the problem task. This information is represented by the phrase **Answer Success** in the data charts in Chapter 4.

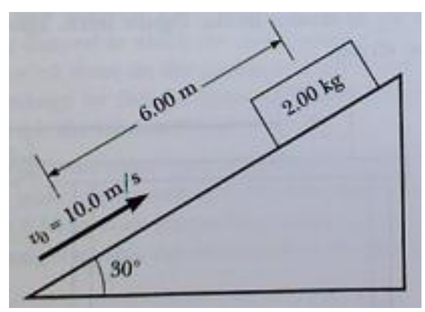
For example, a formative assessment problem could ask about two billiard balls colliding and requesting the final velocity of both billiard balls. Before actually answering the billiard ball problem, students would be asked to identify which model would be best to employ. Students must then support their response with reasoning and evidence. A successful response might look like this:

“Momentum, because there is a collision. Energy cannot deal with collisions because, although conserved, much of the energy is released in the form of heat and is difficult to track. It isn't kinematics because time is not defined or involved in the problem. It isn't centripetal or rotational motion because the system is not going in any type of circular path. I may have to use some dynamics here because forces are involved in the impulse."

Although the instructor rarely saw such detailed sentence structure, the important part was that students could defend their choice of momentum beyond simply identifying the clue word. It was also unnecessary to give explanation for each model on every problem. The instructor looked for explanations which provided at least some evidence for choosing one model over another. Many times, multiple models were required such as using both dynamics and centripetal motion. In these instances, there isn't really a "correct" answer. Instead, the instructor was looking for logical explanations which made sense in the context of the problem.

Here is an example from one of the formative assessments. This example is intended to be similar to some multiple choice problems seen on the AP Exam. It is numerical in nature and requires a numerical answer.

_______ 1. A block with an initial velocity of 10.0 m/s is projected up a rough 30.0° inclined plane. After the block has moved 6.00 m along the incline, its velocity is 5.00 m/s. What is the coefficient of friction between the block and the ramp?



Model and explanation:

A) 0.12 B) 0.16 C) 0.74

D) 0.95 E) 1.56

Students would first read the problem and consider the system in question. They were instructed to identify the model and provide an explanation before attempting to actually solve the problem. One possible student thought process can be seen below:

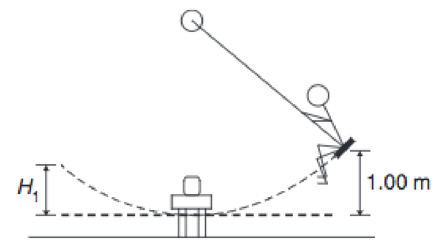
"We see an inclined ramp, but that isn't helpful. It is a block moving under constant forces, so I could use kinematics and dynamics here. However, I don't necessarily need time to solve this problem, and time isn't given in the problem prompt or the answer set. Therefore, I am going to use energy because energy describes motion using only beginning and ending states and doesn't require time. It is also, usually, more effective and easier than kinematics and dynamics."

The student would write energy in the space followed by some reasoning or supporting evidence for that choice. Finally, the student would solve the problem using the tools and methods associated with their chosen model.

Another formative assessment problem can be seen below. This problem is more aligned with one of the AP Exam's free response questions. Note the questions which require an explanation for the prediction based on physical principles and ideas. Ultimately, the innovative curriculum was designed to help students to succeed on exactly this type of problem. It isn't entirely clear, from first glance, which model will be employed on Part A. And, the student cannot simply try to manipulate some random equations and come up with an answer. Solving this problem must first begin with model identification.

"Part A might be something to do with energy, because the question is about the guy getting back up to an original height. On the other hand, we see a collision between guy and jug which would indicate momentum."

5. A student of mass 50.0 kg swings on a playground swing which is very light compared to the student. A friend releases the seat of the swing from rest at a height of 1.00 m above the lowest point in the motion. The student swings down, and at the lowest point of the motion, grabs a jug of water of mass 4.00 kg. The jug is initially at rest on a small table right next to the swing, so it does not move vertically at the student grabs it. The student keeps swinging forward while holding the jug, and the seat reaches a maximum height H_1 above the lowest point. Neglect air resistance and friction.



Note: Figure not drawn to scale.

A) Indicate whether H_1 (circle one) greater than, less than, or equal to 1.00 m. Using physics concepts, justify your answer qualitatively with NO equations or calculations. Which model(s) did you use to answer this? Why did those models apply?

B) Calculate H_1. Show as much work as possible. What model(s) will you use to solve this problem?

C) The student is now swinging back towards the starting point. At the lowest point in the motion, the student drops the water jug. Indicate whether the height the student achieves on the starting side will (circle one): be greater than, less than, or equal to H_1. Using physics concepts, justify you answer. You may use equations in your response. Which models did you use to answer this? Why did those models apply?

The collision aspect of Part A doesn't really play a role here. You could solve this using momentum. The collision aspect "slows" the guy down, but that only means he has less kinetic energy and thus cannot attain the same gravitational potential energy. Even if you used momentum, this problem still comes back to energy. So energy. Then, by identifying energy as the appropriate model, it clues the student into what laws and principles should be utilized in order to justify the response. In this case, conservation of energy states that the guy cannot make it back to 1.00 m. He picks up more mass, and that mass also needs to gain some gravitational potential energy, which means that less gravitational potential can go to the guy. In essence, the very act of identifying the appropriate model indeed shows the way to using the appropriate law, principle, theory, or idea.

The main premise was to get students to identify appropriate models to employ, not to emphasize the *one* way to do physics; there isn't one. In essence, students were tasked with placing this problem in the "story of physics." The students think about how they might describe the system first, rather than first trying to manipulate formulas. Thus, students were getting practice using the model structure taught to them and applied in class while also getting AP-level practice problems. These formative assessments were designed to get the students used to and experienced with the model identification practice, the generalized approach to solving AP physics problems like an expert.

Each formative assessment presented problems associated with the content covered previously in the course, including the unit just covered. Therefore, each formative assessment was on equal footing in terms of probability of correct solutions, and no questions were beyond students' current knowledge base. By plotting average scores as a function of time (assessment number), the experimenter can gauge the magnitude of development of student achievement in model identification and utilization and answer success.

Note that the number of possible model choices increased in each iteration of the formative assessments. For example, the only choices for Formative Assessment 1 included kinematics, dynamics, centripetal motion, and energy. The choices for Formative Assessment 3 included kinematics, dynamics, centripetal motion, energy, simple harmonic motion, momentum, and rotational motion. Therefore, a constant model identification score over the three assessments still indicates individual student growth as the probability of guessing the model correctly at random decreases.

Research Questions.

1. How does student performance on model identification formative assessments change over the course of the school year as the number of possible models increases?
2. How do the AP Physics 1 Exam scores compare between students taught using the model identification curricular structure and assessment series and students not taught using the structure?

Research Methodology. This study utilized a quantitative approach in order to fully address the research questions. The purpose of this study was to test the effectiveness of a formative assessment tool which was intended to help students to develop model identification and utilization skills. Creswell (2014) explained that an effective quantitative survey design identifies trends of a population by studying a sample of that population. The experiment determines the outcome of an intervention by taking some measurement of the population.

The sample population consisted of 69 students, sophomores through seniors, enrolled in an Advanced Placement Physics 1 course offered at a suburban high school. The students were enrolled among four high school sections of daily forty-five minute classes. A majority of the students were of middle to upper economic socioeconomic status, and most were assumed to be headed on to some form of post-secondary education. The sample was intended to be representative, but by no means exhaustive, of the entire population of students taking the AP Physics 1 exam. The experimenter was the sole instructor for this course. He had been teaching high school science for a total of four years and the experimental year was his third year teaching advanced physics. This experimenter/instructor has a rich background and experience in physics. He has a BA in Physics, a BS in Science Education with a Physics Emphasis, and is nearly complete with a Master's in Science Education with a Physics Emphasis.

The experimenter assumed full effort on the part of the population, as most of the students understand that this tool may help to improve their score on the AP exam. For those students not taking the exam, they understand that the tool may improve their achievement on other comprehensive exams such as the semester finals. Student performance on the formative assessments in no way affected their grade in the course, and there were no penalties or advantages associated with any performance. The formative assessment tool constituted part of the curriculum put forth by the AP Physics 1 teacher as described and allowed by his teaching license and his local school board. **Appendix B** includes a basic outline of topics covered in the AP Physics 1 course.

To add reliability and validity to the study, two other forms of measurements were used. First, as this tool was designed to improve achievement on the AP Physics 1 exam, average student scores from the two previous years of AP Physics 1 exams were reported in addition to student scores from the school year of the formative assessment implementation. In this way, improvements in overall physics understanding facilitated by the formative assessment tool was measured by comparing actual AP scores from years in which the tool was not used to AP scores from a year in which it was. Not only can the tool measure improvements over the course of the year in model identification, but the tool itself can also be measured for effectiveness in terms of actual AP Physics Exam scores. This comparison assumed no other changes in curriculum or pedagogy in the AP Physics 1 course. Small changes to individual activities, worksheets, and other curricular items were made, but overarching themes or instructional techniques were not changed.

The Force Concept Inventory (FCI) acted as the second measure to add reliability and validity to the formative assessment tool. The FCI was given to all AP Physics 1 students at the beginning of the year and at the end of Newtonian Mechanics instruction. The FCI can be used to identify and classify misconceptions associated with Newtonian Mechanics, and has been shown to be an accurate and reliable instrument of Newtonian Mechanics understanding (Hestenes, Wells, & Swackhamer, 1992). The FCI assessment measures student understanding of basic mechanics. Therefore, student growth on the FCI demonstrates that students indeed learned physics content, even if the formative assessment scores remain steady or even decreased over time. Comparing improvements on FCI scores to the scores on the formative assessment tool over the course of the year showcased the validity and reliability of the formative assessment tool. If the FCI scores do not directly track the formative assessment scores, the comparison allowed the experimenter to show that any student improvement on the formative assessments is not solely based on learning physics content.

The study's theoretical framework and methodology are based on Bransford et al. (2000) learning theory consisting of prior knowledge and conditionalized knowledge. Using the model outline presented in **Appendix B**, the teacher taught students the content of Newtonian Mechanics using the model structure: "the story of physics." The teacher integrated students' prior experiences, incorporated analogy, and emphasized the usability of the model structure. The formative assessments were designed to be the opportunity for the students to practice using the model structure and to develop their physics intuition.

Additionally, the assessments were designed to help students to conditionalize the models into a useful problem-solving strategy. The old way of teaching disparate facts and separated units turned into teaching patterns and the model structure. Furthermore, the students were presented with multiple opportunities to practice problem solving in similar contexts to the AP Physics 1 exam.

In the following chapters, the phrase "**innovative curriculum**" will refer to the entire implemented experimental strategy including the formative assessment series and associated lessons, the "story of physics" pedagogy, and the advanced Modeling Instruction-style curriculum

Chapter 4: Findings and Results

Formative Assessments

As part of this research, students completed a series of quiz-like formative assessments. The actual formative assessments can be found in **Appendix C.** Each of the three assessments presented students with a number of AP Exam level questions of varying topic. The assessments first tasked students with the identification of the model which would be best suited to solve each individual problem. In the data presented below, this information is represented by the phrase, **Model Identification.** An explanation component accompanied every question: "why did you choose that model?" Students were expected to provide evidence for choosing that model among the others, and the identification and supporting reasoning were scored. Then, students were instructed to solve the problem. Students were also graded on whether or not they correctly answered the problem task. This information is represented by the phrase **Answer Success** in the following data charts.

Part 1: General Averages and Slopes. After grading all three formative assessments, I computed an average score on model identification and answer success on each assessment. Figure 1 on the next page shows that the average scores exhibited a marginal increase in model identification skills and an even smaller increase in answer success over the three assessments. The data shows an average positive slope of 5.7% on model identification and an average positive slope of 2.1% on answer success. Table 1 shows the actual average scores from each formative assessment, with the total score showing the models and the answers added together.

It is important to note that as the formative assessment number increased, so did the number of possible models. On FA1, only four models were available to choose from. FA3 had seven possible models to choose from. First consider FA1. On average, students correctly identified the model 52.45% of the time with a random guessing selection probably of 25%. By FA3, students on average correctly identified models 63.85% of the time with a random guessing selection probability of 14%. Therefore, students did, on average, significantly improve their abilities to identify the appropriate model. Observing that the Answer Success slope also shows a slight increase, and considering that the formative assessment difficulty increased as the number of possible models increased (the amount of understanding needed to solve physics problems increased), students also significantly improved their ability to successfully answer physics problem tasks.

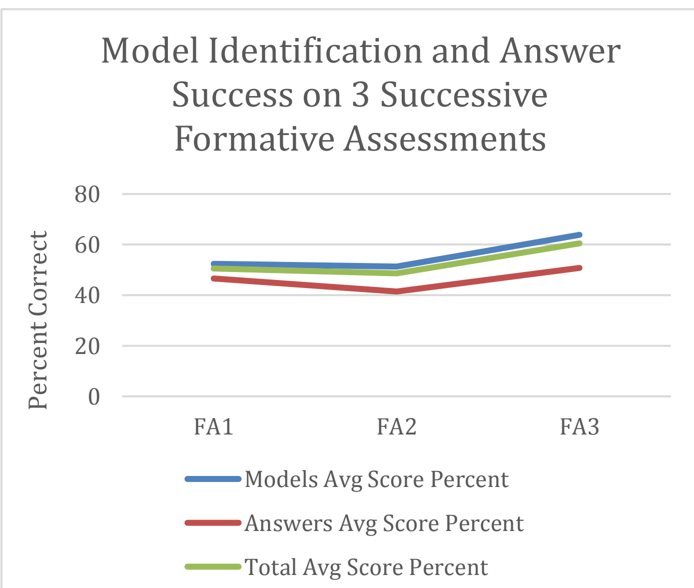


Figure 1 - Model Identification and Answer Success Over 3 FA's

Figure 1 shows average student score percentages on correctly identifying models (blue line), correctly answering the problems (red line), and total score – models and answer – (green line) on the three given formative assessments.

Table 1 presents the same data as Figure 1 in numerical form. Table 1 also presents the values of the slopes of the best fit lines of the three lines.

	Model Avg Score Percent	Answers Avg Score Percent	Total Avg Score Percent
Formative Assessment 1	52.45	46.53	50.59
Formative Assessment 2	51.32	41.45	48.63
Formative Assessment 3	63.85	50.77	60.49
Slope of Avg Scores	5.70	2.12	4.95

Table 1 - Formative Assessment Average Scores

	Minimum Score	Maximum Score	Median Score
Formative Assessment 1 Model Score	11.11	100.00	55.56
Formative Assessment 2 Model Score	3.85	96.15	53.85
Formative Assessment 3 Model Score	34.62	100.00	61.54
Formative Assessment 1 Answer Score	0.00	100.00	42.86
Formative Assessment 2 Answer Score	0.00	100.00	40.91
Formative Assessment 3 Answer Score	0.00	95.00	50.00

Table 2 - Formative Assessment Ranges and Medians

Although the average scores on model identification and answer success stayed relatively constant, some other statistics show important changes. According to the data in Table 2, the minimum model identification score increased from 11% to 35% from FA1 to FA3. This indicates significant growth in model identification skills in students *beginning* on the lower level of this range. In other words, students who began the year with poor marks in model identification showed the most improvement in this category – the bottom minimum scores dropped out.

The median scores provide further evidence of this assertion. According to Table 2, the median scores of model identification increase from 55% to 62% and of answer success from 43% to 50%. This emphasizes the information from the range increases. An increasing median score coupled with the small, yet significant, positive average slopes indicates a slight upward shift in model identification skills and in answer success. Regardless of what is happening for the highest achieving students in the group, an increasing median score indicates that more students are receiving higher scores. Student scores beginning toward the bottom and the middle in model identification and answer success showed significant improvements. The next set of data further supports this idea, because it shows a notable increase in model identification and answer success occurring for students of initial lower ability specifically.

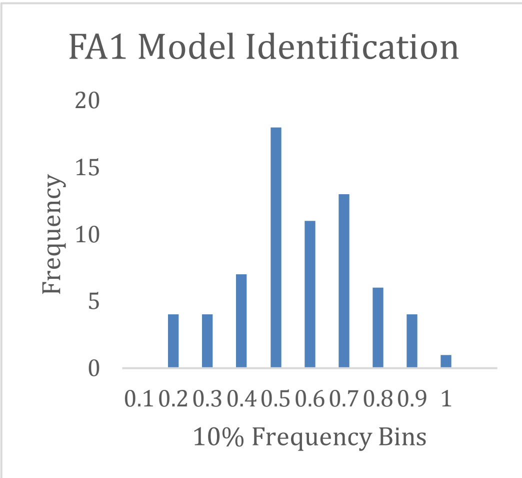


Figure 2 - FA1 Model Identification Score Frequency

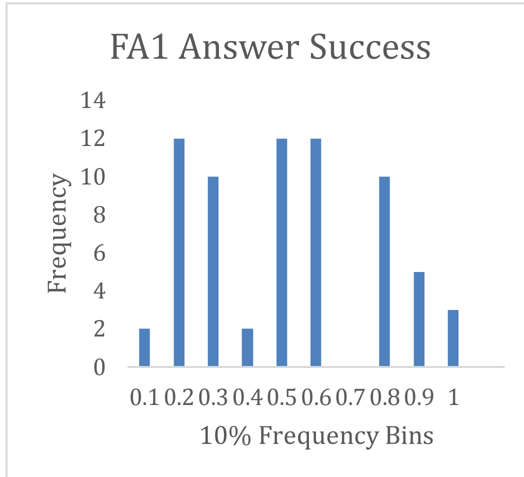


Figure 5 - FA1 Answer Success Score Frequency

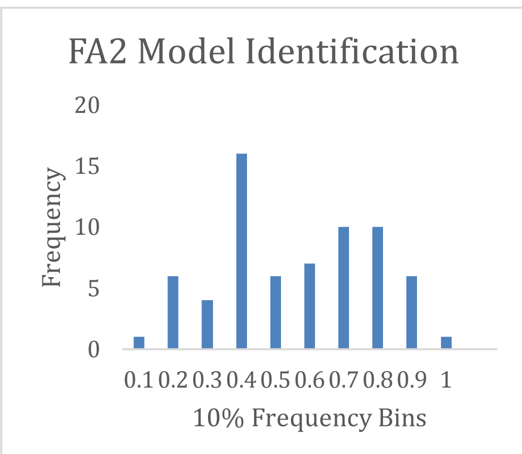


Figure 3 - FA2 Model Identification Score Frequency

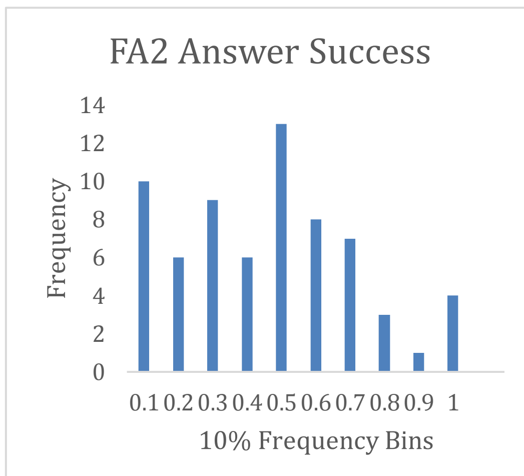


Figure 6- FA2 Answer Success Score Frequency

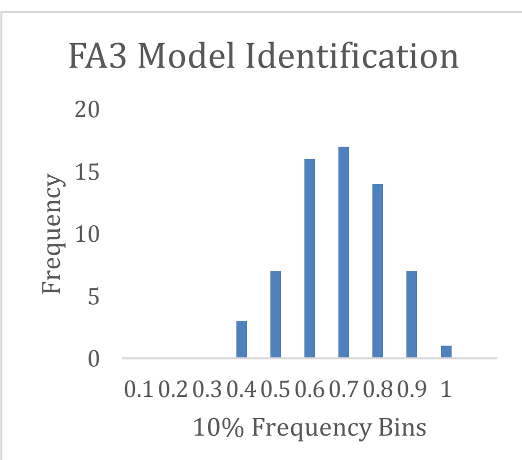


Figure 4 - FA3 Model Identification Score Frequency

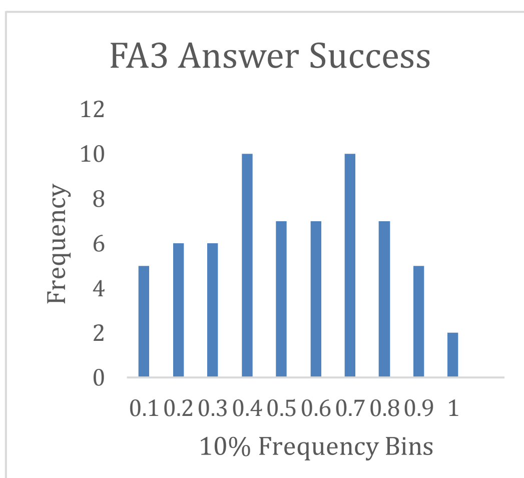


Figure 7 - FA3 Answer Success Score Frequency

Part 2: Score Frequency Distributions. Figures 2, 3, and 4 showcase a noticeable shift upwards in frequency distributions of model identification scores. In fact, the bottom third of model identification scores disappear by the third formative assessment. Students beginning toward the bottom in terms of model identification showed dramatic growth in this area over the course of the three assessments as no students scored below 30% in model identification on FA3.

On the other hand, the frequency distributions of the answer success (Figures 5, 6, and 7) scores stayed fairly constant over the three formative assessments. 55% of students scored below 50% on answer success on FA1. The results changed very little by FA3, with 52% of students scoring below 50% on answer success on FA3.

The data exhibits significant decreases in the frequency of students receiving low scores on model identification and staying relatively constant on answer success. This data, in conjunction with the data from Tables 1 & 2 and Figure 1, demonstrates that the implemented pedagogy and model identification skill development significantly helped students beginning with relatively lower model identification socres, but not necessarily answer success, when compared with their peers. Because the AP Physics Exam really doesn't test whether or not students can identify models, answer success improvements were really what this research was after. The data showed that answer success stayed constant for the students on average. Keep in mind that as formative assessment number increased, the number of models increased and, therefore, the challenge level increased. FA3 had far more necessary physics understanding than did FA1. Because average answer success scores stayed relatively constant, students did significantly improve their answer success overall.

Part 3: Individual Student Percent Growth. The previous data represented information gleaned from average scores and main overarching trends observed in the data. The next set of data looks at individual students' progressions in terms of their specific percent growth from formative assessment 1 to formative assessment 3. This data also includes the percent growth from the pretest FCI to the posttest FCI.

As the FCI assessment measures mechanics content and mechanics conceptual knowledge (not really processing and analysis skills), the FCI data demonstrates major growth for individual students in physics content and conceptual understanding. According to Figures 8, 9, and 10, most students increased their understanding of mechanics content by about 200%, with many students increasing by 300% or 400%. No students scored a negative percent growth and only one student had a percent growth under 50%. Students definitely learned physics content during the course of the academic year according to the FCI data.

However, the FCI data does not correlate to the model identification numbers; nor does it correlate to the answer success numbers. In fact, the correlation value between the FCI percent growth numbers and the model identification percent growth numbers equals -0.08. The correlation value between the FCI percent growth numbers and the answer success percent growth numbers equals -0.11. Essentially, no correlation exists between the FCI and the formative assessments. This lack of correlation implies that the formative assessments are not measurements of physics content knowledge in the same way that the FCI measures physics understanding. The formative assessments are measuring a different skill than simply understanding the basic conceptual physics questions in the field of mechanics. Furthermore, these correlation values support the idea that improvements in model identification or answer success do not result directly from "learning" the physics content. Model identification and the resulting answer success on comprehensive AP-level physics exams stands as a separate skill, one that needs to be included in the AP Physics 1 curriculum.

Overall, only marginal percent growths in model identification were measured in this academic year. Most students landed somewhere between -50% and +50% percent growth in model identification. The same can be said of answer success. While these scores showcase little improvement, and even some declines, two important points must be made about these data.

First, while most students landed under 50% growth in model identification and answer success, a non-negligible number of students showed dramatic growth of 100% or more. Figures 8, 9, and 10 show that 23% of students showed over 100% growth in model identification, and 22% of students showed over 100% growth on answer success. These incredible improvements can *probably* be attributed to those students beginning in the lower third of achievement based on the data from **Results Part 1**.

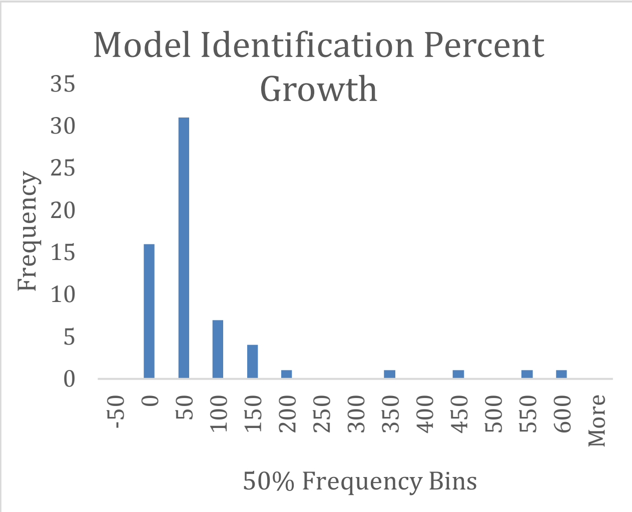


Figure 8 - Model Identification Percent Growth from FA1 to FA3

Labels	Bin	Frequency
<-50	-50	0
-50 - 0	0	16
0 - 50	50	31
50 - 100	100	7
100 - 150	150	4
150 - 200	200	1
200 - 250	250	0
250 - 300	300	0
300 - 350	350	1
350 - 400	400	0
400 - 450	450	1
450 - 500	500	0
500 - 550	550	1
550 - 600	600	1
> 600	More	0

Percent growth on FA's = (FA3 – FA1) / FA1

Percent growth on FCI = (FCI2 – FCI1) / FCI1

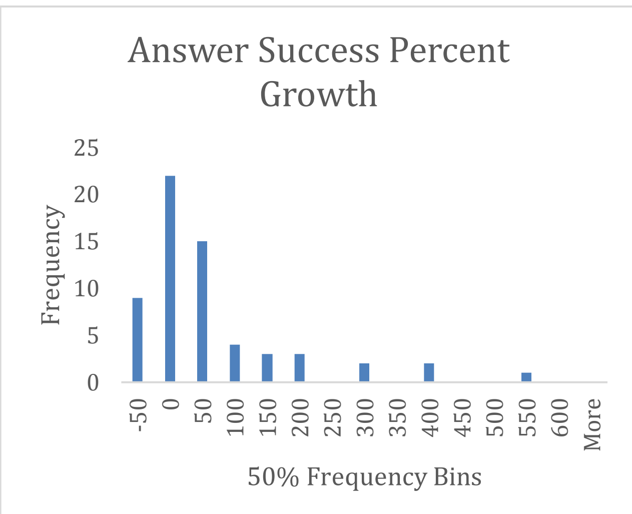


Figure 9 - Answer Success Percent Growth from FA1 to FA3

Labels	Bin	Frequency
<-50	-50	9
-50 - 0	0	22
0 - 50	50	15
50 - 100	100	4
100 - 150	150	3
150 - 200	200	3
200 - 250	250	0
250 - 300	300	2
300 - 350	350	0
350 - 400	400	2
400 - 450	450	0
450 - 500	500	0
500 - 550	550	1
550 - 600	600	0
> 600	More	0

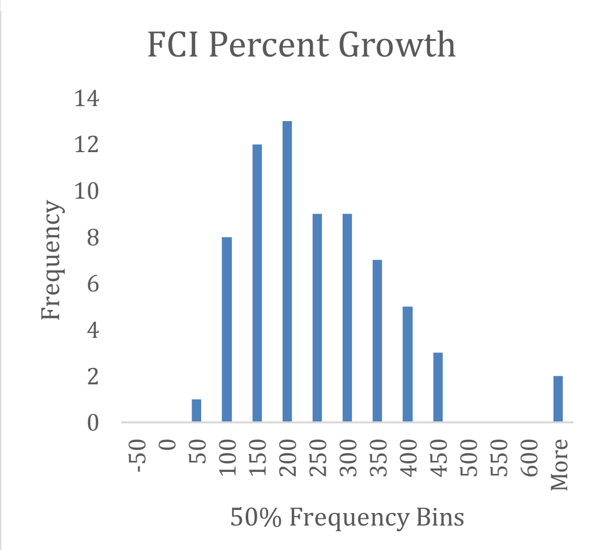


Figure 10 - FCI Percent Growth from Pretest to Posttest

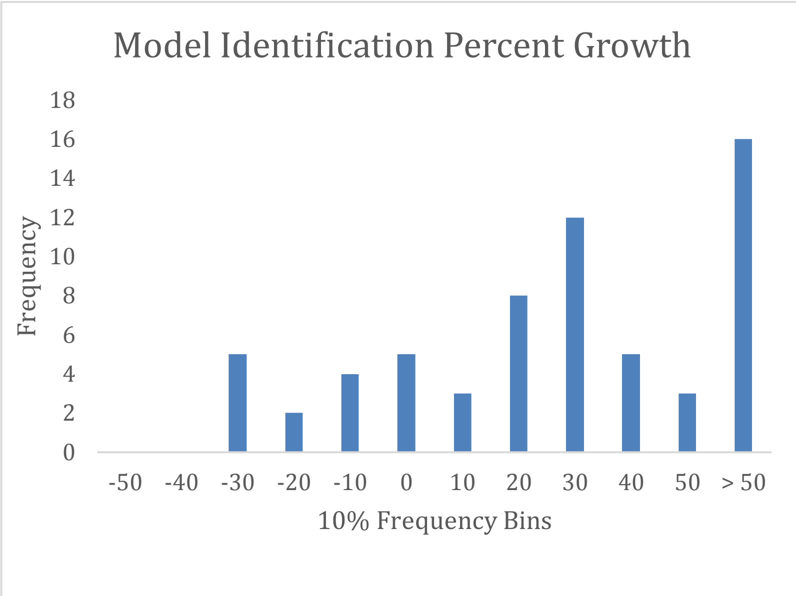
Labels	Bin	Frequency
<-50	-50	0
-50 - 0	0	0
0 - 50	50	1
50 - 100	100	8
100 - 150	150	12
150 - 200	200	13
200 - 250	250	9
250 - 300	300	9
300 - 350	350	7
350 - 400	400	5
400 - 450	450	3
450 - 500	500	0
500 - 550	550	0
550 - 600	600	0
> 600	More	2

	Average	Standard Deviation	Minimum	Maximum	Median
Model Identification Percent Growth	54.99	117.14	-39.42	557.69	24.62
Answer Success Percent Growth	37.54	119.27	-100.00	530.00	-3.75
Total Score Percent Growth	31.43	49.82	-37.50	225.00	18.92
FCI Percent Growth	238.06	152.77	44.44	1050.00	211.11

Table 3 - Individual Student Percent Growth of Model, Answer, and FCI

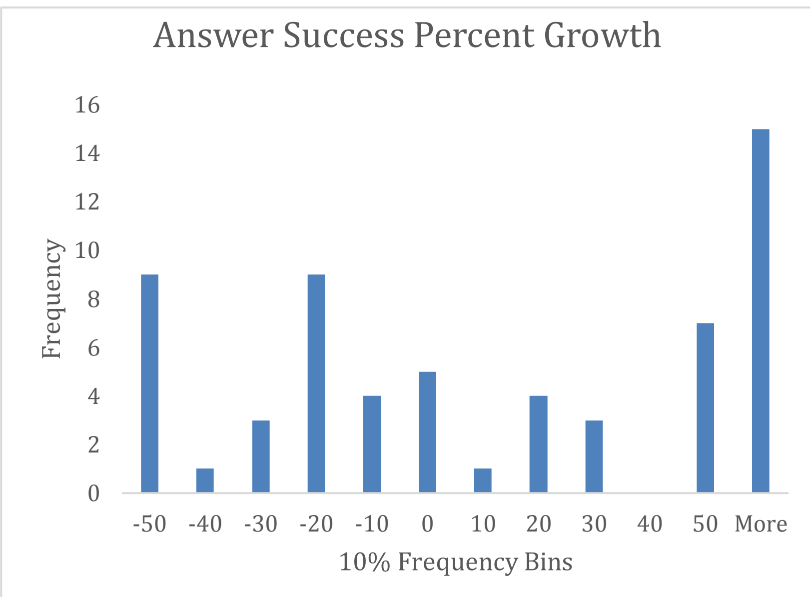
According to Table 3, we see substantial average percent growths in both model identification and answer success. Many students had over 50% growth in model identification, especially considering the incredibly large maximum value of 558%. With a standard deviation of 117, 34% of students landed somewhere in between the average of 55% and 172% growth. Also, a large of number of students had incredible improvements in Answer Success considering the average of 37% and the maximum of 530%. Furthermore, with a standard deviation of 120, 34% of students landed somewhere in between the average of 37% growth and 156% growth in answer success.

We do see some negative percent growth in both model identification and answer success in Table 3. Keeping in mind the increasing number of models and the increasing assessment difficulty, negative percent growth can still be indicative of progress.



Labels	Bin	Frequency
<-50	-50	0
-50 - -40	-40	0
-40 - -30	-30	5
-30 - -20	-20	2
-20 - -10	-10	4
-10 - 0	0	5
0 -10	10	3
10 - 20	20	8
20 - 30	30	12
30 - 40	40	5
40 - 50	50	3
> 50	> 50	16

Figure 11 - Model Identification Percent Growth from FA1 to FA3



Labels	Bin	Frequency
<-50	-50	9
-50 - -40	-40	1
-40 - -30	-30	3
-30 - -20	-20	9
-20 - -10	-10	4
-10 - 0	0	5
0 -10	10	1
10 - 20	20	4
20 - 30	30	3
30 - 40	40	0
40 - 50	50	7
> 50	> 50	15

Figure 12 - Answer Success Percent Growth from FA1 to FA3

Consider a percent growth of 25%, the median value of percent growth in model identification. This is by no means insignificant, especially considering the nature of the formative assessments. Studying the smaller bin width graphs and data tables above, we see large amounts of students with percent growths in this quarter growth range.

According to Figures 11 and 12, 52% of students had a model identification percent growth over 20%. In other words, over half of the students measured improved by at least 1/5 on just model identification, and 35% of the total students grew by 30% or more. In total, there were only 4 models to choose from on the first formative assessment. Consider a student who completely understood only half of the models on the first formative assessment. If this student had an individual percent growth of 25%, he or she could be described as "mastering" a whole additional model compared to the initial score.

This growth, of course, is in addition to an increasing number of models as described in **Chapter 3: Methods**. On average, many students grew by 20% – 30%, which can be described as learning a whole additional model, while also incorporating more models into their physics schema. Ultimately, 68% of students showed at least some positive growth from Formative Assessment 1 to Formative Assessment 3 in model identification while also incorporating more models into their understanding of physics.

Similarly, student answer success also showed moderate increases. 36% of students showed increases of 40% or more. 40% of students showed at least a 20% growth, 47% showed at least a 10% growth, and 49% of students showed an overall positive percent growth on answer success. Unfortunately, that also means that 51% of students had negative percent growth. However, negative percent growth on an increasing amount of knowledge and things to process can still indicate some positive growth. The number of possible models increased from four to seven, a modest decrease in answer values might still represent student improvement.

AP Physics 1 Exam Scores

Possible Implications for AP Exam Scores. Let us consider the possible AP scores relative to the number of correct answers on an AP Physics exam. The first section of the AP Physics 1 Exam contains 50 multiple choice questions and accounts for 50% of the total exam score (free response being the other half of the total score). Table 4 shows the scoring guidelines for the 2016 AP Physics 1 Exam. While the composite score ranges change slightly from year to year, this table is representative of the scoring guidelines over the three years of data under consideration. The composite scores include both multiple choice and free response scores, and it is absolutely true that these two sections of the exam differ in numerous and substantive ways. However, considering the simple idea of answer success, the number of problems that a student answers correctly overall, small increases can have huge impacts on students' overall AP scores. Each point of the composite score represents a correct answer on the multiple-choice section and one correct solution segment on the free response section.

Composite Score Range	AP Score
57 – 80	5
43 – 56	4
31 – 42	3
20 – 30	2
0 – 19	1

Table 4 - 2016 AP Physics 1 Scoring Guideline Chart

A "5" is the top AP score, and a "1" is the lowest AP score. In general, "3" is considered to be passing, with many colleges and universities accepting AP scores as transfer credit from students scoring a "3" or above. Whether or not a student receives transfer credit may depend on declared major, policies within the institution, and even policies within an individual institutional department. Depending on the entrance and credit requirements, some schools only allow AP credit transfer if students receive a score of "4" or above.

According to the chart, a score of 31 out of 80 yields a passing score (3 or above). Imagine a student with a composite score of 25, right in the middle of a score of 2. An increase in answer success of 25% would bump this hypothetical student up from a 2 to a 3. Imagine another student who would score in the middle of the 3-range, a composite score of 36. An increase in answer success of just 20% bumps this student up from an AP score of 3 to an AP score of 4. An increase in answer success of 17% bumps a middle-scoring 4 student up to an AP score of 5.

Now, this formative assessment tool is not designed to *cause* revolutionary changes in students' performance. It probably won't make a 2 turn into a 4. Instead, the goal of this tool is to produce small changes, a point here and a point there. Even small changes can transform a non-passing score into a passing one or a 4 into 5. The data shows that the formative assessment tool and the implemented pedagogy are able to help students develop their physics understanding, cultivate conditionalized knowledge, and become better more able problem solvers. But does this translate into improved performance on the AP Physics Exam?

AP Exam Score Results. Table 5 presents the AP Physics 1 Exam scores from the 2015, 2016, and 2017 spring exam dates (The College Board, 2015 - 2017). The scores are broken up into academic year and my own classroom's scores vs. global scores. The table also showcases the numbers of students earning different AP scores, 1 through 5. Finally, we see the average score on the far right of the table. This average would be out of a maximum of "5."

Academic Year	Total Students taking the AP Physics 1 Exam	5's	4's	3's	2's	1's	Average Score (standard deviation)
My students' scores 2014 – 2015	44	1 (2.3%)	18 (40.9%)	17 (38.6%)	7 (15.9%)	1 (2.3%)	3.25 (0.84)
Global Scores 2014 – 2015	171,074	8,469 (5.0%)	23,322 (13.6%)	35,345 (20.7%)	50,966 (29.8%)	52,972 (31.0%)	2.32 (1.19)
My students' scores 2015 - 2016	27	1 (3.7%)	5 (18.5%)	12 (44.4%)	8 (29.6%)	1 (3.7%)	2.89 (0.89)
Global Scores 2015 – 2016	169,304	7,746 (4.6%)	23,770 (14.0%)	35,840 (21.2%)	51,092 (30.2%)	50,856 (30.0%)	2.33 (1.17)
My students' scores 2016 - 2017 (experimental FA year)	53	3 (5.7%)	20 (37.7%)	26 (49.1%)	4 (7.5%)	0 (0%)	3.42 (0.72)
Global Scores 2016 – 2017	154, 626	7,731 (5%)	24,276 (15.7%)	31,389 (20.3%)	45,460 (29.4%)	45,769 (29.6%)	2.37 (not avail)

Table 5 – 2015 – 2017 AP Physics 1 Exam Scores from experimenter's classroom and global
Note that the 2017 global scores are preliminary; numbers and percentages will change as make-up tests are scored and scoring revisions are made over the coming months.

The first thing to note about the scores from Table 5 is that the Global Scores stay quite steady over the three years of data. The average score consistently hits around 2.35, and the relative percentages of students receiving the possible scores also remain relatively constant. This indicates that the challenge level of the AP Physics 1 exam remained constant over the course of the three years. It could also mean that the score ranges are chosen each year to keep the percentages consistent. In either case, the stable average value of the global scores provide contrast with my students' scores to demonstrate any possible growth. If my students' scores show dramatic change, those changes can be attributed to changes in curriculum or pedagogy. Of course, this also assumes that my students are also similar in ability level year to year.

Second, my students' scores vs. the global scores indicate an important detail concerning my experimental population. On average, students in my classes tend to do substantially better than global averages. Routinely, nearly 60% of global students receive non-passing scores. As discussed in **Chapter 5: Discussion and Implications**, the typical abilities of students in my classes may have played a role in the success of the experiment.

Next, it is extremely important to note the unique circumstances associated with my class scores for the 2014 – 2015 school year. AP Physics 1 as a course, and thus the AP Physics 1 Exam, was first offered during this academic school year. Before that, only the AP Physics B Course and Exam were offered. Because the AP Physics B Exam covered in one school year what we now cover in two (AP Physics 1 and AP Physics 2), students at my high school interested in taking the AP Physics B course first must pass the prerequisite course, Honors Physics. Basically, the honors course gave students experience and practice with most of mechanics and some electricity. Then, the AP Physics B course contained some additional content like magnetism and thermodynamics and expanded on the mechanics from the honors course with higher level mathematics added.

Because of the abrupt change to the AP Physics Exam offerings, many students were "caught" in an unfortunate turn of events. Most of the students who took the AP Physics 1 course and exam during the 2014 – 2015 school year were actually students who had enrolled in the honors course the year before. They had done so to meet the prerequisite for the AP Physics B course, but the transition to AP Physics 1 undermined their honors coursework and ultimately deemed it unnecessary. In the end, most (75 – 80%) of the students who enrolled in the first AP Physics 1 course and, ultimately, took the exam, already had a year of physics under their belts. Considering the numbers from my classes from Table 5, a significant drop in scores occurs between 2014 – 2015 and 2015 – 2016. The reason for this, most likely, is that my 2014 – 2015 students actually had an entire extra year of physics instruction that all of the more recent classes did not. Therefore, the best direct comparison of my sample population is with the previous year (2015 – 2016), not with the average of the previous years.

Academic Year	**Total Students taking the AP Physics 1 Exam**	**5's**	**4's**	**3's**	**2's**	**1's**	**Average Score (standard deviation)**
My students' scores 2014 – 2015	44	1 (2.3%)	18 (40.9%)	17 (38.6%)	7 (15.9%)	1 (2.3%)	3.25 (0.84)
My students' scores 2016 - 2017 (experimental FA year)	53	3 (5.7%)	20 (37.7%)	26 (49.1%)	4 (7.5%)	0 (0%)	3.42 (0.72)

Table 5A –Same table as above for reference

Considering this information, one observation of the data in Table 5A immediately jumps out. The experimental year of my classes' scores (2016 – 2017) had slightly better scores than the 2014 – 2015 scores considering the overall average scores and looking at increases in frequency of 5's and 3's (4's stayed essentially the same). In essence, the students who were taught with the innovative pedagogy and given the formative assessment series scored marginally better than students who had an extra year of physics instruction. Furthermore, the 2016 – 2017 school year (my class experimental year) also saw dramatic decreases in non-passing scores (1's and 2's) when compared to the 2014 –

2015 school year. The experimental year (2016 – 2017) saw zero 1's and only four 2's compared to one 1's and seven 2's from the first year (2014 – 2015).

Note that the 2014 – 2015 and 2016 – 2017 had similar numbers of students taking the exam. Any statistical tests one might perform are more valid with two similar sized pools. If we see dramatic increases in participation, one would expect a widening distribution of scores – extreme values become higher probability. Using the comparison between 2014 – 2015 and 2016 – 2017, a natural experiment was formed. Both academic years had similar pools of students. One pool had two years of physics instruction, while the other only had one which included the experimental formative assessment series and pedagogy. In essence, this comparison evaluated the new innovative curriculum against a two year program.

Academic Year	**Total Students taking the AP Physics 1 Exam**	**5's**	**4's**	**3's**	**2's**	**1's**	**Average Score (standard deviation)**
My students' scores 2015 - 2016	27	1 (3.7%)	5 (18.5%)	12 (44.4%)	8 (29.6%)	1 (3.7%)	2.89 (0.89)
My students' scores 2016 - 2017 (experimental FA year)	53	3 (5.7%)	20 (37.7%)	26 (49.1%)	4 (7.5%)	0 (0%)	3.42 (0.72)

Table 5B –Same table as above for reference

Comparing the 2015 – 2016 school year to the 2016 – 2017 experimental year in Table 5B also yields interesting results. First, note the differences in participation. Because 2016 – 2017 saw so many more students participate compared to the previous year, one might expect a widening distribution. More students in the pool means that both higher and lower extremes became more likely. Instead, we see a dramatic dropoff of non-passing scores. 2015 – 2016 saw a 33.3% non-pass rate, while the experimental year saw a 7.5% non-pass rate. Because the frequency of 3's stayed relatively constant, but the frequency of 4's and 5's increased dramatically, one can conclude that there might be a jump-up effect. Students who previously would have received a 2 or 1 received a 3 during the experimental year. Students who previously would have received a 3 received a 4 during the experimental year. The incredible increase in students receiving a 4 compared to the relatively constant number of students receiving a 3 supports this idea.

Ultimately, the average score on the AP Physics 1 Exam grew by 18.2% from 2015 – 2016 to 2016 – 2017. Comparing the experimental year to the first year in this way would not be valid because of the significant differences in types of students.

This jump-up effect does not, however, seem to translate much into 5's in terms of percentage of each academic years' population. Although more students did receive 5's during the experimental year when compared to the previous year, we do not see the amount of "jump" seen in the 3's and 4's in terms of percentage. Another way of looking at this, though, is simply in the increase in the number of 5's. In both 2014 – 2015 and 2015 – 2016, only one student received a 5. In 2016 – 2017, three students received 5's. This is of marginal change in terms of percentage of total populations. On the other hand, one view could be that the *number* of students receiving 5's grew by 200%. Because a "5" is the highest score, more students receiving it overall can be indicative of significant improvement.

Chapter 5: Discussion and Implications

Considering the data from the formative assessment series and the data from the three years of AP Physics 1 Exam scores, the formative assessment series and the implemented pedagogy and curriculum improved AP Physics 1 Exam scores. First, we will recall the **Research Questions** and reflect on the associated data. **Chapter 4: Findings and Results** came with lots of numbers and figures, and it is definitely worth it to see the primary data points and most interesting numerical evidence all in one place. Then, we must consider possible limitations and errors for this research, and we look at possibilities to continue this research. Finally, I include some of my own thoughts and reflections on this research.

Research Questions.

1. How does student performance on model identification formative assessments change over the course of the school year as the number of possible models increases?

- Slight increases in average answer success as seen by slope of 2.1% over three FA's
- Students who began with poor scores improved the most
  - Model identification minimum score increased from 11% to 35%
  - Median model identification score increased from 55% to 62%
  - Median answer success score increased from 43% to 50%
  - Model identification score below 30% completely disappeared by FA3
  - Answer success score below 50% stayed constant between FA1 and FA3
- Model Identification (while remembering increasing number of models)
  - 23% of students showed over 100% growth in model identification
  - 35% of students showed over 30% growth in model identification
  - 52% of students showed over 20% growth in model identification
- Answer success
  - 22% of students showed over 100% growth in answer success
  - 40% of students showed over 20% growth in answer success
  - 47% of students showed over a 10% growth in answer success
  - 49% showed a positive percent growth in answer success
    - Keeping in mind that even a marginal amount of negative percent growth occurred over an increasing amount of required knowledge and understanding – can indicate improvement
  - Answer success percent growth
    - Average answer success percent growth = 37%
    - Standard deviation = 120
    - 34% of students land somewhere between 37% and 156% growth in answer success
- AP score range chart showed that an increase in about 20% of answer success yields a "jump" up to next highest score value

Figure 13 – Research Question 1 Data

2. How do the AP Physics 1 Exam scores compare between students taught using the model identification curricular structure and assessment series and students not taught using the structure?

- Marginally better scores for experimental year compared to year with students coming in with an entire year of extra physics instruction
  - Average score of 3.415 in experimental year vs. average score of 3.250 in prior year experience group
- Drastically better scores for experimental year compared to previous year without prior year experience or innovative curriculum
  - Average score of 3.415 in experimental year vs. average score of 2.889 in other year
- Dramatic decrease in non-passing scores
  - 18.2% of students with prior year experience
  - 33.3% of students without prior year experience
  - 7.5% of students without prior year experience and with innovative curriculum
- Jump-up effect of non-passing scores turning into 3's and 3's into 4's
- No real change in frequency of 5's in terms of percentage of population
  - Another viewpoint: a 200% growth in the *number* of students receiving a 5
- Average AP Physics 1 Exam score grew by 18.2% from year without innovative curriculum and without prior year experience (2015 – 2016) to innovative curriculum year (2016 – 2017).

Figure 14 – Research Question 2 Data

Discussion

Overall Improvement Correlation. Based on the data above and considering the assumptions made (described below), the innovative pedagogy and the formative assessment series improved AP Physics 1 scores. Growth in model identification and answer success on formative assessments correlate with increased AP Physics Exam scores.

The most prominent indicator here comes from the discussion concerning the AP exam scoring chart. According to the chart, an increase around 20% in answer success yields a bump upwards in overall AP score (from a 2 to 3, 3 to a 4, etc). According to the data from Figure 13, 40% of students showed at least a 20% growth in answer success between FA1 and FA3. If AP Physics scores were improved by this innovative curriculum, we should see a corresponding jump in a single AP Exam score level of about 40% of the students.

Academic Year	**Total Students taking the AP Physics 1 Exam**	**5's**	**4's**	**3's**	**2's**	**1's**	**Average Score (standard deviation)**
My students' scores 2015 - 2016	27	1 (3.7%)	5 (18.5%)	12 (44.4%)	8 (29.6%)	1 (3.7%)	2.89 (0.89)
My students' scores 2016 - 2017 (experimental FA year)	53	3 (5.7%)	20 (37.7%)	26 (49.1%)	4 (7.5%)	0 (0%)	3.42 (0.72)

Table 5B –Same table as above for reference

As described earlier, a jump up effect occurred. Some students who probably would have received 1's or 2's actually scored 3's, and students who probably would've scored a 3 actually scored a 4. This statement is supported by the relative percentages of student scores between the two years. The percent of 3's stayed relatively constant. 37.7% of students scored a 4 in 2016 – 2017, and 18.5% of students scored a 4 in 2015 – 2016. This is a difference of 19.2%. Also considering the drop of about 25% of students receiving a non-passing grade between the two years, the correlation becomes clear. About 20% of students went from a 1 or a 2 and ended up receiving a 3, and about 20% of students went from receiving a 3 and ended up receiving a 4. A correlation between the answer success increase and the increase in AP scores is thus established. 40% of students saw an increase of at least 20% in answer success on the formative assessment series and 40% of students saw a single level improvement on their AP Physics score, which is assumed to have come from about a 20% increase in answer success on the AP Physics Exam. We also see an 18.2% growth in average AP score from 2015 – 2016 to 2016 – 2017: from 2.89 to 3.42. This approximately 20% growth value seems to be quite prominent in the data as many different aspects of the research measured this value.

Why might we have seen this improvement? First, Bransford et al. (2000) described how experts tend to mention or consider the relevant major principles or laws before beginning to solve a problem. This is because experts' knowledge is organized around those principles and laws, rather than around the equation manipulation that most novices organize their physics knowledge around. By designing the curriculum and associated pedagogy to teach physics in a big picture way, students were better suited to organize their thoughts around laws and principles. By offering practice through the formative assessments, students experienced the effectiveness of this organization which further enticed them to conceptualize the content of physics as a whole.

Furthermore, Bransford et al. (2000) described how experts are effective at knowledge retrieval because they have "conditionalized" their knowledge. In essence, experts' conceptions include specifications of where the knowledge is useful. In other words, experts are effective at knowledge retrieval because they know the contexts in which their knowledge applies. This curriculum attempted to teach students to do the same thing. By honing on the necessity of each model and emphasizing the contexts in which each model applies, students were able to more effectively answer questions on the AP Physics 1 exam.

Hammer (1989) showed how students tend to view physics as disparate sets of facts and formulas. Without a generalized approach, students have trouble transferring specific solution methods to new problems. Adams and Wieman (2015) showed how students need a generalized strategy in order to solve novel and unfamiliar problems. This innovative curriculum provided students with that strategy and combined all the facts and formulas into one coherent concept.

Finally, Malone (2008) explained how modeling physics students were better at describing their solution methods and procedures and, ultimately, were better at problem solving. Malone (2008) showed that modeling physics students exhibited a 15% better problem-solving ability over their non-modeling counterparts. My study found an 18.2% increase in performance, as measured by the average AP score, by using the innovative curriculum. This correlates to and supports Malone (2008)'s findings.

It is also interesting to note that the students taking the AP Physics 1 Exam after completing the innovative curriculum year scored slightly better (but very similar to) students with an extra year of physics instruction. The students with the extra year of instruction had an extra year to learn physics, to combine knowledge into a big picture conception, and to improve problem solving. For example, those students already had a full year of mechanics when they "re-learned" kinematics during the AP Physics 1 year. Therefore, they were in a position to see and understand connections between energy, momentum, and kinematics that students just starting out learning kinematics for the first time would not have. In essence, the formative assessment series and the innovative pedagogy bridged the gap for students inexperienced in physics in connecting models together, almost as if they had an extra year of physics to study.

Students Beginning with Lower Physics Models Proficiency. The second prominent conclusion comes from the formative assessment data concerning those students who scored lowest on FA1. In FA1, 48% of students scored below 50% on model identification. By FA3, the number of students scoring below 50% on model identification had dwindled to 15% - keep in mind the increase in the number of models. On the other hand, 55% of students scored below 50% on answer success on FA1, and the number of students scoring below 50% had only dropped to 52% by FA3. The answer success scores stayed relatively constant over the three formative assessments. However, we did see a noticeable shift in the median score on answer success, from 43% to 50%. So, we saw dramatic decreases in poor marks in model identification, but relatively constant marks in answer success throughout the formative assessment series.

In any case, we saw dramatic decreases in non-passing scores on the AP Physics 1 Exam. We see very little correlation between these two sets of data. Nonetheless, something must account for the drop in non-passing scores. First, it does require restating that the challenge level of the formative assessments increased over time. Therefore, a constant answer success score could mean that students showed improvement. Second, as Adams and Wieman (2015) showed, students in small groups tend to show improved problem-solving capability. Students in a group, regardless of individual ability, can latch on to problem-solving strategies of a single exceptional student. Students can also latch onto problem solving strategies provided by the teacher, but they rarely are able to come up with unique or novel strategies on their own. In a sense, that is precisely what happened here. The instructor taught students a method of organizing problem types, and these students may have developed proficiency at utilizing that organization. This was supported by the Model Identification data from the formative assessment series. While these students may still struggle with solving all of the AP-level physics problems which require different strategies depending on the model used, teaching them a sorting strategy has at least shown to be somewhat effective at improving their overall understanding and conceptual application.

One of the most exciting results from this research comes from the goals set out by College Board in the first place. Recall that one of the primary reasons College Board switched from AP Physics B to AP Physics 1 and 2 was to include more students in advanced high school physics coursework. If nothing else, this innovative curriculum and pedagogy has shown to help those previously excluded students to develop and demonstrate proficiency on such advanced coursework. If I can get 53 students to take the AP Physics exam and only have 4 receive a non-passing grade, that is definitely a step in right direction.

The other goals set out by College Board include focusing on conceptual understanding rather than mathematical manipulation. The course was intended to focus on promoting physics dispositions and habits of mind. The innovative curriculum also aimed to meet this objective. This innovative curriculum aimed to teach students to understand how physics is used, how professionals use physics to describe systems and systems' motion, and how to learn content in a complex and multifaceted field such as physics. Furthermore, College Board wants the AP Physics course to provide students with enduring understandings and critical thinking skills. This innovative curriculum and its continued development aims to do just that. Students who understand how and why to use certain models in certain situations have learned to explain and compare, to analyze data, to synthesize incongruent findings, generate and apply new theories, and to communicate ideas and findings to others.

General and Professional Communities. The use of models and the modeling method are no secret. In 2001, The National Department of Education recognized Modeling Instruction as an exemplary program in science education. A number of studies have demonstrated Modeling Instruction's effectiveness in promoting problem solving skills as well as more robust and complete physics understandings (Malone, 2008). Should this strategy be used in other domains other than physics?

Hinsley, Hayes, & Simon (1977) found that the most competent algebra problem solvers did use some sort of organized mental structures which united problems based on similar features. Furthermore, these students were able to more quickly pick out useful formulas and solutions methods and were also able to make more accurate predictions of the outcomes of problems.

Other domains of learning can definitely utilize what we have learned here. According to the findings in the **Chapter 2: Literature Review**, teaching students to successfully and effectively group ideas together for easier retrieval and application can work regardless of the content. Teaching students to learn this way also promotes certain successful habits of mind and general problem-solving skills. Ultimately, that is what the public education community is after: a more intelligent and skilled citizenry. This method has shown to be effective, and I believe it can work in any setting

Study Limitations and Future Research. Regardless of the AP scores from the experimental school year, it is always possible that this year's group of AP Physics students, the experimental group, were of higher ability than previous years. This group could simply be unique in their overall scientific prowess and their mathematical abilities, and their increased scores could simply be a function of those heightened abilities relative to the two previous years of AP Physics 1 students. Furthermore, it is important to restate the higher-than-average scores my typical students received compared to global scores. Based on the data presented in **Chapter 4: Findings and Results,** my students routinely score much higher on the AP Physics 1 Exam when compared to the global average scores. My students' skills and educational background may have played a role in the students' response to the innovative curriculum. Study of students from schools without such routine high AP Physics marks could yield informative results.

As mentioned previously, one of the goals of the College Board was to improve habits of mind and critical thinking skills. Longitudinal tracking of students involved in AP Physics 1 and who have been instructed using the innovative curriculum would be beneficial to the science education field and to College Board. It would be extremely beneficial to know how these students perform in college science and math coursework, how they perform in job tasks, and how they perform in any other task requiring critical thinking skills and system analysis. However, such longitudinal tracking is expensive and time consuming.

It is also the case that the experimental year was only the experimenter's third year teaching AP Physics 1 and fourth year teaching overall. While the experimenter made minimal changes to the overall method of instruction besides what was described in this study, it is possible that the experimenter has simply grown professionally over the course of the previous three years. He may just be better at teaching physics and helping students to learn material. Therefore, further and continued research is required to increase the validity of this study. It would be pertinent to repeat this study again the following year to see if the formative assessment tool yields similar results when compared to the non-experimental years' AP scores.

The instructor associated with this research is also well-versed in the Modeling Instruction curriculum. He has been to a two-week long intensive modeling workshop and numerous modeling day-workshops. He has taught both AP Physics and General Physics using the Modeling Instruction curriculum or, at least, using the modeling method for four years. The idea and implementation of the innovative curriculum might have been easier for this instructor compared to instructors not as well-experienced in modeling. The act of treating physics principles and laws as models and teaching as such can be a huge hurdle for some teachers. The innovative pedagogy probably wouldn't have gone as smoothly for someone less practiced in modeling. Further research should be done with instructors with less or no modeling experience.

In the **Methods** section, it was stated that the students enrolled in this suburban high school would be representative of all students taking the AP Physics 1 Exam. This statement has very little basis, and it would also be pertinent to take this study to other varying school districts to further verify validity. Because of the success of this study, its themes and ideas should definitely be carried on and extended.

This study could have been run in a few different ways.

1. This study used three class-period-long formative assessments. It might be worth trying more numerous shorter length formative assessments instead.
2. This study did not "start" assessing model identification until after the energy unit. It may be pertinent to begin earlier in the year – after kinematics or after dynamics.
    a. Do students really know enough physics in order to get anything out of the formative assessments or the "story of physics" this early in the year? As explained in the appendices, the story of physics doesn't really start until centripetal motion and more explicitly, in energy. Would it really be pertinent to begin the process of showing how certain models are more useful than others if they only have one or two models (kinematics and dynamics), so far?
3. This study did not include electric circuits (simple resistor circuits only) or electrostatics although the AP Physics 1 course and exam do include these topics. It was assumed that students wouldn't need training or practice in identifying electric circuit problems, because those problems would contain circuits. Nonetheless, It may be pertinent to include those topics among the models as they do fit into the larger "story of physics."
4. The experimenter did collect data about model identification using graphs, graph analysis, and free-body diagram tasks during this study. However, this information was not included in the final paper. It may be pertinent to include this section in future studies, as graphing plays a huge role in model identification and on the AP Physics Exam.

Personal Reflection. On a more personal note, I truly feel as though I know more physics because of this research project. I have a Bachelor's in Physics, I teach AP Physics 1 and 2, and I am about to receive my Master's in Science Education with a Physics Emphasis. I feel like I have a fairly respectable understanding of physics content, at least enough to effectively organize and teach my high school courses. When I began thinking of my course curriculum in terms of models, though, I also began to see the bigger picture of physics – how it all fits together. I always kind of knew that the models were tools (like the hammer). However, it wasn't until this study that I truly started to appreciate why I know what I know, why I use momentum to solve certain problems but energy for other problems. I feel like I have a better understanding of physics as a whole because I did this study.

At the beginning of the year, I always tell my students that they will "see" physics sometime this year. "You'll be driving your car, riding a roller coaster, playing with a kids' toy, watching a movie, or even sitting in a chair. Then, it will hit you. You will see a free-body diagram for that system, or you'll actually feel the forces involved in the action. You will *see* physics. And I want you to come and tell me when it happens." They never believe me at first. Usually during or after the forces unit, many students experience physics for the first time. They can't wait to tell me about it.

This year was kind of like that. I've been academically studying physics content for nearly a decade, but something changed this year. I saw physics anew when I started asking myself, "Why is the model important? What are the properties of this model? When would I use it and how would I know to use it?" Each of the models has their own respective significance and usability. If they didn't, they wouldn't be one of the models. I learned about the physics models this year, and it, ultimately, makes me a better physicist and a better teacher.

For my future professional growth, I am going to continue to implement the formative assessment tool and the "story of physics" pedagogy in my AP Physics 1 course. As explained above, I have a few ideas for minor changes in the implementation of the formative assessments. I will also continue to modify my story of physics. There are definitely places where my explanations and instructions can be improved in this area.

Another place for possible future growth is in AP Physics 2. Because of the success of the innovative curriculum AP Physics 1, the idea should carry over to AP2, right? I don't really think so, because AP 2 is such a different course. While AP 1 covers all of mechanics (kinematics, dynamics, energy, and momentum), AP 2 covers a very wide range of topics (fluids, thermodynamics, electrostatics, electric circuits, magnetism, optics, and modern physics). These topics are so very different from one another. Students would never mistake a magnetism problem for a fluids problem. While AP 1 covers, in one word, motion, AP 2 covers a wide range of specific types of systems and processes. In a sense, there is very little possibility for model confusion in AP Physics 2. I don't think spending time taking similar formative assessments would be worth it. Furthermore, I struggle to come up with the "story" separating the models from one another besides restating obvious model properties: magnetism is about magnets.

So for now, my mission is to come up with a similar helpful curriculum and pedagogy which binds the AP Physics 2 content together. One possibility is the different themes that run through the AP Physics 2 content. While magnetism and electrostatics are recognizably different on the surface, both models require an extensive understanding of forces and fields. Energy also plays a major role in all of the AP Physics 2 content. While the model identification techniques may be quite dissimilar from the "story of physics" in AP Physics 1, teaching physics as a whole (big picture, conceptual) can still be beneficial. For example, comparing and contrasting the magnetic field and electrostatic field can go a long way in understanding both. In the end, all of the research above about models, chunking, and conditionalized knowledge still applies, but the AP 2 system will have to be fundamentally different. I haven't yet figured out what that system might look like.

References

Adams, W. K., & Wieman, C. E. (2015). Analyzing the Many Skills Involved in Solving Complex Physics Problems. *American Journal of Physics*, *83* (5), 459-467.

Antonenko, P. D., Ogilvie, C. A., Niederhauser, D. S., Jackman, J., Kumsaikaew, P., & Marathe, R. (2011). Understanding Student Pathways in Context-Rich Problems. *Education and Information Technologies, 16* (4), 323-342.

Bransford, J. D., Brown, A. L., Cocking, R. R., Donovan, M. S., & Pellegrino, J. W. (2000). *How People Learn: Brain, Mind, Experience, and School.* National Research Council, Commission on Behavioral and Social Sciences and Education. Washington D.C.: National Academies Press.

Brewe, E. T. (2002). *Inclusion of the Energy Thread in the Introductory Physics Curriculum: An Example of Long-Term Conceptual and Thematic Coherence.* Doctorate Thesis, Arizona State University.

Byun, T., & Lee, G. (2014). Why Students Still Can't Solve Physics Problems After Solving Over 2000 Problems. *American Journal of Physics, 82* (9), 906-913.

College Board. (2014). *AP Physics 1: Algebra-Based and AP Physics 2: Algebra-Based Course and Exam Description.* College Board.

Creswell, J. (2014). *Research design: qualitative, quantitative, and mixed methods approaches.* Thousand Oaks, CA: SAGE Publications.

Etkina, E., Warren, A., & Gentile, M. (2006). The Role of Models in Physics Instruction. *The Physics Teacher, 44* (34), 15-20.

Gerace, W. J., & Beatty, I. D. (2005). Teaching vs. Learning: Changing Perspectives on Problem Solving in Physics Instruction. *9th Common Conference of the Cyprus Physics Association and Greek Physics Association.* Nicosia, Cyprus.

Gollub, J. P., Berthenthal, M. W., Labov, J. B., & Curtis, P. C. (2001). *Learning and Understanding: Improving Advanced Study of Mathematics and Science in US High Schools.* National Research Council, Committee on Programs for Advanced Study of Mathematics and Science in American High Schools.

Gonzalez, E. J., O'Connor, K. M., & Miles, J. A. (2001). *How Well do Advanced Placement Students Perform on the TIMSS Advanced Mathematics and Physics Tests.* Boston College, International Study Center, Lynch School of Education, Boston.

Hammer, D. (1989). Two Approaches to Learning Physics. *The Physics Teacher, 27*, 664 - 670.

Heitin, L. (2015, September 9). Test-Taking Surged for AP Physics and Computer Science. *Education Week, 35* (3), p. 7.

Heller, P., Keith, R., & Anderson, S. (1992). Teaching Problem Solving Through Cooperative Grouping. Part 1: Group versus Individual Problem Solving. *American Journal of Physics, 60* (7), 627-636.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher, 30*, 141-158.

Hinsley, D. H., Hayes, J. R., & Simon, H. A. (1977). In M. Just, & P. Carpenter (Eds.), *Cognitive Processes in Comprehension.* Hillsdale, NJ: Psychology Press.

Jackson, J., Dukerich, L., & Hestenes, D. (2008, Spring). Modeling Instruction: An Effective Model for Science Education. *Science Educator, 17*(1), 10 - 17.

Jones, L. R., Wheeler, G., & Centurino, V. A. (2015). Chapter 2: TIMSS Advanced Physics Framework. In I. V. Mullis, & M. O. Martin, *TIMSS Advanced 2015 Assessment Framework* (pp. 17-25). Boston: International Study Center, Lynch School of Education, Boston College.

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. (1980a). Expert and Novice Performance and Solving Physics Problems. *Science, 208* (4450), 1335-1342.

Larkin, J., McDermott, J., Simon, D., & Simon, H. (1980b). Models of Competence in Solving Physics Problems. *Cognitive Science, 4*, 317-345.

Malone, K. L. (2008, November 20). Correlations among knowledge structures, force concept inventory, and problem-solving behaviors. *Physical Review Physics Education Research, 4*(2), 1-15.

Marx, J., & Cummings, K. (2010). Development of a Survey Instrument to Gauge Students' Problem-Solving Abilities. *Physics Education Research Conference. 1289*, pp. 221-224. American Institute of Physics.

Mayer, R. E., & Wittrock, M. C. (2006). Problem Solving. In P. Alexander, & P. Winne (Eds.), *Handbook of Educational Psychology* (2nd ed., pp. 287-303). Erlbaum, NJ: Lawrence Erlbaum Associates.

Pawl, A., Barrantes, A., & Pritchard, D. (2009). Modeling applied to problem solving. (pp. 51-54). American Institute of Physics.

Singh, C. (2002). When Physics Intuition Fails. *American Journal of Physics, 70* (11), 1103-1109.

Singh, C. (2009a). Categorization of Problems to Assess and Improve Proficiency as Teachers and Learners. *American Journal of Physics, 77* (1), 73-80.

Singh, C. (2009b). Problem Solving and Learning. *Proceedings of the National Society of Black Physicists* (pp. 183-197). American Institute of Physics.

Stemler, S. E., Sternberg, R. J., Grigorenko, E. L., Jarvin, L., & Sharpes, K. (2009). Using the Theory of Successful Intelligence as a Framework for Developing Assessments in AP Physics. *Contemporary Educational Psychology, 34*, 195-209.

The College Board. (2015 - 2017). *AP Program Participation and Performance Data.* Retrieved June 2017, from Student Score Distributions: https://research.collegeboard.org/programs/ap/data/participation/ap-2016

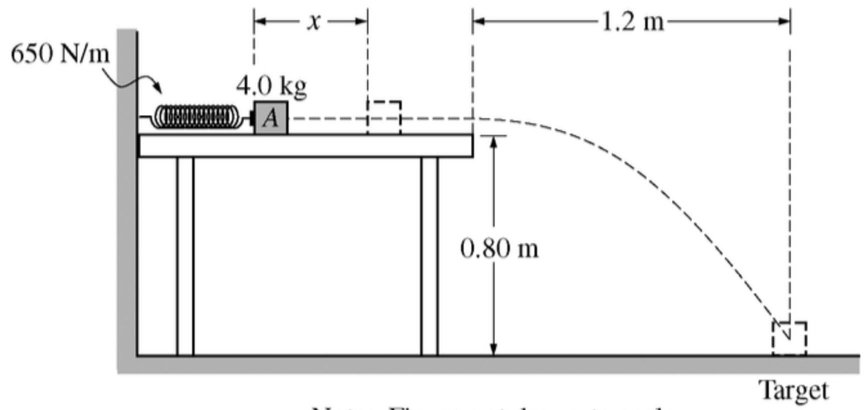
Yerushalmi, E., Singh, C., & Evylon, B. S. (2007). Physics Learning in the Context of Scaffolded Diagnostic Tasks (I): The Experimental Setup. *Physics Education Research Conference.* American Institute of Physics.

Yerushalmi, E., Singh, C., & Evylon, B. S. (2007). Physics Learning in the Context of Scaffolded Diagnostic Tasks (II): Preliminary Results. *Physics Education Research Conference.* American Institute of Physics.

Appendix A

AP Physics Exam Examples

An AP Physics B question from 2010 (College Board)



Note: Figure not drawn to scale.

1. (15 points)

Block *A* of mass 4.0 kg is on a horizontal, frictionless tabletop and is placed against a spring of negligible mass and spring constant 650 N/m. The other end of the spring is attached to a wall. The block is pushed toward the wall until the spring has been compressed a distance *x*, as shown above. The block is released and follows the trajectory shown, falling 0.80 m vertically and striking a target on the floor that is a horizontal distance of 1.2 m from the edge of the table. Air resistance is negligible.

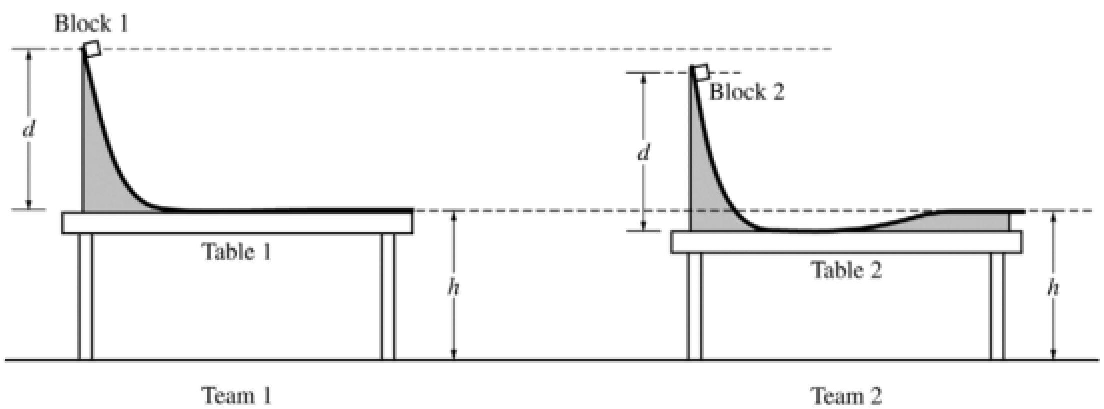
(a) Calculate the time elapsed from the instant block *A* leaves the table to the instant it strikes the floor.

(b) Calculate the speed of the block as it leaves the table.

(c) Calculate the distance *x* the spring was compressed.

An AP Physics 1 question from 2017 (College Board)

2017 AP® PHYSICS 1 FREE-RESPONSE QUESTIONS



4. (7 points, suggested time 13 minutes)

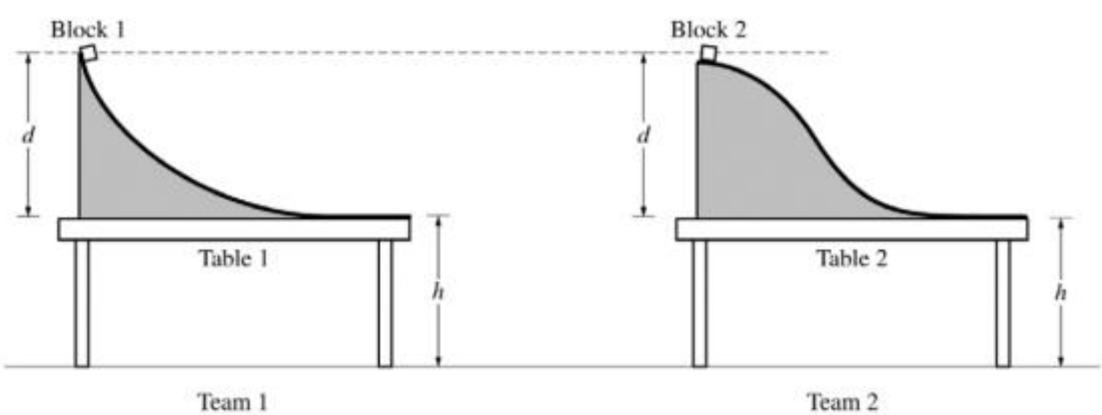
A physics class is asked to design a low-friction slide that will launch a block horizontally from the top of a lab table. Teams 1 and 2 assemble the slides shown above and use identical blocks 1 and 2, respectively. Both slides start at the same height d above the tabletop. However, team 2's table is lower than team 1's table. To compensate for the lower table, team 2 constructs the right end of the slide to rise above the tabletop so that the block leaves the slide horizontally at the same height h above the floor as does team 1's block (see figure above).

(a) Both blocks are released from rest at the top of their respective slides. Do block 1 and block 2 land the same distance from their respective tables?

____ Yes ____ No

Justify your answer.

In another experiment, teams 1 and 2 use tables and low-friction slides with the same height. However, the two slides have different shapes, as shown below.



(b) Both blocks are released from rest at the top of their respective slides at the same time.

i. Which block, if either, lands farther from its respective table?

____ Block 1 ____ Block 2 ____ The two blocks land the same distance from their respective tables.

Briefly explain your reasoning without manipulating equations.

ii. Which block, if either, hits the floor first?

____ Block 1 ____ Block 2 ____ The two blocks hit the floor at the same time.

Briefly explain your reasoning without manipulating equations.

Appendix B

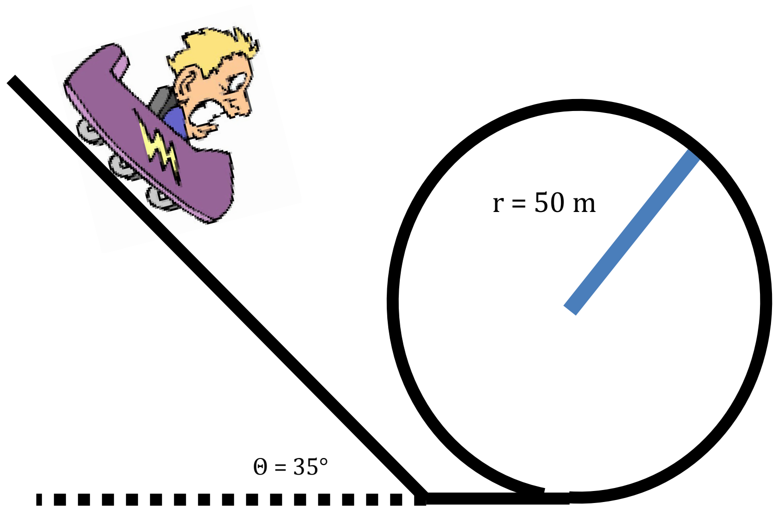
The Model Identification Strategy Outline

The Model Identification skill development program implemented in this research has two components. The first of these parts is "the story of physics," an innovative pedagogical approach utilized by the instructor.

The topics covered in the AP Physics 1 course include:

- Kinematics – constant velocity and accelerated motion; projectile (2D) motion
- Dynamics – Newton's Laws, forces, and free-body diagrams
- Centripetal Motion – constant speed motion in a circular path; gravitation and Newton's Universal Law
- Energy – the law of conservation of energy; work
- Momentum, the law of conservation of momentum; impulse
- Simple harmonic motion, mechanical waves, and sound
- Rotational Motion and Torque
- Electrostatics - electric charge and electric force
- DC Circuits – simple resistor circuits only

The Story of Physics. First, the instructor emphasized the need for each different new model by introducing a problem task which the previous model could not solve in large group discussion. For example, after completing the Dynamics Unit (Newton's Laws and forces) and the Centripetal Motion Unit (motion at a constant speed with the net force always pointing into the circle), the instructor presented the following problem.



A man and a roller coaster car have a total mass of 500 kg. How tall does the ramp have to be in order for the rollercoaster car to just make it around the loop? Assume a frictionless track and no loss of velocity in the sharp ramp edge

After just having completed the Dynamics Unit and the Centripetal Motion Unit, students attempt to solve the problem using their knowledge and understanding of kinematics, dynamics, and centripetal motion. However, their efforts remain in vain unless the students know some calculus, which most do not. The instructor leads a class discussion about the difficulty in solving this problem. Through Socratic Questioning, the students develop the idea that one difficulty with the task rests upon the fact that the magnitude of the force and the magnitude of the speed change as the rollercoaster car moves along the circular part of the path. As constant force was a prerequisite for solving dynamics problems and constant speed was a prerequisite for solving centripetal motion problems, the students find it impossible to solve this problem using their current models.

The instructor then says, "Well, I guess we need a new model, one which can solve the task. What properties should this new model have? What should the new model be like?" Students discuss these questions, but usually do not see where this is going, yet. The instructor then mentions, "What was the problem, or shortcoming, of the old models? Where did these models break down?" The answer, of course, is that we needed certain properties to be constant, but this task did not have those constant properties. The students, then, see the proper course. In almost unison, "The new model needs to be something that can be held constant no matter what the motion is like."

The instructor then asks if there is such a model, a property which can never be lost, destroyed, created, etc. Is there a property which is held constant, or conserved, no matter what? The students, remembering that phrasing from their chemistry course, identify energy as the new model. Similar problem tasks begin other units. For example, a car collision problem initiates the momentum unit. Students attempt to use energy to solve the problem, but find that, although the energy is conserved in a collision, much of the energy goes to forms which have no equation (that they know of). "So, we need a new model which doesn't succumb to entropy."

By introducing the new models in this way, students begin to get a sense of the intrinsic value of each model. Each model has its own set of rules and limitations. Dynamics has a hard time dealing with changing forces, so don't use dynamics to solve systems which have changing forces. *Dynamics has a limit to its utility*. By learning not just the equations but the models, students become better physics problem solvers. Furthermore, students understand *WHY* each model is important and useful. By teaching students how each model is related to one another, what type of system each model can describe, and how to identify model types, students, ultimately, become more expert-like physicists. They begin to understand the big picture of physics and can utilize "the story of physics" on the AP Physics 1 Exam.

Graphing and Units. During the course of the year, the instructor continually emphasizes the importance of graph analysis and unit analysis. Students should be able to identify the model by recognizing a graphical relationship from the graphical properties of slope or area under the curve. For example, if a student sees a force vs. displacement graph, they should immediately identify and employ the model of energy. The reason for this is that the units of the area under the curve of this graph are N*m, which are equivalent to the units of Joules (work). Similarly, a force vs. time graph should indicate the need to utilize the momentum model as the units of the area under the curve are N*s (impulse). The slope of the position vs. time graph has units of m/s, which are units of velocity. This hints at using kinematics. In addition to system properties and clue words learned in the "story of physics" part of the pedagogical method, students should also learn to utilize units and graphs to identify the appropriate model to employ.

Furthermore, recognizing units in the problem task prompt or in the possible multiple-choice answers can also clue students to model identification. For example, if the units of the answer choices were in Joules, it should be a pretty good clue to employ the energy model.

Model Identification Method. Putting these two components together, students were better equipped to identify the appropriate model to employ on the AP Physics 1 Exam. The problem-solvers learned and followed the set of steps and clues proposed by this research and described in the two previous sections. The method is based on Pawl et al. (2009)'s models, Etkina et al. (2006)'s *Classifying Models* method, and Larkin, McDermott, Simon & Simon (1980b)'s *Knowledge of Physics and Algebra Strategy*

The following description follows the "story of physics," which the instructor repeated periodically and continually over the course of the academic year. It also utilizes the graphical and unit analysis outline in the previous section. By the time students take the AP Physics 1 Exam, they should be able to identify the appropriate model using clue words, certain given system properties, graph axis labels, graphical properties of slope and area under the curve, and/or processes within the given system or systems.

The main models include: kinematics, dynamics, energy, momentum, simple harmonic motion, centripetal motion, and rotational motion. The first bullet point of each model provides the aspects of that model that the instructor taught the students to recognize. For example, if a student encountered a problem which necessitated a description of motion where the time interval over which the motion occurred was essential, then the student should choose **Kinematics**. The second bullet point gives a little bit more in depth reasoning behind each model's framing. The AP Physics 1 exam also includes basic circuits and electrostatics, but the instructor did not include circuits or electrostatics on the formative assessments because problems needing circuit analysis should be obvious. Electric circuits AP Physics 1 Exam problems rarely, if ever, contain aspects of mechanics.

- **Kinematics:**
  - Describes a single object's or single system's motion under constant forces and at constant acceleration and utilizes time to do so, includes projectile motion
    - Graphs: x vs. t, v vs. t, and a vs. t
  - This is the first model students learn, and it is usually the one students turn to first. However, energy is a much more effective model to describe the motion

because it covers a wider range of systems including those not under a constant force. However if time must be involved, then energy cannot help you. The energy model contains no time variables.

- **Dynamics**:
  - Use this anytime you are using free-body diagrams and/or Newton's Laws (especially Newton's 2nd Law – $F_{net} = ma$)
  - Dynamics may be a precursor to using other models – need to do a force analysis in order to determine work or impulse, for example. Nonetheless, it is useful to first identify the model of Dynamics before use because it brings to mind the universal truth of Newton's 3rd Law and how to solve for a system's acceleration or for internal forces (such as tension in an Atwood's Machine).
- **Centripetal Motion** (note that this is usually called *circular motion*, but I use centripetal motion to differentiate it from rotational motion – I found that calling this unit circular motion unneccessarily confused students once we got to rotational)
  - Constant speed circular motion where the net force is ALWAYS perpendicular to the motion vector and points into the circular path
  - Centripetal motion is different from other periodic motions such as SHM or rotational motion which have different directions for the force, and you can remember this one because of the etymology of centripetal – center seeking. It is also important to remember that the object's motion must be at a constant speed (recall the constant speed term in the equation) and it is the direction of motion that is changing at a constant rate. Also remember that the object does not have

to go through an entire circular path in order to allow centripetal motion analysis.

- **Energy:**
    - Describes an object's or a system's motion
        - Graph: *F* vs. *Δx*
    - The system does not need to be under constant forces, but it helps. If friction is present, the force of friction must be constant. Energy does not care about time, and only concerns initial and final states. If you have the choice between kinematics and energy, use energy. Remember that the energy model can usually only deal with one object or system having the energy at any one time. It has a really hard time dealing with multiple objects simultaneously.
    - Use the work-energy principle!

$$W_{tot} = \Delta E_{tot} = 0 = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_0^2 + mgy_f - mgy_0 + \frac{1}{2}kx_f^2 - \frac{1}{2}kx_o^2 + F_f*\Delta x$$

- **Momentum:**
    - Describes collisions and splits
        - Graph: *F* vs. *t*
    - Concerns more than one object having energy at a single time. The magnitude of mechanical energy conservation during a collision depends on the type of collision.
    - Special elastic collision equation: $v_{20} - v_{10} = v_{1f} - v_{2f}$
    - Remember that it is the center of mass (not necessarily individual objects in a system) which conserves momentum unless acted upon by an external unbalanced force over some time interval

- **Simple Harmonic Motion:**
  - Periodic or repeating motion which can be described by a sine or cosine graph where the force is always in the opposite direction from displacement relative to rest
    - Graph: a sine or cosine x vs. t
  - Can usually use energy to describe SHM, but might have to use the special position as a function of time and frequency equation
  - Recall how to use SHM to describe mechanical waves like sound (resonating tubes and strings) and the associated harmonics. Know the period dependencies of SHO's and pendulums.
- **Rotational Motion:**
  - Motion about a pivot point, not necessarily repeating and not necessarily at constant velocity, where any effective forces are parallel to the motion vector. The properties of torque, rotational kinetic energy, angular momentum, and the momentum of inertia require and identified pivot point.
  - Remember that rotational motion is nothing new. It is the whole year of physics but in a circle.
  - Know the difference between centripetal motion and rotational motion.

The One Page Model Identification Sheet

What type of graph is it?
Which model's units are used in the answer choices and in the prompt?

1. **Kinematics:**
   a. Describes a single object's or single system's motion under constant forces and at constant acceleration and utilizes time to do so, includes projectile motion
   b. Graphs: x vs. t, v vs. t, and a vs. t

2. **Dynamics**:
   a. Use this anytime you are using free-body diagrams and/or Newton's Laws (especially Newton's 2nd Law – $F_{net} = ma$)

3. **Centripetal Motion**:
   a. Constant speed circular motion where the net force is ALWAYS perpendicular to the motion vector and points into the circular path

4. **Energy:**
   a. Describes an object's or a system's motion
   b. Graph: F vs. Δx

5. **Momentum:**
   a. Describes collisions and splits
   b. Graph: F vs. t

6. **Simple Harmonic Motion:**
   a. Periodic or repeating motion which can be described by a sine or cosine graph where the force is always in the opposite direction from displacement relative to rest
   b. Graph: a sine or cosine x vs. t

7. **Rotational Motion:**
   a. Motion about a pivot point, not necessarily repeating and not necessarily at constant velocity, where any effective forces are parallel to the motion vector. The properties of torque, rotational kinetic energy, angular momentum, and the momentum of inertia require an identified pivot point.

Appendix C

The Formative Assessment Tools and Data

The formative assessment tools can be found beginning on the next page. They can also be accessed in addition to keys to the formative assessment tools and the student data at the following link. Note that only formative assessments 1, 2, and 3 were used during the experimental academic year 2016 – 2017. I ran out of time to use formative assessment 4 for the research.

www.tinyurl.com/unispangfas

Put an "X" on this line if you are NOT involved in the research: ______ Name:___________________________

AP Practice Exam Formative Assessment 1

Models to choose from:

- Kinematics
- Dynamics
- Centripetal Motion
- Energy

Before attempting to solve the problem, please respond to the prompts below the question.

______ 1. A spring-loaded dart gun shoots straight up launching a dart to a maximum height of 24 m. The same dart is shot straight up again, but this time the spring is compressed only half as far before firing. What maximum height does the dart achieve the second time?

A) 48 m B) 24 m C) 12 m D) 6 m E) 3m

1.A. Which model applies? ____

1.B. Explain your reasoning for choosing this model:

1.C. Now that you have identified an appropriate model, write out which equation(s) from the green sheet you will use to solve the problem.

****

______ 2. A diver initially moving horizontally with speed v dives off the edge of a vertical cliff and lands in the water a distance *d* from the base of the cliff. How far from the base of the cliff would the diver have landed if the diver initially had been moving horizontally with speed 2v?

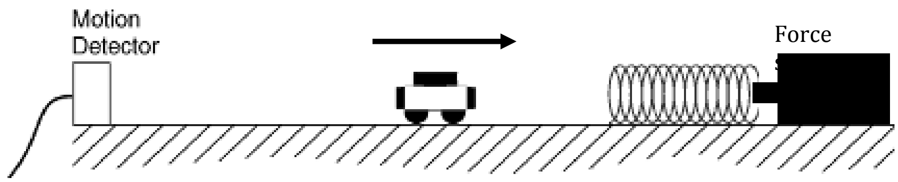
A) $\frac{1}{2}d$ B) d C) $\sqrt{2d}$ D) *2d* E) *4d*

2.A. Which model applies? ____

2.B. Explain your reasoning for choosing this model:

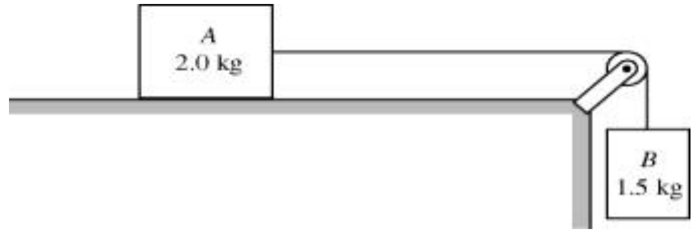
2.C. Now that you have identified an appropriate model, write out which equation(s) from the green sheet you will use to solve the problem.

3. Consider the system depicted to the right. A cart of known mass *m* is traveling to the right with a known velocity *v*. The cart strikes a spring and rebounds in the opposite direction at a different speed. You have set-up a motion detector which will plot acceleration vs. time, velocity vs. time, and position vs. time graphs. A force sensor is connected to the spring which will plot a force vs. time graph. Your computer program will take both measurements together and plot a force vs. position graph. Which of these graphs, if any, can be used to measure or predict the value of the cart's final velocity? Neglect friction.



If the graph can be used to determine the final velocity, fill out the rest of the chart. If it cannot, leave it blank.

Graph	Model used (kinematics, energy, etc)	Property of graph used (slope, area, etc)	Brief explanation of process used to measure or calculate final velocity
Acceleration vs. time			
Velocity vs. time			
Position vs. time			
Force vs. time			
Force vs. position			



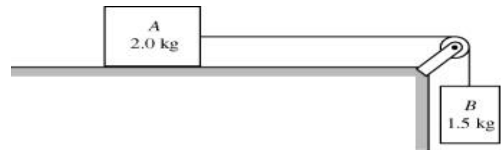
4. Block *A* of mass 2.0 kg and Block B of mass 1.5 kg are connected by a massless rope which is strung over a massless/frictionless pulley. The coefficient of kinetic friction between Block A and the surface is 0.25, and the system is released from rest.

A) In the space to the right, draw free – body diagrams for Block A and Block B as the system is in motion.

B) If you were asked to calculate the tension in the rope as the system moves, which model would you use? Briefly explain why that model applies. Calculate the tension in the rope.

C) If you were asked to calculate the distance Block A moves in 0.4 seconds, which model would you use? Briefly explain why that model applies. Calculate the distance.

D) If you were asked to calculate the velocity of Block A when it has moved 0.75 m, which model would you use? Briefly explain why that model applies. Calculate the velocity.



E) Calculate the velocity from part (D) again using a different model. Which model did you use this time?

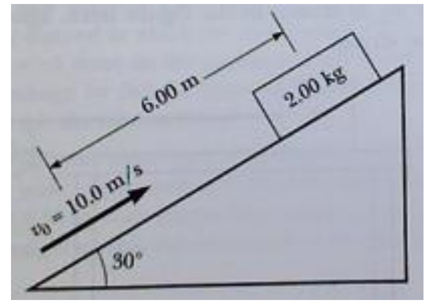
F) If friction were NOT present in this system, what would Block A's velocity be after it has moved 0.75 m? Which of the two models (your choice from D or your choice from E) did you use to answer this? Explain why you chose to use that model over the other one.

Put an "X" on this line if you are NOT involved in the research: ______ Name:____________________________

AP Practice Exam Formative Assessment 2

Models to choose from:

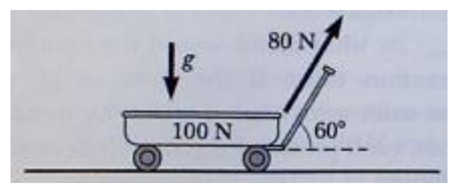
- Kinematics
- Dynamics
- Centripetal Motion
- Energy
- Simple Harmonic Motion/Sound
- Momentum



______ 1. A block with an initial velocity of 10.0 m/s is projected up a rough 30.0° inclined plane. After the block has moved 6.00 m along the incline, its velocity is 5.00 m/s. What is the coefficient of friction between the block and the ramp?

Model and brief explanation:

B) 0.12 B) 0.16 C) 0.74 D) 0.95 E) 1.56



______ 2. What is the magnitude of the frictional coefficient between the ground and a 100 N wagon if the wagon accelerates at 2.2 m/s/s by pulling on its handle with 80.0 N of force at an angle of 60.0° above horizontal as shown?

Model and brief explanation:

A) 0.2 B) 0.4 C) 0.6 D) 0.7 E) 0.8

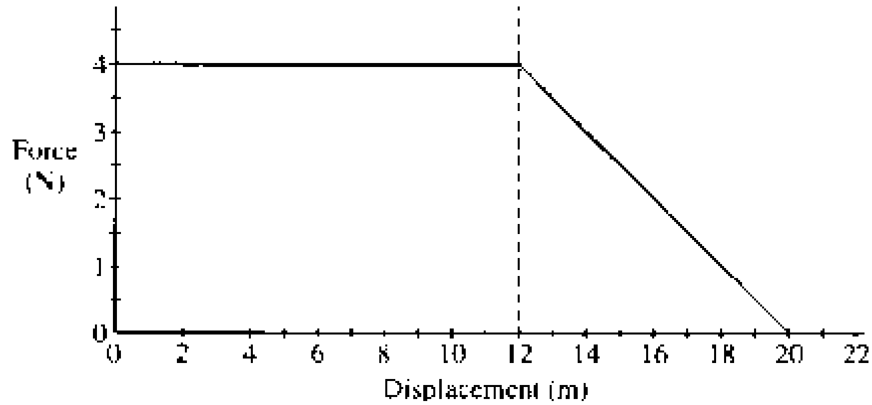
The dot to the right represents the wagon. Draw a free-body diagram showing the forces (not components) exerted on the wagon.

3. You place a penny on a turntable. If the coefficient of friction between the turntable and the penny is 0.1, how far from the center of the turntable can the penny be without slipping off if the turntable rotates at 33.3 rpm (rotations per minute)? First, derive an expression for this distance. Then solve the problem.

Model and explanation:

4. A ball is dropped from a height *h* onto the floor and keeps bouncing. Consider this situation to be ideal and assume no energy is lost or dissipated such that the ball regains height h after each bounce. Sketch graphs of (A) y vs. t,
(B) gravitational potential energy, kinetic energy, and mechanical energy vs. time (put all three on same graph, indicate which is which), and (C) force vs. y. (D) Is this situation considered simple harmonic motion? Explain your response and support it with specific reference to sections of your graphs.

5.



A 0.20 kg box is on a frictionless horizontal table. A force acting on the object varies with the object's displacement as shown in the graph. The object starts from rest at displacement x = 0 and time t = 0 and is displaced a distance of 20 m. Calculate each of the following.

Model and brief reasoning

a. The acceleration of the object when its displacement x = 6 m.

b. The amount of work done by the force in displacing the object the first 12 m.

c. The Kinetic Energy of the object when the object is at displacement x = 12 m.

d. The speed of the object at displacement x = 12 m.

e. The final speed of the object at displacement x = 20 m.

f. At x = 20 m, the object elastically hits another box of mass 0.3 kg which was initially at rest. Calculate the final velocity for both objects. Assume the force disappears during and after this event. Write your answer on the back of this page.

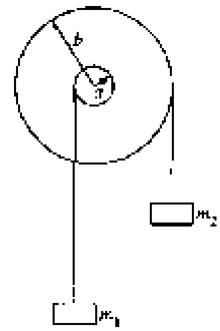
Put an "X" on this line if you are NOT involved in the research: ______ Name:____________________________

AP Practice Exam Formative Assessment 3

Models to choose from:

- Kinematics
- Dynamics
- Centripetal Motion
- Energy
- Simple Harmonic Motion/Sound
- Rotational Motion
- Electrostatics
- Electric Circuits

______ 1. Consider the wheel-and-axle system shown at right. Two masses are hung from massless strings, one attached to the wheel and one attached to the axle. Which of the following expresses the condition required for the system to be in static equilibrium?

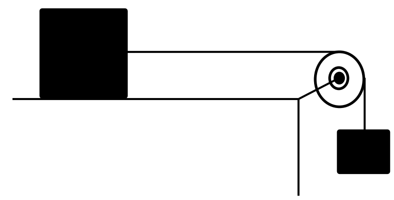


Model and explanation:

A) $m_1 = m_2$ B) $am_1 = bm_2$ C) $am_2 = bm_1$

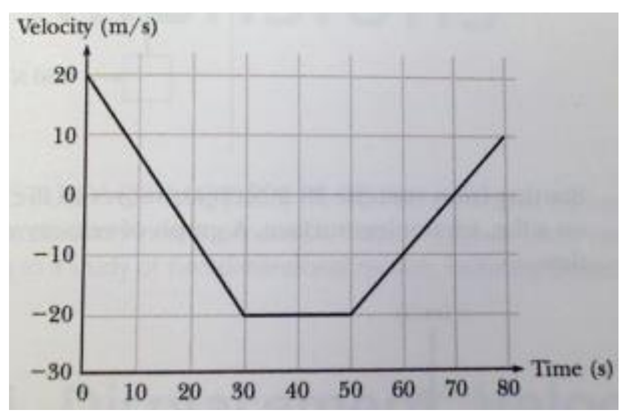
D) $a^2m_1 = b^2m_2$ E) $a^2m_2 = b^2m_1$

______ 2. A student proposes a method to determine the frictional coefficient acting on an accelerating mass by setting up the experiment shown to the right and performing a Newton's 2nd Law experiment. Assume the big block does not fall off the table and the small block does not hit the ground. The experimental data the student will need to take in order to calculate the coefficient of friction between the big block and the surface include….



Model and explanation:

A) The mass of both objects, the distance the small block falls, and the time the small block falls for
B) The mass of both objects and the distance the big block moves along the table top.
C) The mass of the small block, the distance the small block falls, and the time the small block falls for
D) The mass of the big block, the distance the small block falls, and the time the small block falls for
E) None of these will yield the coefficient of friction



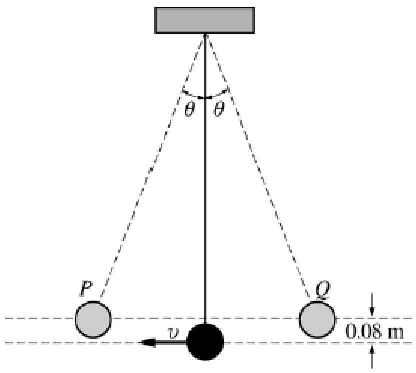
______ 3. Consider the graph seen to the right. What would the car's position be at t = 80.0 s if it started at position x_0 = -10.0 m at t = 0 s?

Model and explanation:

A) -560 m B) -550 m C) 960 m D) 950 m E) None of these

Describe the motion of the car in the trip shown.

4. A simple pendulum consists of a bob of mass $m_1 = 0.085$ kg attached to a string of length 1.5 m. The pendulum is raised to point *Q*, which is 0.08 m above its lowest position, and released so that it oscillates with small amplitude θ between the points *P* and *Q* as shown below. Neglect friction and air resistance.



Note: Figure not drawn to scale.

Free-Body Diagram at Point P	Free-Body Diagram at Lowest Position (darkened in picture)

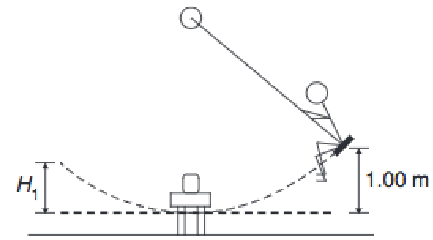
A) To the right of the figure above, draw free-body diagrams for the bob when it is at point P and when it is in motion at its lowest position. Do not include component breakdowns → Model: _______________________

B) What is the frequency of this pendulum? Model: ___________________ Evidence: ________________________

C) Describe one modification that could be made to double the period of oscillation. Indicate what quantity would have to be changed and by what factor would it have to be changed. Support your answer algebraically.

D) Consider a second mass $m_2 = 0.05$ kg which is placed at rest at the location of the lowest vertical position of the first mass (blackened in the picture). If the first mass were to collide elastically with the second, calculate the post-collision velocity of each mass. Model:__________________________ Evidence: __________________________

5. A student of mass 50.0 kg swings on a playground swing which is very light compared to the student. A friend releases the seat of the swing from rest at a height of 1.00 m above the lowest point in the motion. The student swings down, and at the lowest point of the motion, grabs a jug of water of mass 4.00 kg. The jug is initially at rest on a small table right next to the swing, so it does not move vertically at the student grabs it. The student keeps swinging forward while holding the jug, and the seat reaches a maximum height H_1 above the lowest point. Neglect air resistance and friction.

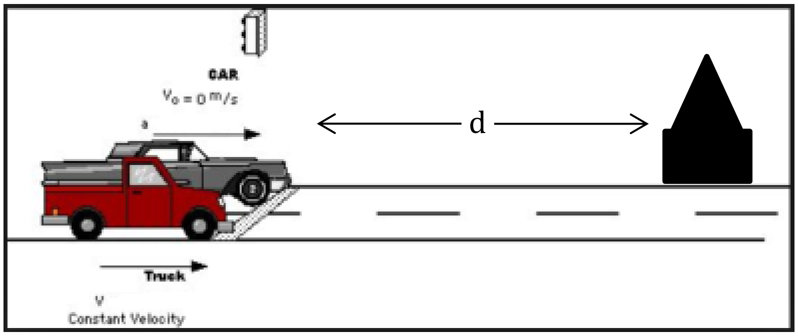


Note: Figure not drawn to scale.

D) Indicate whether H_1 (circle one) greater than, less than, or equal to 1.00 m. Using physics concepts, justify your answer qualitatively with NO equations or calculations. Which model(s) did you use to answer this? Why did those models apply?

E) Calculate H_1. Show as much work as possible. What model(s) will you use to solve this problem?

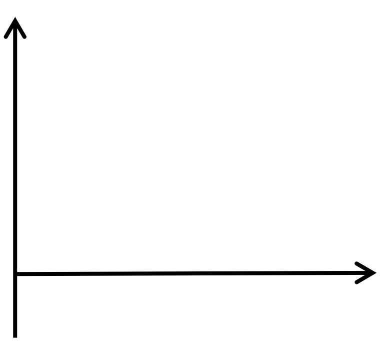
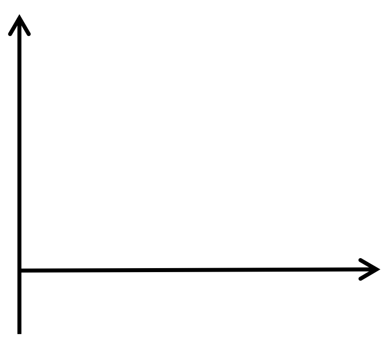
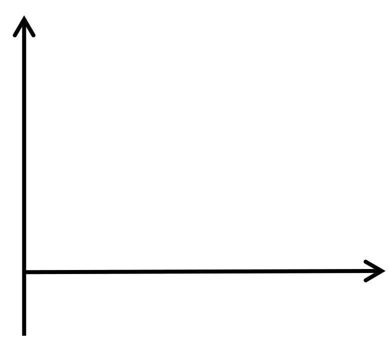
F) The student is now swinging back towards the starting point. At the lowest point in the motion, the student drops the water jug. Indicate whether the height the student achieves on the starting side will (circle one): be greater than, less than, or equal to H_1. Using physics concepts, justify you answer. You may use equations in your response. Which models did you use to answer this? Why did those models apply?



6. A car is stopped at a traffic light (v_0 = 0 m/s) at position x_0 = 0 m. The light turns green at t = 0 s and the car begins to move with a constant acceleration *a*. Also at t = 0 s, a truck with a constant velocity *v* passes x_0 and passes the car. Both the truck and the car pass the house at position *x = d* at the same time.

   A. On the axes below, sketch the graphs of position vs. time, velocity vs. time, and acceleration vs. time for both the truck and the car. Put both vehicles on the same graph and make sure to label which lines go with which. Label any important values.

Model: ______________________________________

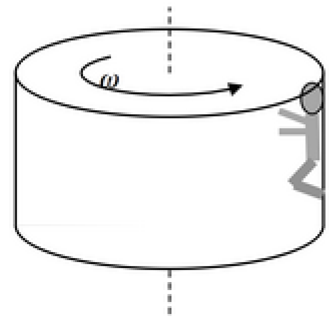
Put an "X" on this line if you are NOT involved in the research: _____ Name:___________________________________

AP Practice Exam Formative Assessment 4

Models to choose from:

- Kinematics
- Dynamics
- Centripetal Motion
- Energy
- Simple Harmonic Motion/Sound
- Momentum
- Rotational Motion
- Electrostatics
- Electric Circuits

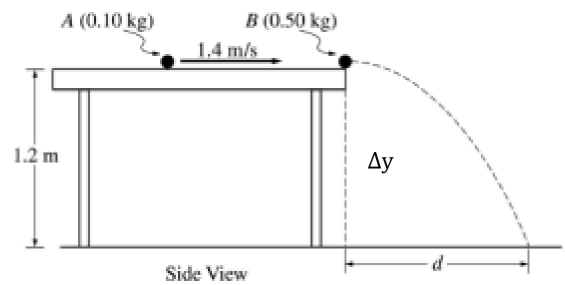
_____ 1. An amusement park ride consists of a large spinning cylinder of radius r with rough walls. At a given angular velocity ω the horizontal floor of the cylinder drops, but a rider of mass m remains safely pinned against the wall of the cylinder. What is the minimum coefficient of static friction μ necessary for the rider to keep from sliding down the wall?



Model and Evidence:

A) $\frac{rg}{\omega^2}$ B) $\frac{g}{r\omega^2}$ C) mg D) $\frac{mg}{r\omega^2}$ E) $\frac{rg}{mv^2}$

2. Ball A, m_A = 0.10 kg, is sliding at v_0 = 1.4 m/s on a horizontal tabletop of negligible friction as shown in the picture. It makes a head-on collision with Ball B, m_B = 0.50 kg, which is initially at rest at the edge of the table. As a result of the collision, Ball A rebounds sliding in the opposite direction at v_F = -0.70 m/s immediately after the collision. The entire tabletop is Δy = 1.2 m above the floor.



Side View
Before Collision

Note: Figures not drawn to scale.

A) Calculate the speed of Ball B immediately after the collision.

Model and Evidence:

B) Derive an expression for the horizontal distance d Ball B travels after the collision using m_A, m_B, v_0, v_F, Δy, and physical constants. Use your expression to determine d.

Model(s) and Evidence:

3. A bowling ball can be modeled as a sphere with I = $\frac{2}{5}mr^2$. The ball has a mass of 4.5 kg and a diameter of 10 cm. It is rolling along a flat surface with a linear velocity of 3 m/s without slipping. It encounters a ramp angled at 37° above the horizontal.

A) What length of the ramp will the ball roll before coming to a momentary stop?

Model and Evidence:

B) Calculate the linear acceleration of the bowling ball while it is on the ramp.

Model and Evidence:

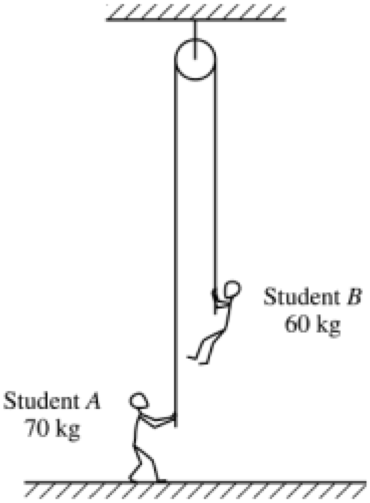
C) How many rotations (revolutions) will the ball go through while moving up the ramp?

Model and Evidence:

D) Assuming the angular acceleration of ball on the way up the ramp is equal angular acceleration of the ball on the way back down the ramp, determine the force of friction acting on the wheel as it rolls down the ramp.

Model and Evidence:

4. A rope of negligible mass passes over a pulley of negligible mass attached to the ceiling, as shown at right. One end of the rope is held by Student A of mass 70 kg, who is at rest on the floor. The opposite end of the rope is held by Student B of mass 60 kg, who is suspended at rest above the floor.



A) On the dots at right that represent the students, draw and label free-body diagrams showing the forces on Student A and on Student B.

• *B*

<u>Model and Evidence for A -> E:</u>

• *A*

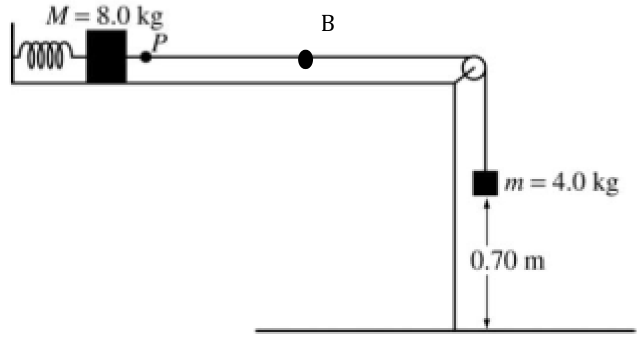
B) Calculate the magnitude of the force exerted by the floor on Student A.

C) Student B now climbs up the rope at a constant acceleration of 0.25 m/s^2 with respect to the floor. Calculate the tension in the rope while Student B is accelerating.

D) As Student B is accelerating, is Student A pulled upward off the floor? Justify your answer.

E) With what minimum acceleration must Student B climb up the rope to lift Student A upward off the floor?

5. An ideal spring of unstretched length 0.20 m is placed horizontally on a frictionless table as shown to the right. One end of the spring is fixed and the other is attached to a block of mass M = 8.0 kg. The 8.0 kg block is also attached to a rope that passes over a small frictionless pulley. A block of mass m = 4.0 kg hangs from the other end of the rope. When this spring-and-blocks system is in static equilibrium, the length of the spring is 0.25 m and the 4.0 kg block is 0.70 m above the floor.



$$v_{wave} = \sqrt{\frac{F_T}{m/l}}$$

A) Calculate the spring constant k of the spring.
Model and Evidence

B) The rope has a linear mass density of 1.0 x 10^{-4} kg/m. A person plucks the rope at point B like a guitar. Considering the equation stated under the diagram, where m/l is the linear mass density and F_T is the tension force, find the first and second harmonic frequencies of the oscillation of the rope if the distance between the block and the pulley is 1.5 m. How many anti-nodes would the second harmonic have?
Model and Evidence

C) The system is returned to rest, and the rope is cut at P. Calculate the oscillation frequency of the 8 kg block.
Model and Evidence

D) After rope is cut and the box-spring system is in oscillation, calculate the maximum speed and maximum acceleration attained by the 8.0 kg block. When in the motion of the block does each occur?
Model and Evidence