

THE IMPACTS OF LEARNING WITH MULTIPLE REPRESENTATIONS IN A
HIGH SCHOOL PHYSICS CLASSROOM

by

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ABSTRACT

Student learning in physics takes on many forms. Equations, diagrams, graphs and words all can be used to describe physical phenomena. Constructing descriptions of physical situations with these representations and focusing on their correct usage is a goal of all physics instruction. Teaching students the strengths of these representations in communicating conceptual ideas and guiding students in usefulness of representations in problem-solving will is how this goal can be accomplished. This study investigated whether learning physics with an emphasis on multiple representations had an effect on student conceptual understanding, student problem solving, and student attitude in a high school introductory physics classroom. Through instruction that emphasized student practice with the representations themselves, developing a problem-solving method that included multiple representations, and assessment of quality of representations, students learned a unit on unbalanced forces. Results and conclusions showed low increases in student conceptual understanding and problem-solving ability. Student attitude improved in regard to their view of its application in the real-world. This classroom research project showed that students should be well-versed in all representations in order to achieve high gains in learning and attitude.

INTRODUCTION AND BACKGROUND

This research was conducted at Greenville High Academy of Business, Finance, and Law. Greenville High is one of 18 public high schools in the School District of Greenville County and a magnet school for students who desire to focus on the subjects of Business, Finance, or Law while completing regular high school coursework. Our school is located in the downtown of Greenville, South Carolina, a thriving county of 498,000 with a growing population (“Quick Facts” n.d.). Greenville High enrolls 1,500 students and has been named to the list of America’s Most Challenging High Schools in recent years (“School Profile” n.d.). The school serves a population of students that live in the downtown Greenville area from both affluent and low-income families (J. Tuttle, personal communication, June 3, 2015).

Honors Physics at Greenville High is usually taken after all science course requirements for graduation have been fulfilled. Most students enrolled in the class are willing to take a challenging course to become more prepared for college and learn in a hands-on manner. Fifty-four students were enrolled in two honors physics classes and the students were a mix of 11th and 12th graders.

This classroom research project was started to explore the benefits of using multiple representations in my high school physics classroom. Representations are used by physicists to describe a physical situation. Often, more than one representation can be used to describe the same physical situation. When used together, and referring to the same physical situation, these representations are referred to as multiple representations. Examples of these representations are diagrams, graphs, equations and verbal

expressions. Like many other physics students, the high school students in my classroom see physics mainly in terms of abstract formulas and disconnected concepts. For a novice student who does not have experience with the way in which physics addresses many of the physical situations they come across in life, solving real life problems can be a daunting task. Students need to be given the chance to change their own thinking on the matter of physics concepts and the truths asserted by physics concepts. Students also require time and practice using the language of physics to become more adept physics thinkers and problem solvers. Many students struggle with taking a problem, recognizing key features from physics concepts that they know and understand, and then choosing a path for a solution. Traditional physics teaching methods work by demonstrating the necessary steps for problem solving to students first. Then students are exposed to new situations to test their understanding of the concepts and problem-solving ability. In my own experience, these traditional physics teaching methods also involve student frustration. The students struggle with learning how to apply problem solving steps to new situations and this is often a cause of frustration. Many students are often discouraged and feel they are not doing well in physics. Students need the thinking tools and the practice required to become competent in my physics classroom. My thinking was that the use of multiple representations could help in solving the problem.

Multiple representations and their use in the physics classroom exist to bridge the gap in understanding between a written representation of a physics problem and the quantitative calculations required in most physics problem solutions (Zou, 2001). By instructing students in my classroom to move from one type of representation to another,

students can learn how to represent a physical situation in concert with physics concepts through diagrammatic representations and their agreement with other types of representations (written sentence, graphical, pictorial, and mathematical). Thus, a bridge can be built through instruction and practice that allows students to develop mathematical solutions from problems that start in written and pictorial representation. This strategy of using multiple representations will also give the students a means to communicate with one another and their teacher, discuss and explain ideas to peers, and ask clear questions about the physics concepts represented in the representations.

Through this classroom research project, I hoped to equip students with the tools needed to help them think and apply their understanding of physics phenomena in the real world. A well-constructed diagram can speak volumes about a real-life physics situation. I also hoped to alleviate some of the student frustration with the difficulty of the course. The accomplishments of learning and problem solving in a physics course can be deeply satisfying. After all, I didn't first come to enjoy physics because it was difficult, but I loved it because I was able to progress and learn through the difficulty of it. I wanted my students to experience their own satisfaction instead of a frustration with our course.

I also started this classroom research project to benefit my colleagues. Physics teachers in my district, especially those who teach AP Physics courses, would benefit from seeing another teacher integrate a successful strategy for using multiple representations in the physics classroom. Using multiple representations in the physics classroom can address problems that are common across college and high school level introductory physics courses. Other physics teachers could use the representations in the

manner I use them in my classroom or simply as another instructional tool within their own teaching methods. Multiple representations can be flexible when used in instruction and are able to be integrated into any physics pedagogy.

My own perception of the needs of my students led me to the formation of my focus statement, what are the impacts of learning with multiple representations in a physics unit in a high school classroom? With this, the following sub-questions were addressed, 1) What are the impacts of learning with multiple representations on student conceptual understanding? 2) What are the impacts of learning with multiple representations on student ability in problem solving? and 3) What are the impacts of learning with multiple representations on student attitude in physics class?

CONCEPTUAL FRAMEWORK

Interactive Engagement teaching methods (IE) are teaching methods used by an instructor that allow for students to spend time in class actively working on problems, rather than passively listening to lectures (Meltzer & Thornton, 2012). IE teaching methods are based on research regarding the best practices in the teaching and learning of physics. These teaching methods have also been tested in classroom settings and have been shown to yield evidence of improvement in student learning. IE teaching methods incorporate classroom activities that require students to express their thinking to one another in groups or pairs. With IE teaching methods, students also must communicate with the instructor beyond listening and copying notes. Courses where instructors use a majority of methods that require students to be “heads- on”, through guided learning and

inquiry, and “hands-on”, with labs and activities, fall into the category of IE methods (Hake, 1998).

Some components of IE teaching methods are: group work, model-building, peer discussion, and multiple representations. Group work in the context of IE teaching methods allows students to learn from peers and support one another to solve problems they would not be able to solve on their own. Having students work with one another to solve problems, design labs, or accomplish lab-based tasks provides this support. Students often accomplish more together than on their own. When learning physics, situations are simplified and assumptions are made involving important physical features of the real-world. Model-building allows students to be involved in making the assumptions required to solve physics problems and practice sense-making as real-world topics in the course are studied. Peer-discussion allows students to verbalize their thinking to one another and challenges higher-achieving students to explain their ideas while supporting lower achievers by giving more examples of how problems can be solved. Multiple representations and their use in the classroom provide a language for physics in words, pictures, diagrams, graphs and equations. A focus on the interpretation and usage of each of these in problem solving is another practice that is considered to be a part of IE teaching methods.

Multiple representations can be described as student use of different representations such as words, pictures, diagrams, graphs, and equations to represent a physical situation or problem (Meltzer & Thornton, 2012). This allows students to

understand physics concepts more deeply and in a less context-dependent way and can also support students in becoming expert problem solvers.

The use of multiple representations has been suggested for both college-level and high school level physics classes. In an AP Physics workshop special publication, the authors outlined the usage of multiple representations of knowledge in an introductory algebra-based physics course. Included were uses of multiple representations in units on motion, forces, energy, and momentum. Advice commonly given for using the representations in each unit was that students would be trained to use the representations correctly, required to translate from one representation to another, and that the usefulness of the representations in problem solving would be demonstrated to students. Using formative assessment that included multiple representations was also recommended. The use of the strategies in the classroom resulted in growth in student understanding of physics concepts, increased ability in physics problem solving, and correct use of multiple representations in physics problem solving (Etkina, Rosengrant, & Van Heuvelen, 2008).

Many students who take introductory physics courses leave the class not having accomplished the conceptual learning objectives set by their instructors (Hake, 1998). To correct this, there is a call on teachers to match the learning needs of their students. One way to meet these learning needs is to support student thinking in multiple representations. To adequately support students, teachers should first demonstrate a process of constructing multiple representations for a physical situation. Then teachers should show the physics concepts found in the representations. After this, teachers need

to demonstrate the correct method of constructing a mathematical representation along with the help of the visual representations. Finally, demonstrate how to solve a problem quantitatively if required (Van Heuvelen, 1991). After a teacher has demonstrated this process, students practice with the process of constructing the multiple representations and solving problems. To successfully meet the learning needs of students, a change in instructional practice must occur. Students need to become active participants in the construction of concepts and the use of multiple representations (Van Heuvelen, 1991). When implementing multiple representations in the classroom, a teacher should not only show students the multiple representations, but train and guide students in their use in the context of physics concepts and physics problems.

One way to train a student to become a better problem solver is to train them in the thinking and skills of an expert. Students who are experts were found to have more knowledge and a more efficient means of indexing knowledge than novice problem solvers (Larkin, Mcdermott, Simon, & Simon, 1980). The physics knowledge of experts also contained pieces of information that guided the interpretation of a problem and guided the process of finding a solution. These pieces of information often take on the form of a diagram, graph, equation or a combination of these representations. A possible solution to the problem of novice thinking in physics could be that if students are trained in the different types of multiple representations, trained in the analysis of physics situations, and trained in the use of problem solving techniques used by experts; then students would be more equipped to solve complex physics problems and relate them to real world phenomena.

A picture is said to be worth a thousand words. When using multiple representations in physics instruction, this is only partly true. When performing a comparison study between putting problems in sentences and putting problems in visual representations, it was found that the advantages of the diagrams are computational. This means the diagrams did not necessarily contain more information than sentences, but that they made the information available to the problem solver more readily useful and available for computation and analysis. Although a diagram offered an advantage in this manner, students still needed to be taught the rules for using the diagram, the processes of thinking and the processes of problem solving to take advantage of the information provided. Also, a student needed to be taught what comprises a "good" diagram in order to use it effectively (Larken & Simon, 1987).

A specific example of one of the multiple representations found in a unit on kinematics in introductory physics is stacks of kinematics graphs. Stacks of these graphs contain a simple labeled vertical position axis and a horizontal time axis with position on the top of the stack. Below the position versus time graph are velocity and acceleration graphical representations of motion, along with a diagrammatic representation of the objects motion (Figure 1).

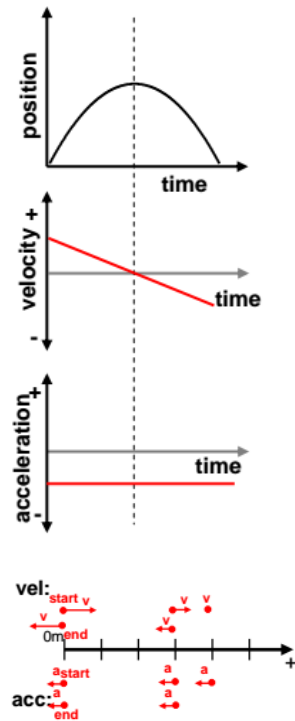


Figure 1. Stacks of Kinematics graphs and motion map.

In a unit on kinematics, students need to deal with graphs of position, velocity and acceleration over time and subsequent algebraic and diagrammatic representations of the motion (Beichner, 1994). It has been found that many students struggle with particular aspects of graphical representations of motion and that it should not be assumed by the instructor that students can use graphs fluently. Students need to be carefully instructed in gaining important and relevant information from the representations to be able to use them correctly. Students should be required to go back and forth between representations of motion graphically and diagrammatically. This means if a problem involves motion, students should be able to construct a diagram of the object's motion, such as a motion map, and construct matching graphs of the same motion for the position, velocity, and acceleration of the object over time. Also, students should be provided with one of the representations of an object's motion, such as the

velocity versus time graph, and then be required to construct a diagram that represents the motion of the object, or vice versa. It was apparent from this study that traditional lecture-based physics instruction did not work well with this teaching methodology. Students should be asked to predict, draw, and then test predictions of graphical values of motion for a conceptual change to take place.

For many years, the Force Concept Inventory (FCI), written by a team of teachers led by David Hestenes, has been used as a pre-test and post-test of student understanding of the basic concepts of forces in mechanics (Hestenes, Wells, & Swackhamer, 1992). The FCI was developed and designed to be a test that forces students with wrong thinking to choose incorrect non-Newtonian ideas about force, and ideas incongruent with Newtonian thinking. The test can be used for targeting specific student misconceptions as well as a tool for evaluation of instruction (Hestenes, Wells, & Swackhamer, 1992). One way to use the FCI that has been popularized in the physics education research community is the Hake Gain (Hake, 1998). The simple average normalized gain was used by Hake to evaluate over six-thousand students and their respective physics education programs (Hake, 1998). The tool can be used to evaluate the effectiveness of interactive engagement teaching methods and has been used to do so in the past.

METHODOLOGY

The purpose of this classroom research project was to determine the effect of learning with multiple representations (MR) on student conceptual understanding, student problem-solving ability, and student attitude in a high school physics classroom. A total of fifty-four high school students, who made up two introductory algebra-based physics

courses participated in this classroom research project. The treatment for both classes began at the end of the first semester. At the beginning of the treatment unit, a graphic organizer was constructed to introduce the representations used in the unit. Direct instruction was given to help students construct this graphic organizer and the specific representations for the unit were named. The Overview of Representations Graphic Organizer was used for this introduction (Appendix A). The Overview of Representations Graphic Organizer was modified from a graphic organizer used in the Modeling Instruction Curriculum Materials. The Overview of Representations Graphic Organizer was used in the non-treatment unit of instruction prior to the treatment unit to introduce the representations used as well. This was done to familiarize students with the concepts related to learning with multiple representations. The non-treatment unit given immediately before the treatment unit and did not focus on student learning with multiple representations. This was done so a comparison could be made between units.

After the representations were presented, students worked together in groups for multiple days on problem sets, solving a mix of traditional physics problems and limitless physics problems from the Student Problem Set using the representations discussed at the beginning of the unit (Appendix B). During the treatment unit, students were required to convert between multiple representations, show at least four diagrams or graphs that represented the situation with all problem solving, and use these representations to complete limitless problems (Appendix B). The limitless problems contained in the problem sets were non-traditional physics problems where no specific variable or value was asked to be solved for. Students were instructed to represent the situation as fully as

possible with multiple representations, with at least four of them being diagrams or graphs, and to solve for as many unknowns as possible. Students were also asked to state which physics models applied to the problem situation and were also asked to solve for the same variables in multiple ways. During the treatment unit, students were also required to include at least four different diagram and graph representations on their quizzes and tests. These items were checked for correctness. These problem sets, quizzes and tests were taken from the Modeling Instruction Curriculum and adapted for my students. The section on limitless problems was taken from Physics Blog! (O'Shea, 2000). Students were also encouraged to use the representations in class labs and activities. Students were required to present multiple representations with every item on the Treatment Unit Quiz during the treatment unit (Appendix C).

To collect data on student conceptual understanding, the Force Concept Inventory (FCI) was given to the students before and after treatment (Appendix D). The first administration of the FCI occurred before the treatment and non-treatment units at the beginning of the school year. Each question on the FCI was multiple-choice with five options and none of the questions required any calculations. The topics assessed on the FCI were common to the forces and motion topics covered in an introductory physics course. The results of the FCI were analyzed for normalized gain, presented in a box and whisker plot and compared to research that studied student performance on the FCI in other high school and college introductory physics courses (Hake, 1998).

Data collected on student problem solving ability was done through the Traditional Problem-Solving Test (Appendix E). The first administration of the

Traditional Problem-Solving Test occurred before the treatment and non-treatment units at the beginning of the school year. The results of the Traditional Problem-Solving Test were analyzed for normalized gain, presented in a box and whisker plot and scores were compared pre- and post- treatment unit. Also, a comparison between quizzes taken pre- and post- treatment unit and a comparison between tests taken pre- and post- treatment unit was used to measure student problem solving ability (Appendix C). The quizzes and tests from the non-treatment unit were taken from a similar unit on forces where no focus on learning with multiple representations was applied. The results of student performance on unit quizzes and tests were presented in a box and whisker plot and scores were compared pre- and post- treatment unit. A comparison was also made through analyzing test and quiz scores from the unit and comparing these scores to the scores on the previous non-treatment unit through the Wilcoxon signed rank test. Another quantitative analysis of student quizzes was performed through observing the students' use of diagrams in their multiple representations and evaluating their use of diagrams as 3 - correct, 2 - needs improvement, 1 - inadequate, and 0 - no representation. The evaluation was given for the student use of diagrams on the entire quiz. The rubric used is shown in Table 1. This diagram evaluation data was put into bar graphs and non-treatment quiz diagram use was compared to treatment quiz diagram use. Graphs of diagram evaluation score versus quiz and test score were also made and a line was produced to examine any relationship between diagram evaluation and quiz or test score. To determine the strength of correlation among the data, Spearman's Correlation Coefficient was used.

Table 1
Rubric for Diagram Evaluation

3 - Correct	2 - Needs Improvement	1 - Inadequate	0 - No Representation
Diagram is specific in form. (lengths on force diagram, clear direction on motion map, clear direction on graphs, clearly labeled)	Diagram is not specific in form.	Diagram is not specific in form.	--
Diagram is suitable to situation. (diagram is used for solving problem)	Diagram is suitable to situation.	Diagram is not suitable to situation.	--
Diagram contains no mistakes.	Diagram contains no mistakes.	Diagram contains mistakes.	--

In order to understand student attitude, data was collected regarding student attitude towards the subject of physics, student motivation, student confidence, student attitude towards problem solving, and student attitude towards classroom methods used during instruction. This was done with the Physics Student Likert Survey, adapted from the University of Colorado at Boulder CLASS student survey (Adams, Dubson, Finkelstein, Perkins, Podolefsky, Wieman, 2006) (Appendix F). Statements were presented to the students in a Google Form and students selected how they felt about each statement with strongly disagree, disagree, neutral, agree, or strongly agree. The data was displayed in a bar chart, and a Chi-squared test of independence was used to determine if there were any differences in student responses pre- and post-treatment administration of the survey. Then, due to low student response among categories, the Fisher Exact Test was used to compare survey responses given before and after treatment to determine any statistically significant changes in student attitude during the treatment unit. Due to small

student responses, the responses in categories of strongly agree and agree were lumped together and the categories of strongly disagree and disagree were lumped together to obtain a more reliable statistical result.

One group interview from one section of honors physics was conducted post treatment and conversations were analyzed in order to see what impacts learning through multiple representations had on student attitude towards problem solving and conceptual understanding. Questions were given to groups of students from the class. During the class period when interviews were conducted, six students, chosen through a random number generator, were announced to participate in the interviews. Out of these six, students could volunteer to participate or not participate in the interview for any reason. All six students chose to participate. Questions during the Physics Student Interviews explored the student's problem-solving strategies as well as perception on the strengths and weaknesses of their abilities in physics (Appendix F). The data collection strategies are summarized in the Data Triangulation Matrix (Table 2). The research methodology for this classroom research project received an exemption by the Montana State University Institutional review board and compliance for working with human subjects was maintained.

Table 2
Data Triangulation Matrix

Focus Questions	Data Source 1	Data Source 2	Data Source 3
<i>Primary Question:</i> What are the impacts of learning with multiple representations in a physics unit in a high school classroom?	Force Concept Inventory	Traditional Problem-Solving Test, Student Quizzes, Unit Test	Student Interviews
<i>Secondary Question:</i> What are the impacts of learning with Multiple Representations on student conceptual understanding?	Force concept Inventory	Student Quizzes, Unit Test	Student Interviews
<i>Secondary Question:</i> What are the impacts of learning with multiple representations on student ability in problem solving?	Force Concept Inventory	Traditional Problem-Solving Test, Student Quizzes, Unit Test	Student Work
<i>Secondary Question:</i> What are the impacts of learning with multiple representations on student attitude in physics class?	Physics Student Likert Survey	Student Interview	--

DATA AND ANALYSIS

The FCI Pre- and Post-Tests assessed student conceptual understanding of the basic concepts of forces in mechanics. The results indicated the average percent increase from beginning of the school year to after treatment for conceptual understanding was 98% ($N=54$). The median score on the FCI increased from 20% to 37% and there was an increase in standard deviation of the scores (Figure 2). Normalized gains were calculated for the FCI. The average normalized gain for the FCI was 24%. This means the average student improvement was 24%, out of all possible improvement that could be made. When compared to the end of course Normalized Gain found in other similar introductory physics courses, the students gain is considered a low gain (Hake, 1998). Although when ranked against other classes, student learning was considered low, evidence of an improvement in conceptual understanding was found in student interviews with detailed correct conceptual ideas mentioned as a part of a student's explanation of the usefulness of diagram representation. One student mentioned about the usefulness of representation, "Using the position versus time graphs are easy. They help you know which way the direction of the object is going."

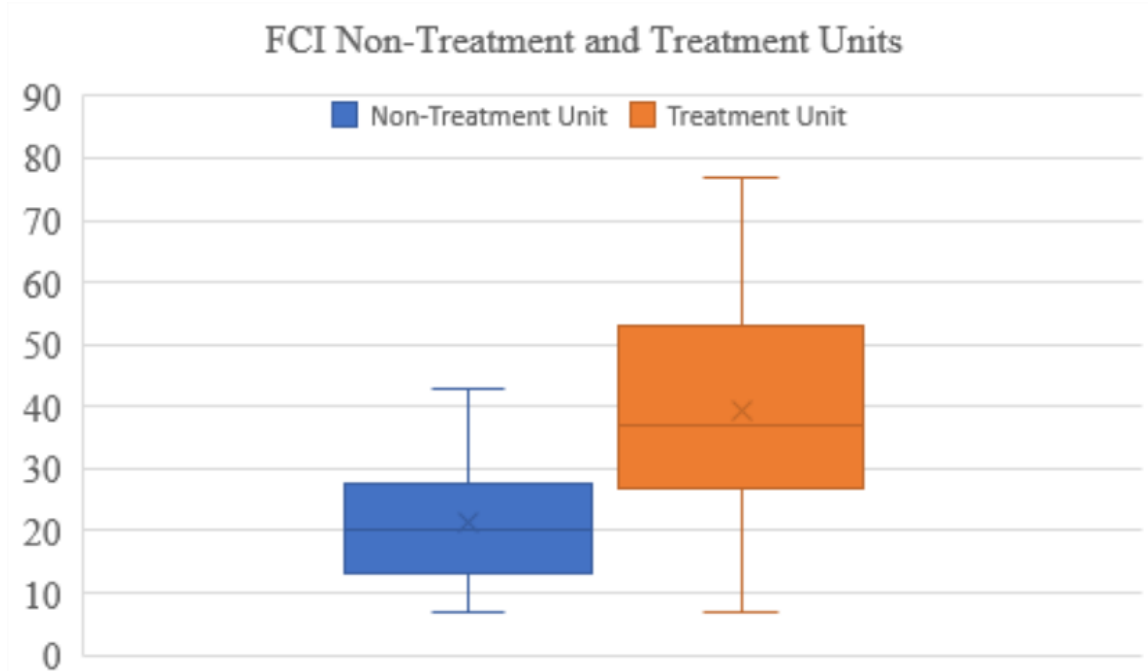


Figure 2. Box and whisker plot of student scores on FCI Pre- and Post- Test, ($N = 54$).

The Traditional Problem-Solving Test assessed student ability in problem solving through a variety of traditional multiple-choice physics problems. The results for this test indicated the average percent increase from beginning of the school year to after treatment for conceptual understanding was 55% ($N=54$). The median score on the FCI increased from 30% to 38.5%, and there was an increase in standard deviation of the scores. Normalized gains were calculated for the Traditional Problem-Solving Test. The average normalized gain for the Problem-Solving Test was 17%. This means the average student improvement was 17%, out of all possible improvement that could be made. This can be interpreted as low score increase (Figure 3).

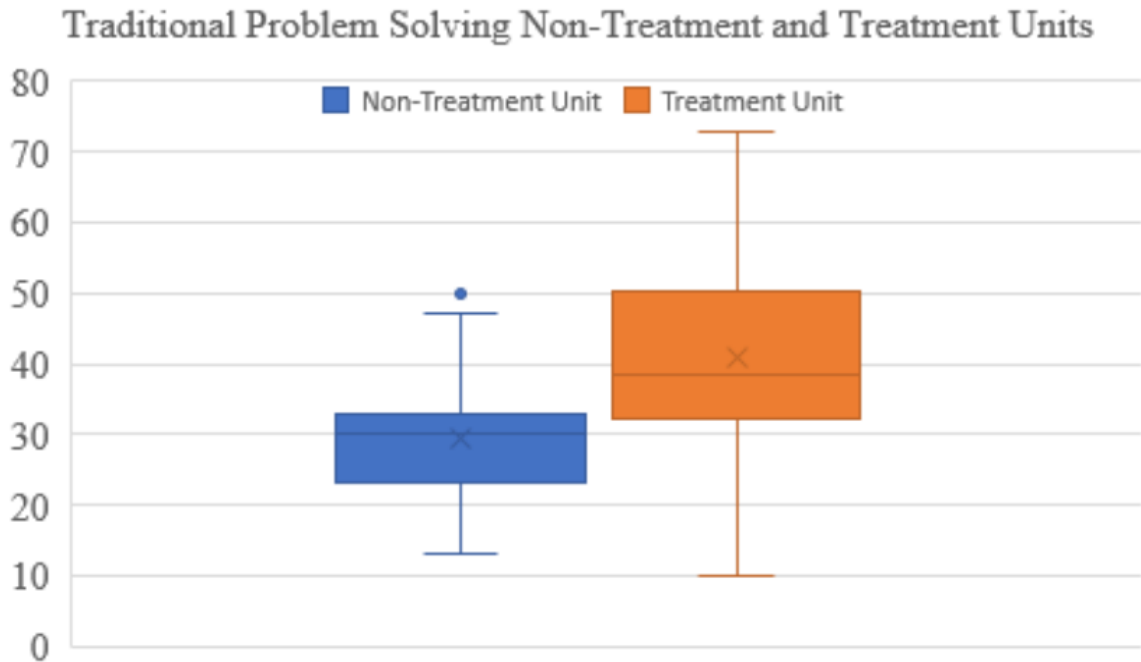


Figure 3. Box and whisker plot of student scores on Pre- and Post- Traditional Problem-Solving Test, ($N = 54$).

Changes in student ability to problem solve was also measured through end of unit tests. These assessments were given during the non-treatment and treatment units. When scores were analyzed, the average increase in test score from the pre-treatment unit to the treatment unit was 28% ($N=53$). The median score increased from 62% to 76%. Along with this increase in test score, the standard deviation was different between the non-treatment and treatment unit. The treatment unit test standard deviation was lower than the non-treatment unit. The two groups were determined to be different by the Wilcoxon Signed Rank Test (Figure 4).

When asked about how they go about solving a physics problem, students mentioned, “start with diagrams and move on to plugging in”, “I list the information that I have in the problem and then when I see what I have, I compare it to the equation. That’s how I solve it”, and “highlight key parts that will help me figure out what I need

so far”. All of these ideas are useful methods to go about correctly representing and solving a traditional physics problem.

It is also noted that both the FCI and the Traditional Problem-Solving Test were initially administered at the beginning of the year. In light of this, the treatment unit is likely not the only factor that caused a score increase on the assessments.

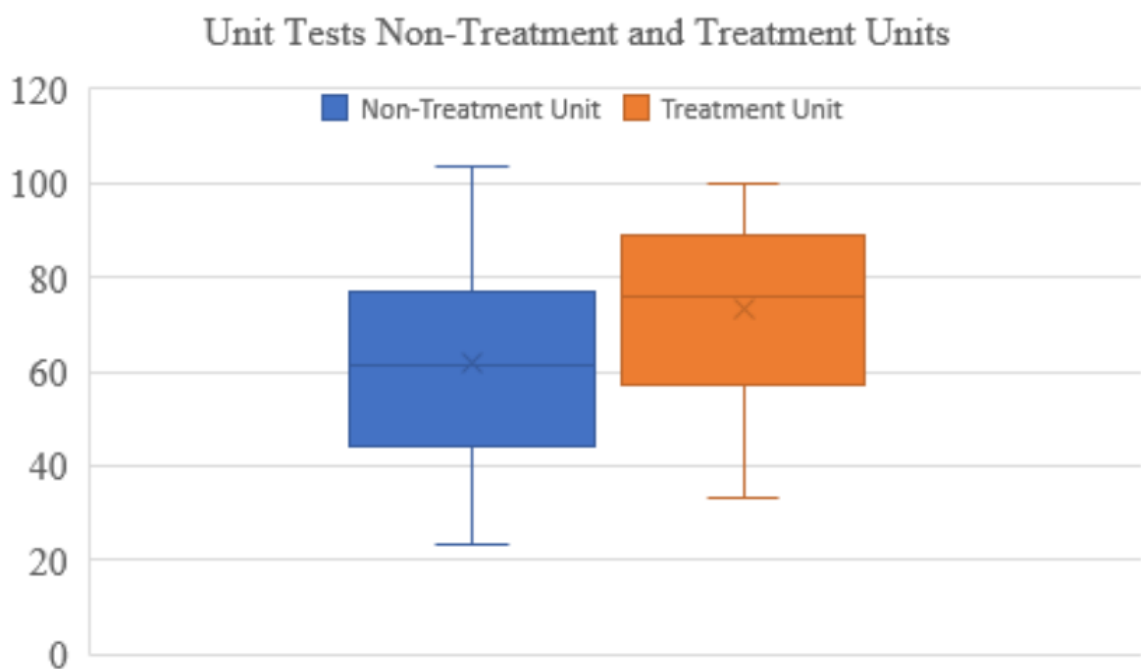


Figure 4. Box and whisker plot of student scores on Non-treatment and Treatment Unit Tests, ($N = 53$).

Students were given formative assessments in the form of quizzes during the non-treatment and treatment units of instruction. Student use of diagram and graphical representation were evaluated on a scale of 3 - correct, 2 - needs improvement, 1 - inadequate, and 0 - no representation. The Representation Evaluation Bar Chart shows a growth in student ability to represent problems in diagrams and graphs (Figure 5). From the data, there is a decrease in the evaluation of 2 – needs improvement, and a slight

growth in the evaluation of 3 – correct. It can also be seen that there is an increase in 1 –

Inadequate. Evidence from student interviews indicate that students are aware of the usefulness of diagrams and their need to construct them correctly to solve problems.

When asked about their use of diagrams in problem solving, one student responded, “they help, but sometimes if you did something wrong (in the diagram) the equation might be messed up and I sometimes get that happening.”

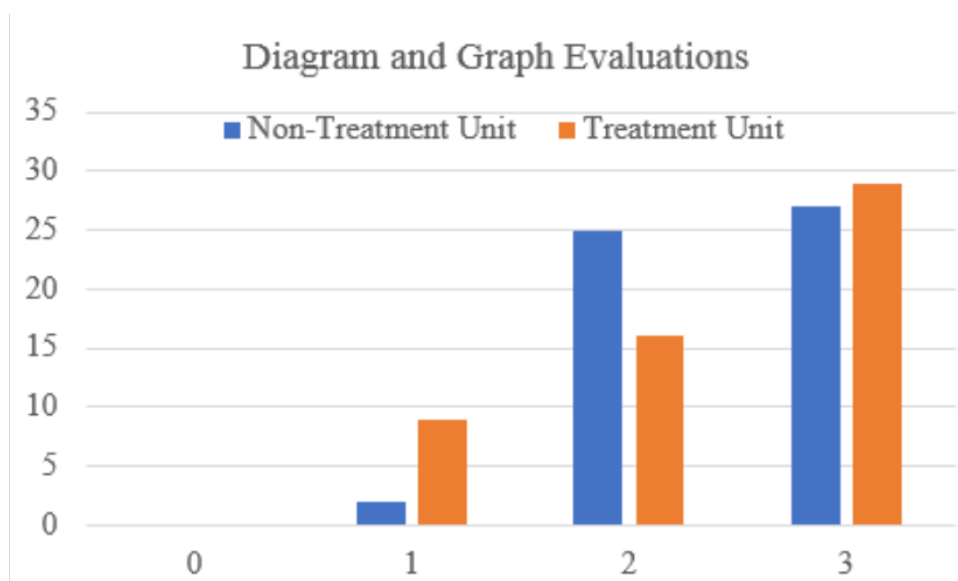


Figure 5. Bar Graphs of Representation Evaluation in non-treatment and treatment units of instruction, (N=54).

Evaluation of Student Representations was plotted with test and quiz scores to determine if there was any monotonic or, “constantly increasing” relationship between the two data sets. It was found that as the scores on Representation Evaluations increased, the scores on tests and quizzes also increased. In addition to this, the scores from the treatment unit seemed to have a greater per point increase in evaluation score (Figures 6 - 9.) The slope of each of the graph is meaningful when interpreted as, for every evaluation point improved, the test or quiz score increased by the slope amount. The use of these

plots and interpretation is supported through the calculation of the Spearman correlation. The result yielded for the treatment unit test versus evaluation of diagram was a +0.68. The result of the non-treatment unit test versus evaluation was much lower at +0.2. The result of the non-treatment unit quiz versus evaluation was +0.78. The result of the treatment unit quiz versus evaluation was +0.57. The values of the Spearman Correlation can range from -1 to +1 and since all the ranges are positive, we can say that there was at all times, an increase in test and quiz score with an increase in diagram evaluation score. Also, most of the Spearman Correlations were greater than 0.5, indicating that the relationship between the test and quiz score and the diagram evaluation is moderate to high. From non-treatment to treatment unit, student ability to solve problems increased more, if they improved in their ability to use representations effectively. Overall treatment unit evaluation scores were a better predictor of student understanding and test scores. This is shown in both the change of spread of student scores with the smaller standard deviation of the tests from non-treatment to treatment unit. Also, the dramatic increase in the value of the spearman coefficient from +0.2 to +0.68 demonstrated that the relationship between Representation Evaluation and problem-solving ability became more monotonic from the treatment to non-treatment units. This is not only an indication that the instrument use was more reliable, but the measures given by the instrument showed a better indication of correlation between diagram use and success or non-success in problem solving (Table 3).

Table 3
Spearman Coefficient and Slope Comparison Table

	Quiz		Test	
	Non-treatment unit	Treatment Unit	Non-treatment unit	Treatment unit
Spearman Correlation Coefficient	0.78	0.57	0.2	0.68
Slope (interpreted as assessment points gained for every one point of improvement on evaluation of representations)	8.4	18	8.7	17.5

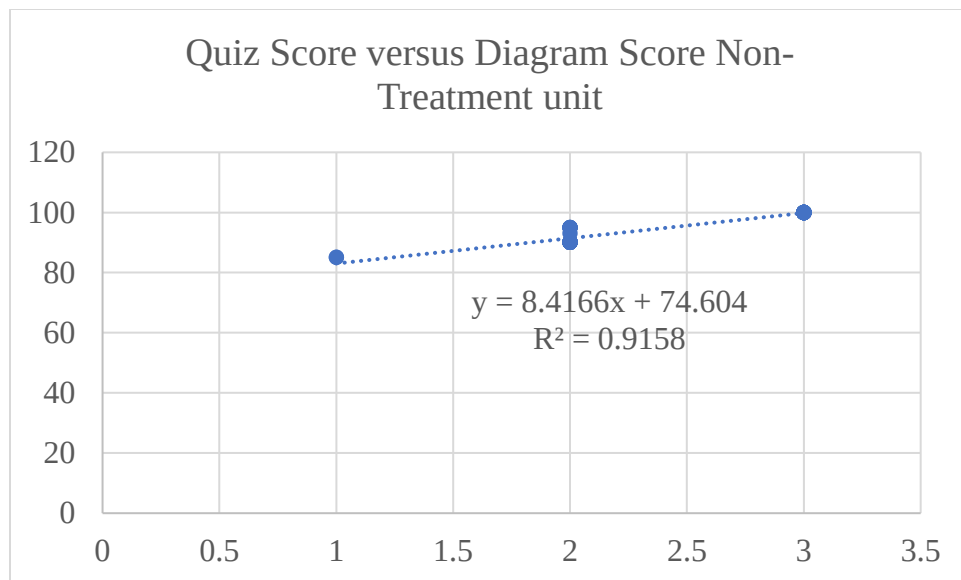


Figure 6. Non-treatment unit quiz score versus Evaluation of Representation, (N=54).

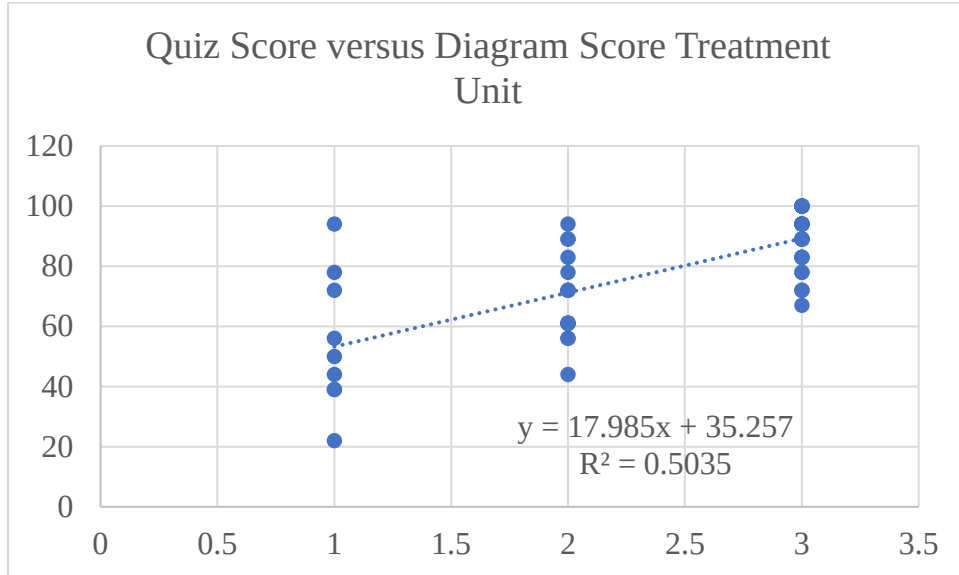


Figure 7. Treatment unit quiz Score versus Evaluation of Representation, ($N=54$).

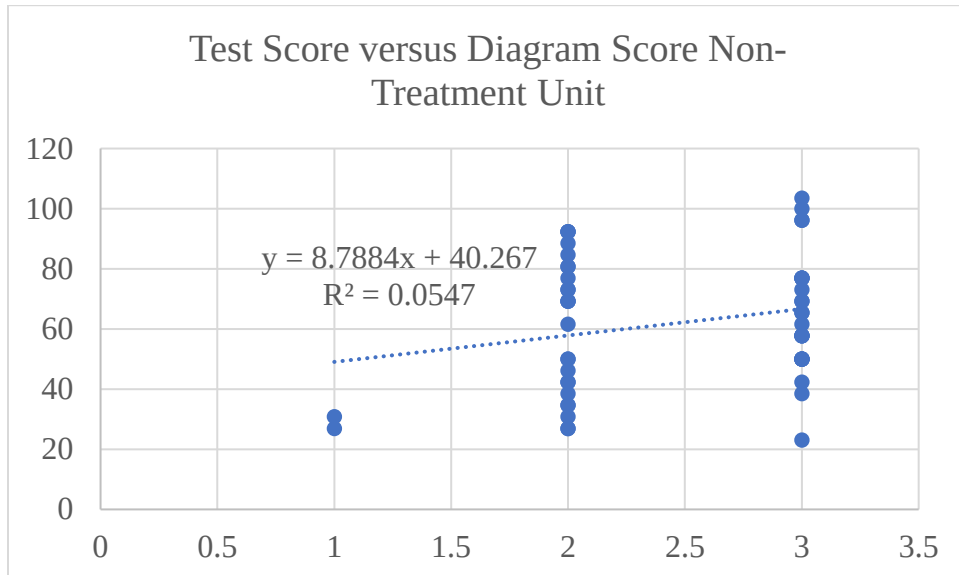


Figure 8. Non-treatment unit test score versus Evaluation of Representation, ($N=53$).

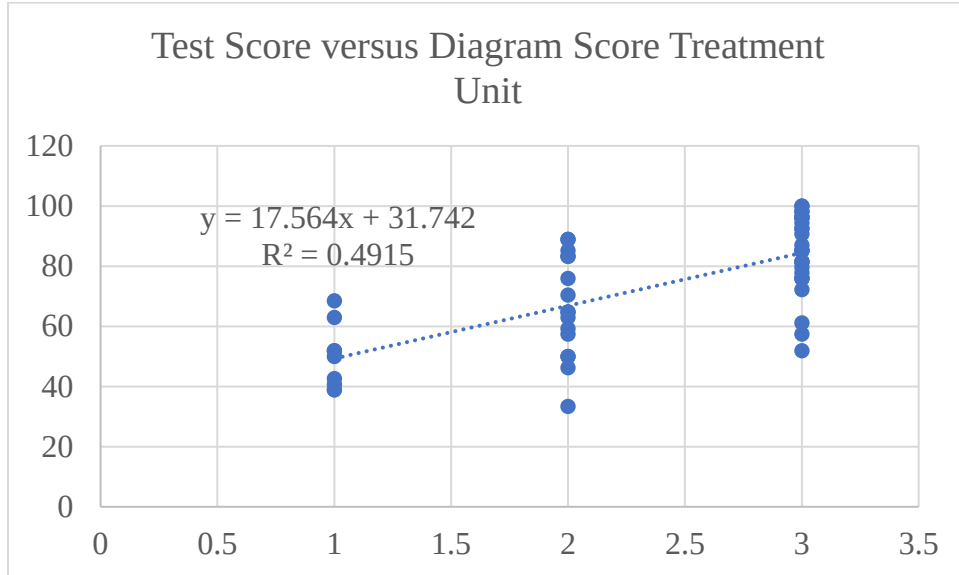


Figure 9. Treatment unit test score versus Evaluation of Representations, ($N=53$).

Student Likert Surveys were given just before the non-treatment unit and just after the treatment unit to assess student attitude in motivation, confidence, problem-solving, and attitude toward classroom teaching methods (Figures 10-11). The surveys were analyzed using the chi-square test and one question out of the ten was shown to have a significant change from non-treatment to treatment unit. This question, “I tend to think about physics in the real-world”, increased from the non-treatment unit to the treatment unit. This shows that student motivation towards physics and its connection to the real world improved with the treatment unit. Evidence of this was also found in the student interviews. A student stated that when they go about solving a problem, “I read the question and I put it in like a real-world situation and I draw a diagram from that and just plug in numbers, then solve.” A large change in disagreement on an issue can be seen in item 7. “It is possible to explain physics ideas without the use of mathematical formulas. Student started off with being more in agreement with this statement, but as the unit progressed, they changed their standing. From non-treatment to treatment unit, students

were thinking much more that physics could not be explained without mathematics. This trend in thinking was also heard in the student interviews, when students mentioned mathematical representation being an integral part to problems and physics situations. A student stated “when you add numbers to the problem you have to use an equation as a part of it too” and another, “diagrams are helpful because they help you come up with an equation and then plug in variables and solve for it”. Another finding that was discovered through the surveys was that item 9, had no change in response. This item stated, “To understand physics I discuss it with friends and other students.” This integral part of our class seemed to remain important in the same ways throughout the non-treatment and treatment units of instruction.

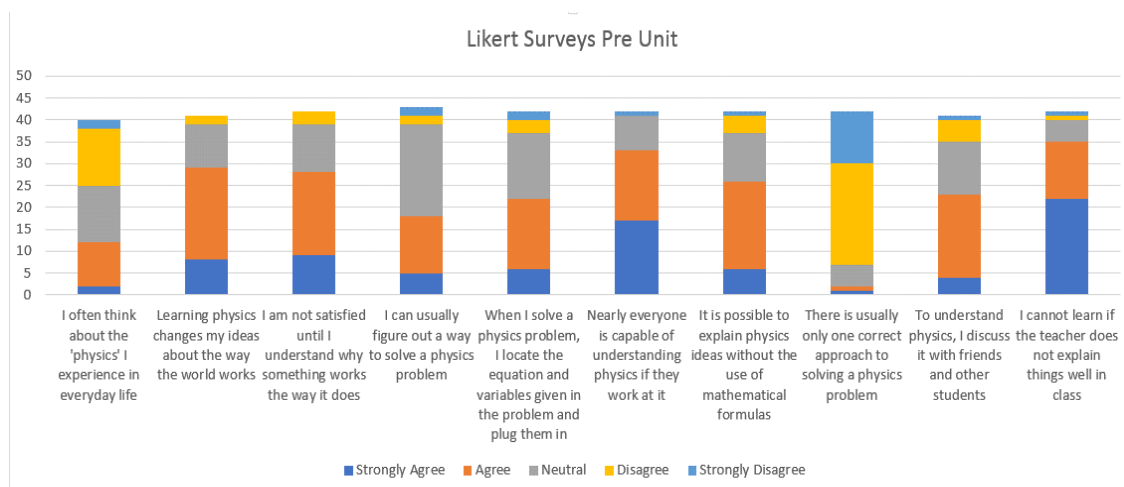


Figure 10. Likert Survey Responses during the non-treatment unit of instruction, (N=42).

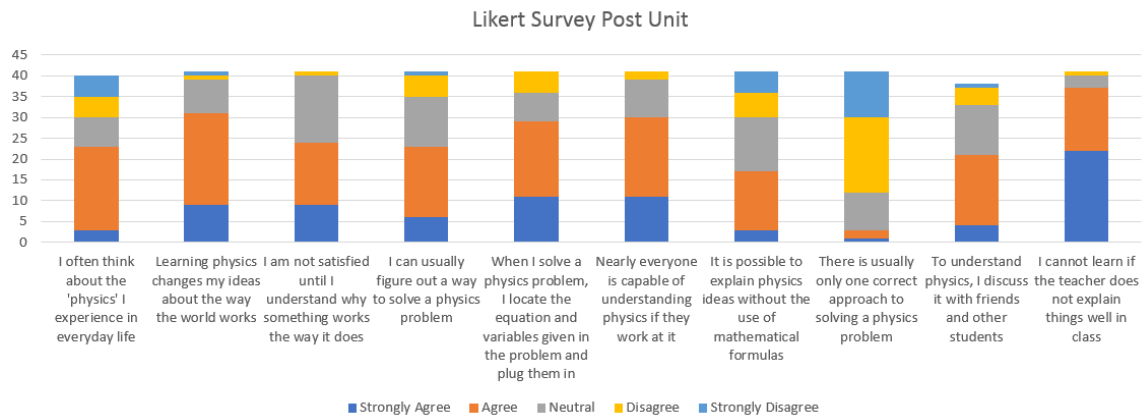


Figure 11. Likert Survey Responses during treatment unit of instruction, ($N=42$).

Although there were no significant changes from non-treatment to treatment unit on any Likert question other than the question on how often students think about physics experienced in everyday life, students did show some important attitude trends across non-treatment and treatment units of instruction. For example, students agreed more than disagreed that “Nearly everyone is capable of understanding physics if they work at it” and that more students agreed than disagreed that “I can usually find a way to solve a physics problem”. This was also observed in the student interviews with only one of six students stating that there was “confusion” that occurred when problem solving and all students agreed that they possessed some sort of problem solving method that was successful for them. Another trend was that students more disagreed than agreed that “There is only one correct approach to solving a physics problem” although some students mentioned during the interview that this caused confusion in the expectations for their work when they were working on non-traditional limitless problems.

Analysis of the student interview showed a few emerging themes. On the subject of problem solving, every student stated that “drawing diagrams” was a part of their own problem-solving methods. This theme of using diagrams for problem solving was spoken

of in these interviews and seen in the data analysis of the Evaluation of Representations. It seems that students became more aware of the importance of diagrams and more aware of how to use diagrams correctly from pre to post treatment. Still, more work can be done in using diagrams correctly as seen in one student's indication that "Like he said, the LOL diagram, they help, but sometimes if you did something wrong, the equation might be messed up and I sometimes get that happening". In addition to diagram use, students noted that "finding formulas" and "comparing the information I have to an equation" was an important part of their problem-solving process. Multiple students stated that they were not good at working with equations. They stated they sometimes "plug in the wrong formula" or even "forget what to do with equations". This is not surprising in that there was a larger standard deviation in the Traditional Problem-Solving Benchmark scores, indicating that while the class overall improved their scores, the average student score tended to get further from this improved score. Some students improved in problem solving from pre- to post- treatment, but a large portion of students did not. Another problem-solving method found in the interviews was listing or noting the important information in the problem. Three of the students stated that it was important for them to "highlight important information in the problem" or "list important information from the problem".

Students were also asked about the helpfulness and limitations of diagrams in problem solving during the interview. One trend was that students stated diagrams helped them see the problem or situation. This was stated in various ways, such as "they help you see motion", "see how a situation starts and stops", "helps you see it", "diagrams

help me see what an object does with forces” and that diagrams provide “imagery”.

These statements were in agreement with findings of other investigations in teaching introductory physics. My students also indicated that they understood that diagrams make information in the problem more readily available and useful for analysis and problem solving (Larken & Simon, 1987).

Students were also asked what their strengths and weaknesses were in physics class. Students mostly agreed that they can “solve for missing variables” in the algebraic sense and that it was a strength, but that they also struggle with “plugging numbers into the wrong formula” and even “forget what to do with equations” or don’t “use equations correctly”. One student also stated that when a problem is presented, and equations are attempted to be used, that they sometimes “get confused about what is going on”. This difficulty that students have with equations and physics could also contribute to some of the low performance on the Traditional Problem-Solving Benchmark. Other strengths that student communicated having were their skills in being “visual learners”, having the ability to “follow steps given for problem solving” and were strong with “graphs and other visuals”.

When asked about the limitless problems used in the treatment unit, all students agreed that as their teacher I should communicate “what they need to do to receive full credit on the problems”. Also, students responded that they “don’t know when to stop in solving for unknowns” with these problems and that they “needed guidance” and that “big problems are confusing”. This feedback on this specific classroom method was

informative in using the challenging problems. Students had difficulty adjusting to the new problem types and this was expected as the problems used were non-traditional.

INTERPRETATION AND CONCLUSION

The goal of this action research project was to increase students' conceptual understanding and problem-solving ability, while making the class more satisfying. In this project, multiple qualitative and quantitative data collection methods were utilized along with multiple data analysis methods.

Increase in student conceptual understanding occurred from pre- to post treatment as shown by the FCI and student interviews. When starting in physics class this year many students had misconceptions related to the Newtonian world-view. As the year progressed, students became more Newtonian in their thinking. The treatment unit on multiple representations gave students a reinforcement of correct thinking. This reinforcement occurred when students noticed the agreement among different representations on the same physics situation. Through representing a situation in diagrams, graphs, words, and equations, student understanding of counterintuitive concepts became more concrete. Students relied on the representations and their agreement with one other to be more confident in correct thinking on physics concepts. But when compared to similar courses, these gains in conceptual understanding are considered low (Hake, 1998). It is likely that a greater reliance on IE teaching methods can improve student scores on the FCI and conceptual understanding as it has been found that using more IE methods increased conceptual understanding in other similar courses (Hake, 1998). Low increases in student ability to problem solve were also seen on the

Traditional Problem-Solving Test and were supported in the student interview. This gain occurred from the beginning of the year and the treatment unit helped with providing diagrams as a central tool or hub to problem solving. With a problem where forces are involved, force diagrams could be utilized, along with sum of forces equations to describe the problem more clearly and then unknowns could be solved for. Students spoke of diagrams as core and essential to the work they did in problem solving. Students also spoke of them as the main idea to be referred to when a unit was discussed.

Students used multiple representations in their problem solving on the traditional problem-solving test and throughout the treatment unit, often when it was not required of them. Students also spoke of their general problem-solving routine during the Student Interviews. In general, the routine started with constructing a few representations that went with the problem statement. After this, students used an equation that matched a representation they had just constructed to plug in values they were given. Finally, students used the equation to solve for the value asked for in the problem. One factor that seemed to keep students from gaining more ability in problem solving was forgetting how to use the equations correctly and making errors with the equations when using them in their problem-solving routine.

When it came to diagrams themselves, as students learned how to use them more effectively from treatment to non-treatment unit, their learned effectiveness made them better at meeting the goals and objectives set by the unit test effectiveness. This was seen in that their ability to correctly construct a diagram was correlated strongly with test scores during the treatment unit. Students learned that diagrams allowed them to see the

important information in the problem. This ability made the process of solving problems feel easier for students because the information and the goal of the problem became clearer to students. This was also shown to be true in other studies on student learning in introductory physics. My students became more expert-like in their ability to solve problems because of the treatment unit on multiple representations. The fact that students stated that the diagrams made the problems “easier” for them demonstrates clearly that students were using a problem-solving method that guides a problems interpretation and solution (Larkin, Mcdermott, Simon, & Simon, 1980).

Both the non-treatment unit and treatment unit were conducted with high communication among peers in groups and with the teacher, and with a low reliance on rote-memorization-problem solving methods. In the past, a poor attitude was observed regarding these teaching methods, but little change in attitude was observed from the non-treatment to treatment unit. One significant growth in change in attitude from non-treatment to treatment unit occurred with seeing physics in everyday life. Students became more aware of how physics describes real situations in the physical world and this was affirmed in student responses in the interviews. It makes sense that this change occurred. The main lab for the treatment unit was an elevator lab where students investigated the changes on a scale during an elevator ride. Students then calculated the resulting accelerations of the motion of the elevator from collected data. The completion of the lab also required the use of multiple representations for analysis of forces and motion on the elevator. Students found that multiple representations were also useful to communicate ideas about a physics situation. During discussion in groups, students were

able to discuss if forces on a diagram were balanced or unbalanced and discuss the resulting direction of an acceleration vector for a given object. Discussion of these features of the situation would not be possible without the construction of multiple representations. It was also seen in the Physics Student Likert Survey that student attitude on the importance of group work and communication with peers to understand physics concepts remained the same from non-treatment to treatment unit.

In student responses to the Physics Student Likert Survey, it was found that student motivation only changed significantly on the issue of thinking about physics experienced in everyday life. Positive attitude changes were seen in responses to the questions regarding figuring out a way to solve a physics problem and feeling that nearly everyone is capable to understanding physics if they work at it. Although the changes in attitude for these questions were positive, the changes were non-significant and there is no evidence that the treatment unit taught with multiple representations provided help on these aspects of student attitude. Throughout both non-treatment and treatment units, students were given the ability to work with others on complex problems and were also given much face to face time with their teacher. Confidence should have been built through access to these resources. Students worked together and figured things out on their own in groups. Also, students were given direct encouragement and feedback from their teacher. These two factors should have been enough to keep student attitude on confidence in physics work positive. With the treatment in learning with multiple representations there was no significant gain in confidence in student ability to solve problems or understand physics. One way to make sense of this is to think about the ways

multiple representations allow a student to improve. When using multiple representations in problem solving, students construct diagrams, graphs and equations from a problem statement. This requires that students identify the correct representations to be used, then correctly use the representation, interpret the need of the problem statement, and finally solve for the unknown. This method of multiple representation use helps students become better at understanding physics concepts and helps them solve problems more effectively. However, since students needed to perform so many tasks correctly related to the use of the representations, and since student confidence is related to student ability, it makes sense that learning with multiple representations would not increase student confidence in a significant way. The amount of small errors that could occur among each of these complex steps could feel overwhelming to the students. There is also a possibility an incorrect solution, or no solution, could be found when these errors were made. When you learn how to problem solve and understand physics concepts with multiple representations, you have to learn and develop many abilities. This could have made some students more confident in that it offered an effective approach to problem solving and understanding. For other students, it could have felt like there were too many routines, skills, and knowledge required to use each representation correctly. This is one explanation, related to the use of multiple representations, for why confidence did not change in a significant way. The student interviews showed some evidence to support this explanation. Students mentioned that they had difficulties with each individual representation. Some mentioned difficulty in using a diagram correctly and others mentioned difficulty in using an equation correctly. When students were reluctant to

speak about the difficulties they encountered when solving complex problems, it also showed that confidence was low with respect to solving physics problems with multiple representations.

The use of multiple representations in learning physics is a strategy that promotes an all-around understanding of physics. Both the ability to understand concepts and problem solve are promoted through this methodology, as long as the representations are used correctly. The usefulness of explaining physical phenomena through multiple representations can be seen when students are constructing representations for new situations for the first time together. Physics concepts become clear and important to students when they connect the rules of the diagram to the rules of the real world.

VALUE

The experience in conducting this research project has provided me a model for professional development and improving my classroom over time. I envision the model like this: implement informed changes in instruction, monitor the results of the changes, analyze the results, and make more changes. This is a process and a sustainable way to improve student learning and student experience in my physics classroom. This research project allowed me to choose an aspect of my own teaching and investigate its effectiveness in order to understand the scope of that effectiveness. I was able to answer questions about how student learning improved and answer questions about changes in student attitude in my classroom. I was also able to trust more in some things that I always thought were true. Diagrams had been helpful for me in my own understanding of physics due to how they can hold important information required to understand physics situations. Also, in the past, I had become more successful at solving physics problems

through diagrams and thought this method would benefit students. I found that these things were partly true for my own students as well. I built up and confirmed some of my own prior understanding through this classroom research project. In contrast to this, I was also prompted to put less trust in things I previously thought were true that I now know are likely to be false. For example, even though I became more confident as a student when I learned the usefulness of diagrams in solving physics problems, there was not enough evidence to say that my own students grew in confidence. Useful strategies for problem solving with multiple representations, on their own, might not be enough to increase student confidence in physics. Seeing these unexpected results in my classroom research project caused me to examine my own thinking and allowed me to trim up my understanding and get rid of parts of it that are likely wrong. This resulted in me having more clarity and confidence in what is effective for students in physics. I am now clearer on what is helpful in learning physics and what is not. I also know more about the ways in which the helpful learning strategies are effective. For example, diagrams hold information for students to easily access and problem solve with as long as students have been trained in their correct usage. I also now have more knowledge about how non-helpful learning strategies are ineffective. For example, the finding that student confidence might not increase due to helpful learning strategies alone was a revelation for me. This gives me more confidence as a teacher. I am not just a person with the information in my head, and I am not just a guide with knowledge of what is helpful or not helpful for learning, but now I am more intimately familiar with how things are helpful for my students. I will become better at helping students learn physics because I

am able to investigate not just whether something is helpful or not, but the nature of its helpfulness. This will make me better at choosing and implementing strategies for learning and improving my students learning experiences.

My students also benefitted from this research project. They were able to take rigorous assessments that held high expectations for learning. They were proud to improve upon their learning in ways that looked dramatic to them. The work they put in and the learning that occurred was impressive and would not have taken place without this research project. They also participated in thinking about their own attitudes towards physics and problem solving. Thinking about one's own attitude towards an idea is often the first step in being able to improve it. As the year went on, students were glad they had taken physics and seemed to enjoy their challenging class experience. Students were able to voice their concerns and ideas freely in the student interviews and knew that they were being listened to. Students were also challenged to think and problem solve with the treatment through learning with representations. The method of using multiple representations does not involve a method that can be memorized. This means that students had to rely on prior lab experience, conceptual understanding, and the work they did with their peers to solve the problems. When multiple representations were used in problem solving, students took the problem statement given in words, converted the information into diagram, graph, or equation and then chose a problem-solving method. The problem-solving methods sometimes looked like putting a box around a value they had found in their representations. At other times it involved solving for multiple values and using them together to determine another unknown. Whatever the process, through

the treatment unit, students were able to learn a problem-solving method that required them to think more like a physics expert. Translating the meaningful information from a problem into multiple representations gave students a method that could be used in many problem situations, including real-life problems. Also, since the diagrams, graphs and equations carried information specific to the physics concepts involved, students were able to recall, use, apply, and understand concepts while problem solving. More, in the minds of my students, the properties of mathematics and equations, that tend to be disconnected from the reality of the physical situation, were more likely to be connected to the physics of the situation. This was due to the process of deriving their mathematical representations from their own student produced diagrammatic representations. These diagrammatic representations were constructed in the minds of the students after reading and interpreting the problem statement or seeing the physical situation. This connection of math to the real-world was valued by my students.

The practice of conducting these types of classroom research projects is also applicable to other classrooms. I am now able to inform other teachers of the simplicity and empowerment of the process used in this classroom research project. Also, I can inform other teachers of any helpful findings from my own classroom research projects to support them and their own classrooms.

In the future, I think that more can be done to improve student conceptual understanding, problem-solving ability, and student attitude toward physics. Since the general finding was that the implementation of learning with multiple representations was impactful to the conceptual understanding and problem-solving ability of my students, I

will continue to find more ways to implement it fully in my classroom among the IE methods I use. I believe this can be done relatively easily with the current practices of group work, model building, and peer discussion. Also, the manner in which it will be implemented is now very important to me. Next year I will start with focus on using representations correctly and especially focus on the weaknesses my students had this year. It surprised and disappointed me that the standard deviation increased, showing that students did not all perform better on the pre- and post- tests given in this classroom research project. One way to improve learning and help all students to perform better is to target the weaknesses that all students have. The weaknesses in familiarity and usage of equations along with the weakness in clear thinking in complex problems will be two things I will aim to work on with students next year. Also, using representations correctly will be a focus with our formative assessments.

The information found this year will also be shared with the students I have next year. The results of this classroom research project can be presented in a way where it will be useful information for how to be successful in physics. I also believe a presentation on the project will be motivating for my future students. Students often do not want to try new things that require a lot of investment because they are unsure it will be successful for them. The information I presented on the success provided by using multiple representations in problem solving was very motivating for my students this year and it could also help motivate future students in physics. Another finding that will be shared with students is that the task of using multiple representations offers success to students but it comes with a cost of hard work and attention to detail. Making sure each

representation is understood and recalled correctly and connected to the physics of each particular situation is difficult and it might make students feel like they are not successful for a time. I am more prepared to support students and spur them on in their use of multiple representations because I found out through this classroom research project that in the process of using these methods of learning physics, students may feel like they are not doing well. Next year, I will be more prepared to build student confidence and meet students in the middle of the difficulties with support. The information found in this classroom research project can be used as a guide for success in student learning and also as motivation for hard work and commitment to practicing with multiple representations for next year.

As a result of this classroom research project, I hope to be better at making choices in my instructional improvement using the analysis and reflection methods of this classroom research project. I especially hope to use the evaluation of representation tools and informal interview data in directing my decisions. These two tools provided the most insightful information and served as the best assessments for students to participate in. The evaluation of their diagrams gave them a clear idea of their standing and need to improve. The interviews allowed them to see that I listened and cared about their feedback in my instruction. They are the people I am trying to benefit and support. Showing them that I want to listen helps tremendously in our student-teacher relationship. Specific to the findings of this classroom research project, I hope to become clearer in my communication on what makes a good diagram and hope to give students more individual practice with using the representations. I hope students will take their

hard work and focus on making correct thorough representations of physics problems and situations. I also hope they will not lose this focus on the outcome of improved learning and ability to think and problem solve. I believe this is a valuable pursuit for them as young people and that greatest improvements in confidence towards problem solving will result from this focus.

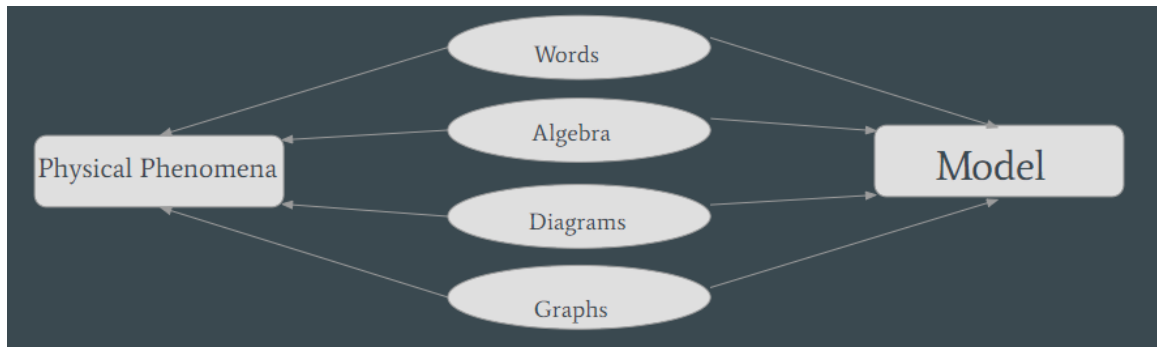
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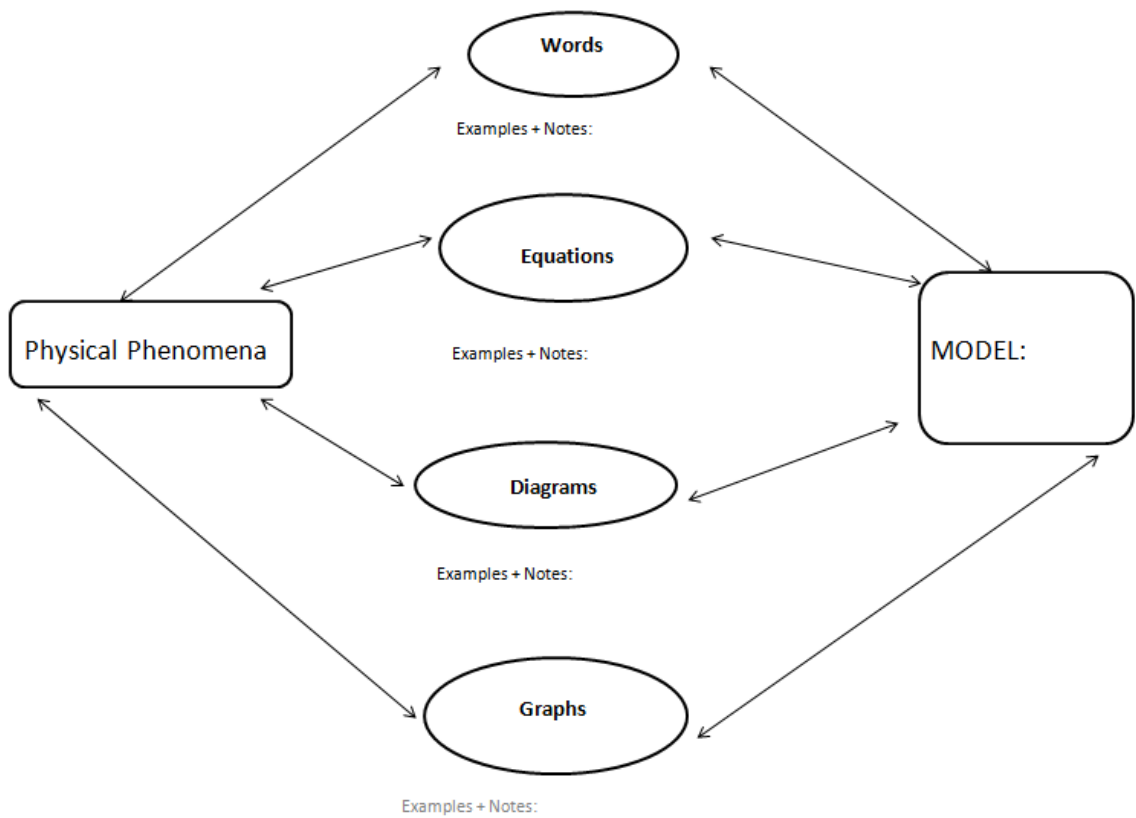
APPENDICES

APPENDIX A

OVERVIEW OF REPRESENTATIONS GRAPHIC ORGANIZER



Overview of Multiple Representations



APPENDIX B
PROBLEM SETS

Demonstration: Buddy on a board!

Sketch and label the experiment setup:

What could we measure? How could we measure it?

Objective of the experiment:

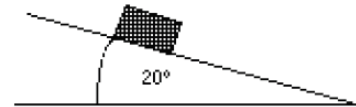
Whiteboarding and Post-Lab Notes

Practice 1: Limitless problems

1.

The 80 kg box travels to the bottom of the 2 m long ramp with a constant speed of 1.4 m/s.

- a. What models apply to this situation and why? (See the italics + bold + underline? That part is way important!)



- b. Draw *at least four* diagrams/graphs to illustrate the situation. Choose the diagrams and graphs that you find most useful. *Draw these BIG enough to be useful and annotate them like crazy. The diagrams are key.*

c. Using the models you have chosen, solve for any unknown quantities. Show your work and use units.

2.

The 80 kg box starts from rest and travels to the bottom of the 2 m long ramp, but its motion is opposed by a 150 N frictional force. *Follow the same general procedure as in the previous problem: tell which models apply, draw and annotate diagrams, solve for unknowns.*



3.

The 80 kg box starts from rest and travels to the bottom of the 2 m long, frictionless ramp. *Again, follow the same general procedure.*



4. Suppose the box in problem 3 were given a shove so that it started sliding up the ramp with a velocity of 3.0 m/s. How far up the ramp would it go?

Practice 2: Calculations with Coefficient of Friction

1. A horizontal 100 N force is applied to a 50 kg classmate resting on a level tile floor. The coefficient of kinetic friction is 0.15.

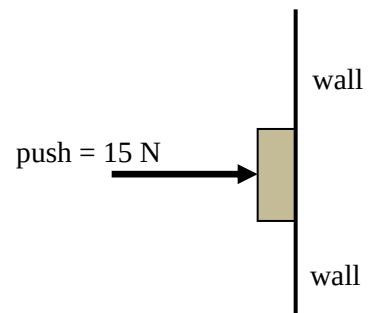
- a. Draw a system schema and force diagram to represent this situation.

- b. What is the acceleration of the classmate?

- c. Suppose the classmate in was resting on a carpet where the coefficient of static friction is 0.25. Is the horizontal 100 N force sufficient to cause the classmate to accelerate? Draw a force diagram, and then explain why or why not.

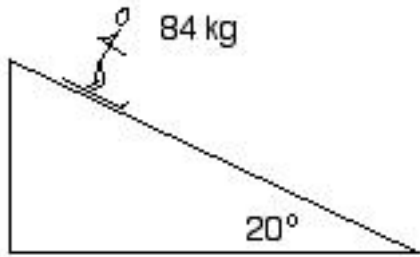
2. When 15 newtons of force is applied to the 0.50 kg book, the friction keeps the book from sliding down the wall.

- a) Make a system schema and force diagram for the book. Include the amount of each force.



b) What is the minimum force and minimum coefficient of friction to keep the book from sliding?

3. An 84 kg skier glides down a hill with $\mu_k = 0.15$.



a. Draw a system schema and force diagram for the skier.

b. What is the value of the frictional force opposing the skier's slide down the hill?

c. Calculate the acceleration of the skier.

Elevator Lab

In this activity you will look at how the forces change on you as you ride in an elevator.

Prep-lab: Read the following questions **before** riding on the elevator, and note the observations you need to make:

1. At what times in the motion of the elevator does the bathroom scale show your weight (or the weight of the person standing on the scale)? Make a mental note of the scale reading.
2. At what times in the motion does the scale show a value **greater than** your weight? Make a mental note of the scale reading.
3. At what times in the motion does the scale show a value **less than** your weight? Make a mental note of the scale reading.

Experiment: Take the bathroom scale with you and take a ride in the elevator. Have someone stand on the bathroom scale that doesn't mind revealing his or her weight to others. Observe and record the forces for numbers 1, 2 and 3 above.

Data/Observations: When you return to the classroom record your observations.

	Force in pounds	Force in newtons (1 pound = 4.5 N)
Scale reading at rest:	_____	_____
Maximum scale reading:	_____	_____
Minimum scale reading:	_____	_____

Label the following as **equal** to, **greater** than, or **less** than the scale reading at rest.

- _____ At rest at the bottom
- _____ Starting to go up
- _____ Going up at constant speed
- _____ Slowing to stop at the top
- _____ Stopped at the top
- _____ Starting to go down
- _____ Going down at constant speed.
- _____ Slowing to stop at the bottom.

Calculate the mass of the person on the scale in kilograms: _____

Force Analysis: Draw a quantitative force diagram for the passenger in each of the following situations during the elevator ride. Label the forces in newtons. To the right of each diagram draw a **velocity** and **acceleration** vector that describes the motion of person in the elevator. Calculate the net force and the acceleration of the person.

1. At rest at the bottom <u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =	2. Starting to go up <u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =
3. Going up at constant speed <u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =	4. Slowing to stop at the top <u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =
5. Stopped at the top	6. Starting to go down

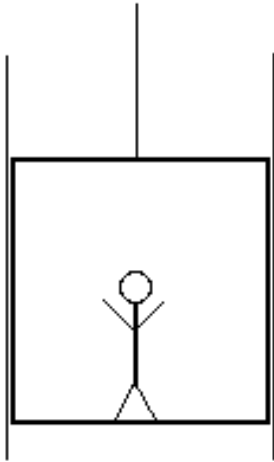
<u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =	<u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =
7. Going down at constant speed. <u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =	8. Slowing to stop at the bottom. <u>Quantitative force diagram</u> velocity vector: acceleration vector: net force = acceleration =

APPENDIX C
TREATMENT UNIT QUIZ

UBFPM Quiz 1

For the following problems, **state the model** that applies, include at least **4 helpful diagrams or graphs** that illustrate the situation and solve for the values you are asked for.

1. An elevator is moving up at a constant velocity of 2.0 m/s, as illustrated in the diagram below: The passenger has a mass of 75 kg.



- a. Calculate the force the floor exerts on the passenger.

2. The elevator now accelerates upward at 1.0 m/s^2 .

- a. Calculate the force the floor exerts on the passenger.

3. a. A 900 kg car that exerts 5000 N of traction force on a level road while being opposed by 1000 Newtons of friction and drag forces combined.

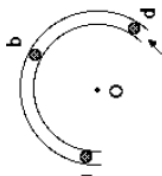
- a. Calculate the acceleration of the car.

APPENDIX D
FORCE CONCEPT INVENTORY

- Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:
 - about half as long for the heavier ball as for the lighter one.
 - about half as long for the lighter ball as for the heavier one.
 - about the same for both balls.
 - considerably less for the heavier ball, but not necessarily half as long.
 - considerably less for the lighter ball, but not necessarily half as long.
- The two metal balls of the previous problem roll off a horizontal table with the same speed. In this situation:
 - both balls hit the floor at approximately the same horizontal distance from the base of the table.
 - the heavier ball hits the floor at about half the horizontal distance from the base of the table than does the lighter ball.
 - the lighter ball hits the floor at about half the horizontal distance from the base of the table than does the heavier ball.
 - the heavier ball hits the floor considerably closer to the base of the table than the lighter ball, but not necessarily at half the horizontal distance.
 - the lighter ball hits the floor considerably closer to the base of the table than the heavier ball, but not necessarily at half the horizontal distance.
- A stone dropped from the roof of a single story building to the surface of the earth:
 - reaches a maximum speed quite soon after release and then falls at a constant speed thereafter.
 - speeds up as it falls because the gravitational attraction gets considerably stronger as the stone gets closer to the earth.
 - speeds up because of an almost constant force of gravity acting upon it.
 - falls because of the natural tendency of all objects to rest on the surface of the earth.
 - falls because of the combined effects of the force of gravity pushing it downward and the force of the air pushing it downward.
- A large truck collides head-on with a small compact car. During the collision:
 - the truck exerts a greater amount of force on the car than the car exerts on the truck.
 - the car exerts a greater amount of force on the truck than the truck exerts on the car.
 - neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
 - the truck exerts a force on the car but the car does not exert a force on the truck.
 - the truck exerts the same amount of force on the car as the car exerts on the truck.

USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT TWO QUESTIONS (5 and 6).

The accompanying figure shows a frictionless channel in the shape of a segment of a circle with center at "O". The channel has been anchored to a frictionless horizontal table top. You are looking down at the table. Forces exerted by the air are negligible. A ball is shot at high speed into the channel at "p" and exits at "r".



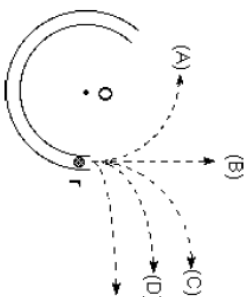
- Consider the following distinct forces:

- A downward force of gravity.
- A force exerted by the channel pointing from q to O.
- A force in the direction of motion.
- A force pointing from O to q.

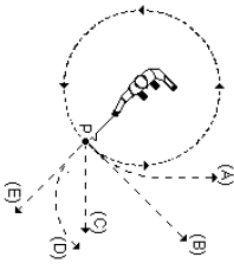
Which of the above forces is (are) acting on the ball when it is within the frictionless channel at position "q"?

- 1 only.
- 1 and 2.
- 1 and 3.
- 1, 2, and 3.
- 1, 3, and 4.

- Which path in the figure at right would the ball most closely follow after it exits the channel at "r" and moves across the frictionless table top?



- A steel ball is attached to a string and is swung in a circular path in a horizontal plane as illustrated in the accompanying figure. At the point P indicated in the figure, the string suddenly breaks near the ball. If these events are observed from directly above as in the figure, which path would the ball most closely follow after the string breaks?

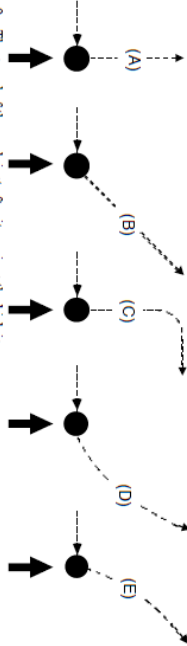


USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (8 through 11).

The figure depicts a hockey puck sliding with constant speed v_0 in a straight line from point "a" to point "b" on a frictionless horizontal surface. Forces exerted by the air are negligible. You are looking down on the puck. When the puck reaches point "b," it receives a swift horizontal kick in the direction of the heavy print arrow. Had the puck been at rest at point "b," then the kick would have set the puck in horizontal motion with a speed v_k in the direction of the kick.



8. Which of the paths below would the puck most closely follow after receiving the kick?



9. The speed of the puck just after it receives the kick is:

- (A) equal to the speed " v_0 " it had before it received the kick.
- (B) equal to the speed " v_k " resulting from the kick and independent of the speed " v_0 ".
- (C) equal to the arithmetic sum of the speeds " v_0 " and " v_k ".
- (D) smaller than either of the speeds " v_0 " or " v_k ".
- (E) greater than either of the speeds " v_0 " or " v_k ", but less than the arithmetic sum of these two speeds.

10. Along the frictionless path you have chosen in question 8, the speed of the puck after receiving the kick:

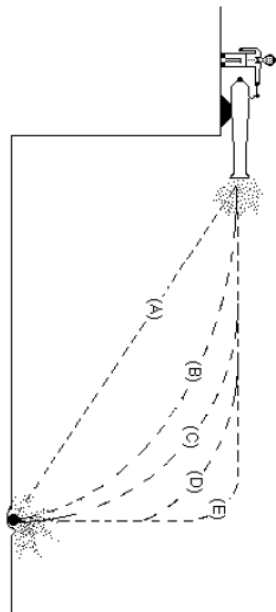
- (A) is constant.
- (B) continuously increases.
- (C) continuously decreases.
- (D) increases for a while and decreases thereafter.
- (E) is constant for a while and decreases thereafter.

11. Along the frictionless path you have chosen in question 8, the main force(s) acting on the puck after receiving the kick is (are):

- (A) a downward force of gravity.
- (B) a downward force of gravity, and a horizontal force in the direction of motion.
- (C) a downward force of gravity, an upward force exerted by the surface, and a horizontal force in the direction of motion.
- (D) a downward force of gravity and an upward force exerted by the surface.
- (E) none. (No forces act on the puck.)

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12. A ball is fired by a cannon from the top of a cliff as shown in the figure below. Which of the paths would the cannon ball most closely follow?

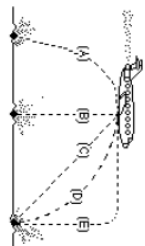


13. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it touches the ground, and assume that forces exerted by the air are negligible. For these conditions, the force(s) acting on the ball is (are):

- (A) a downward force of gravity along with a steadily decreasing upward force.
- (B) a steadily decreasing upward force from the moment it leaves the boy's hand until it reaches its highest point, on the way down there is a steadily increasing downward force of gravity as the object gets closer to the earth.
- (C) an almost constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point, on the way down there is only a constant downward force of gravity.
- (D) an almost constant downward force of gravity.
- (E) none of the above. The ball falls back to ground because of its natural tendency to rest on the surface of the earth.

14. A bowling ball accidentally falls out of the cargo bay of an airliner as it flies along in a horizontal direction.

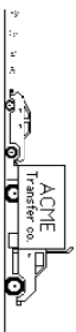
As observed by a person standing on the ground and viewing the plane as in the figure at right, which path would the bowling ball most closely follow after leaving the airplane?



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USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT TWO QUESTIONS (15 and 16).

A large truck breaks down out on the road and receives a push back into town by a small compact car as shown in the figure below.

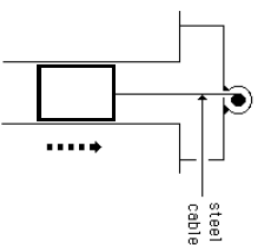


15. While the car, still pushing the truck, is speeding up to get up to cruising speed:
- (A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.
 - (B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.
 - (C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.
 - (D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.
 - (E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

16. After the car reaches the constant cruising speed at which its driver wishes to push the truck:
- (A) the amount of force with which the car pushes on the truck is equal to that with which the truck pushes back on the car.
 - (B) the amount of force with which the car pushes on the truck is smaller than that with which the truck pushes back on the car.
 - (C) the amount of force with which the car pushes on the truck is greater than that with which the truck pushes back on the car.
 - (D) the car's engine is running so the car pushes against the truck, but the truck's engine is not running so the truck cannot push back against the car. The truck is pushed forward simply because it is in the way of the car.
 - (E) neither the car nor the truck exert any force on the other. The truck is pushed forward simply because it is in the way of the car.

17. An elevator is being lifted up an elevator shaft at a constant speed by a steel cable as shown in the figure below. All frictional effects are negligible. In this situation, forces on the elevator are such that:

- (A) the upward force by the cable is greater than the downward force of gravity.
- (B) the upward force by the cable is equal to the downward force of gravity.
- (C) the upward force by the cable is smaller than the downward force of gravity.
- (D) the upward force by the cable is greater than the sum of the downward force of gravity and a downward force due to the air.
- (E) none of the above. (The elevator goes up because the cable is being shortened, not because an upward force is exerted on the elevator by the cable).



Elevator going up at constant speed

18. The figure below shows a boy swinging on a rope, starting at a point higher than A. Consider the following distinct forces:

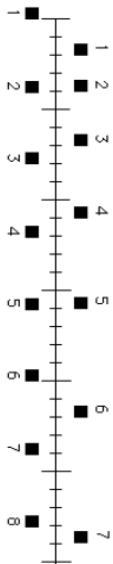
1. A downward force of gravity;
2. A force exerted by the rope pointing from A to O.
3. A force in the direction of the boy's motion.
4. A force pointing from O to A.

Which of the above forces is (are) acting on the boy when he is at position A?

- (A) 1 only.
- (B) 1 and 2.
- (C) 1 and 3.
- (D) 1, 2, and 3.
- (E) 1, 3, and 4.



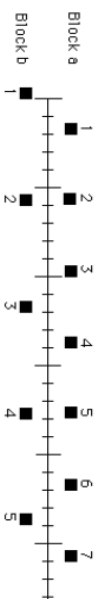
19. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



Do the blocks ever have the same speed?

- (A) No.
(B) Yes, at instant 2.
(C) Yes, at instant 5.
(D) Yes, at instants 2 and 5.
(E) Yes, at some time during the interval 3 to 4.

20. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



The accelerations of the blocks are related as follows:

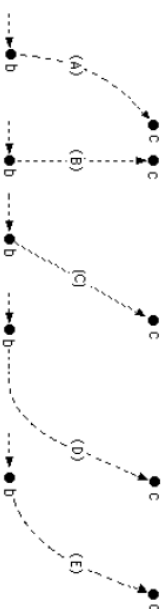
- (A) The acceleration of "a" is greater than the acceleration of "b".
(B) The acceleration of "a" equals the acceleration of "b". Both accelerations are greater than zero.
(C) The acceleration of "b" is greater than the acceleration of "a".
(D) The acceleration of "a" equals the acceleration of "b". Both accelerations are zero.
(E) Not enough information is given to answer the question.

USE THE STATEMENT AND FIGURE BELOW TO ANSWER THE NEXT FOUR QUESTIONS (21 through 24).

A rocket drifts sideways in outer space from point "a" to point "b" as shown below. The rocket is subject to no outside forces. Starting at position "b", the rocket's engine is turned on and produces a constant thrust (force on the rocket) at right angles to the line "ab". The constant thrust is maintained until the rocket reaches a point "c" in space.



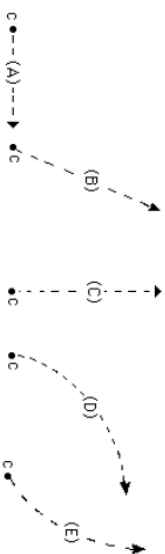
21. Which path below best represents the path of the rocket between points "b" and "c"?



22. As the rocket moves from position "b" to position "c", its speed is:

- (A) constant.
(B) continuously increasing.
(C) continuously decreasing.
(D) increasing for a while and constant thereafter.
(E) constant for a while and decreasing thereafter.

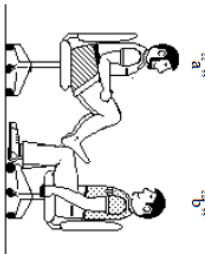
23. At point "c" the rocket's engine is turned off and the thrust immediately drops to zero. Which of the paths below will the rocket follow beyond point "c"?



24. Beyond position "c" the speed of the rocket is:

- (A) constant.
(B) continuously increasing.
(C) continuously decreasing.
(D) increasing for a while and constant thereafter.
(E) constant for a while and decreasing thereafter.

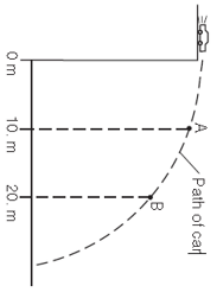
25. A woman exerts a constant horizontal force on a large box. As a result, the box moves across a horizontal floor at a constant speed " v_o ".
The constant horizontal force applied by the woman:
(A) has the same magnitude as the weight of the box.
(B) is greater than the weight of the box.
(C) has the same magnitude as the total force which resists the motion of the box.
(D) is greater than the total force which resists the motion of the box.
(E) is greater than either the weight of the box or the total force which resists its motion.
26. If the woman in the previous question doubles the constant horizontal force that she exerts on the box to push it on the same horizontal floor, the box then moves:
(A) with a constant speed that is double the speed " v_o " in the previous question.
(B) with a constant speed that is greater than the speed " v_o " in the previous question, but not necessarily twice as great.
(C) for a while with a speed that is constant and greater than the speed " v_o " in the previous question, then with a speed that increases thereafter.
(D) for a while with an increasing speed, then with a constant speed thereafter.
(E) with a continuously increasing speed.
27. If the woman in question 25 suddenly stops applying a horizontal force to the box, then the box will:
(A) immediately come to a stop.
(B) continue moving at a constant speed for a while and then slow to a stop.
(C) immediately start slowing to a stop.
(D) continue at a constant speed.
(E) increase its speed for a while and then start slowing to a stop.

28. In the figure at right, student "a" has a mass of 95 kg and student "b" has a mass of 77 kg. They sit in identical office chairs facing each other. Student "a" places his bare feet on the knees of student "b", as shown. Student "a" then suddenly pushes outward with his feet, causing both chairs to move.
- 
- During the push and while the students are still touching each other:
(A) neither student exerts a force on the other.
(B) student "a" exerts a force on student "b", but "b" does not exert any force on "a".
(C) each student exerts a force on the other, but "b" exerts the larger force.
(D) each student exerts a force on the other, but "a" exerts the larger force.
(E) each student exerts the same amount of force on the other.
29. An empty office chair is at rest on a floor. Consider the following forces:
1. A downward force of gravity.
2. An upward force exerted by the floor.
3. A net downward force exerted by the air.
Which of the forces is (are) acting on the office chair?
(A) 1 only.
(B) 1 and 2.
(C) 2 and 3.
(D) 1, 2, and 3.
(E) none of the forces. (Since the chair is at rest there are no forces acting upon it.)
30. Despite a very strong wind, a tennis player manages to hit a tennis ball with her racquet so that the ball passes over the net and lands in her opponent's court. Consider the following forces:
1. A downward force of gravity.
2. A force by the "hit".
3. A force exerted by the air.
Which of the above forces is (are) acting on the tennis ball after it has left contact with the racquet and before it touches the ground?
(A) 1 only.
(B) 1 and 2.
(C) 1 and 3.
(D) 2 and 3.
(E) 1, 2, and 3.

APPENDIX E

TRADITIONAL PROBLEM-SOLVING TEST

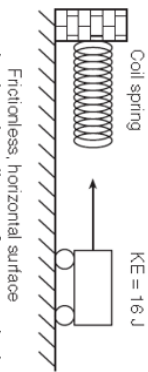
1. A force of 25 newtons east and a force of 25 newtons west act concurrently on a 5.0-kilogram cart. What is the acceleration of the cart?
 (a) 1.0 m/s^2 west (c) 5.0 m/s^2 east
 (b) 0.20 m/s^2 east (d) 0 m/s^2
2. An unstretched spring has a length of 10. centimeters. When the spring is stretched by a force of 16 newtons, its length is increased to 18 centimeters. What is the spring constant of this spring?
 (a) 0.89 N/cm (c) 1.6 N/cm
 (b) 2.0 N/cm (d) 1.8 N/cm
3. What is the acceleration due to gravity at a location where a 15.0-kilogram mass weighs 45.0 newtons?
 (a) 675 m/s^2 (c) 3.00 m/s^2
 (b) 9.81 m/s^2 (d) 0.333 m/s^2
4. As a car is driven south in a straight line with *decreasing* speed, the acceleration of the car must be
 (a) directed northward
 (b) directed southward
 (c) zero
 (d) constant, but not zero
5. A baseball dropped from the roof of a tall building takes 3 seconds to hit the ground. How tall is the building? [Neglect friction.]
 (a) 15 m (c) 45 m
 (b) 30 m (d) 90 m
6. The diagram below represents the path of a stunt car that is driven off a cliff, neglecting friction.



Compared to the horizontal component of the car's velocity at point A, the horizontal component of the car's velocity at point B is

 - (a) smaller
 - (b) greater
 - (c) the same
7. If the speed of a moving object is doubled, the kinetic energy of the object is
 (a) halved (c) unchanged
 (b) doubled (d) quadrupled

8. The diagram below shows a toy cart possessing 16 joules of kinetic energy traveling on a frictionless, horizontal surface toward a horizontal spring.



If the cart comes to rest after compressing the spring a distance of 1.0 meter, what is the spring constant of the spring?

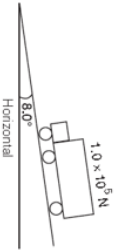
- (a) 32 N/m (c) 8.0 N/m
(b) 16 N/m (d) 4.0 N/m

9. How much work is required to lift a 10.-newton weight from 4.0 meters to 40. meters above the surface of Earth?
(a) 2.5 J (c) $3.6 \times 10^2\text{ J}$
(b) 3.6 J (d) $4.0 \times 10^2\text{ J}$

10. Which situation describes a system with *decreasing* gravitational interaction energy?

- (a) a girl stretching a horizontal spring
(b) a bicyclist riding up a steep hill
(c) a rocket rising vertically from Earth
(d) a boy jumping down from a tree limb

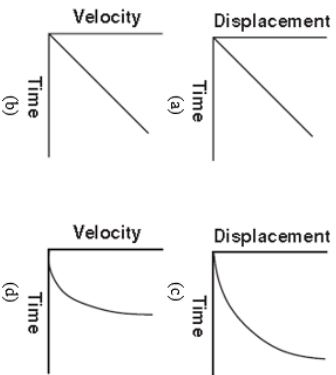
11. The diagram below shows a 1.0×10^3 newton truck at rest on a hill that makes an angle of 8.0° with the horizontal.



What is the component of the truck's weight parallel to the hill?

- (a) $1.4 \times 10^3\text{ N}$ (c) $1.4 \times 10^4\text{ N}$
(b) $1.0 \times 10^3\text{ N}$ (d) $9.9 \times 10^4\text{ N}$

12. Which graph best represents the motion of an object in equilibrium?



13. A child does 0.20 joule of work to compress the spring in a pop-up toy. If the mass of the toy is 0.010 kilogram, what is the maximum vertical height that the toy can reach after the spring is released?

- (a) 20. m (c) 0.20 m
(b) 2.0 m (d) 0.020 m

14. A book of mass m falls freely from rest to the floor from the top of a desk of height h . What is the speed of the book upon striking the floor?

- (a) $\sqrt{(2gh)}$ (c) mg/h
(b) $2gh$ (d) mh

15. A car increases its speed from 9.6 meters per second to 11.2 meters per second in 4.0 seconds.

The average acceleration of the car during this 4.0-second interval is

- (a) 0.40 m/s^2 (c) 2.8 m/s^2
(b) 2.4 m/s^2 (d) 5.2 m/s^2

16. A plane flying horizontally above Earth's surface at 100. meters per second drops a crate. The crate strikes the ground 30.0 seconds later. What is the magnitude of the horizontal component of the crate's velocity just before it strikes the ground? [Neglect friction.]

- (a) 0 m/s (c) 294 m/s
(b) 100. m/s (d) 394 m/s

17. A 0.15-kilogram baseball moving at 20. meters per second is stopped by a catcher in 0.010 second.

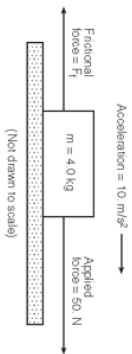
The average force stopping the ball is

- (a) $3.0 \times 10^{-2}\text{ N}$ (c) $3.0 \times 10^3\text{ N}$
(b) $3.0 \times 10^0\text{ N}$ (d) $3.0 \times 10^2\text{ N}$

18. A spring with a spring constant of 80. newtons per meter is displaced 0.30 meter from its equilibrium position. The interaction energy stored in the spring is

- (a) 3.6 J (c) 12 J
(b) 7.2 J (d) 24 J

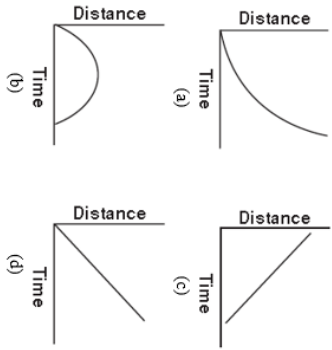
19. The diagram below shows a 4.0-kilogram object accelerating at 10. meters per second² on a rough horizontal surface.



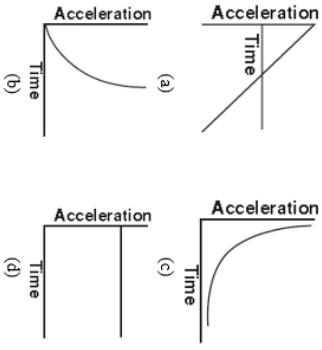
What is the magnitude of the frictional force F_f acting on the object?

- (a) 5.0 N (c) 20. N
(b) 10. N (d) 40 N

20. A cart travels with a constant nonzero acceleration along a straight line. Which graph best represents the relationship between the distance the cart travels and time of travel?



21. Which graph best represents the relationship between the acceleration of an object falling freely near the surface of Earth and the time that it falls?



22. What is the magnitude of the force needed to keep a 60.-newton rubber block moving across level, dry asphalt in a straight line at a constant speed of 2.0 meters per second? The kinetic coefficient of friction between rubber and dry asphalt is 0.67.

- (a) 40. N (c) 60. N
(b) 51 N (d) 120 N

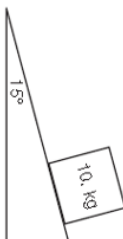
23. In the diagram below, a 60.-kilogram roller-skater exerts a 10.-newton force on a 30.-kilogram roller-skater for 0.20 second.



What is the magnitude of the impulse applied to the 30.-kilogram roller-skater?

- (a) 50. N•s (c) 6.0 N•s
(b) 2.0 N•s (d) 12 N•s

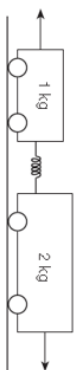
24. In the diagram below, a 10.-kilogram block is at rest on a plane inclined at 15° to the horizontal.



As the angle of the incline is increased to 30° , the mass of the block will

- (1) decrease
- (2) increase
- (3) remain the same

25. Two carts are pushed apart by an expanding spring, as shown in the diagram below.



If the average force on the 1.-kilogram cart is 1. newton, what is the average force on the 2.-kilogram cart?

- (a) 1 N
- (b) 0.0 N
- (c) 0.5 N
- (d) 4 N

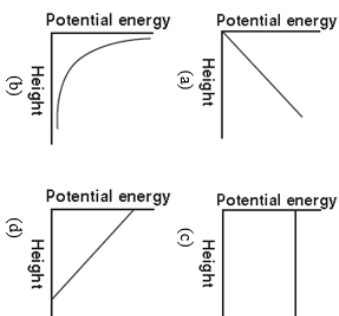
26. A 60.0-kilogram runner has 1920 joules of kinetic energy. At what speed is she running?

- (a) 5.66 m/s
- (b) 8.00 m/s
- (c) 32.0 m/s
- (d) 64.0 m/s

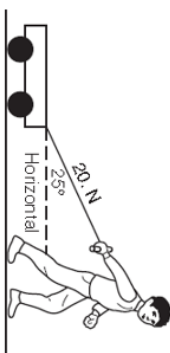
27. A 0.50-meter-long spring is stretched from its equilibrium position to a length of 1.00 meter by a weight. If 15 joules of energy are stored in the stretched spring, what is the value of the spring constant?

- (a) 30. N/m
- (b) 60. N/m
- (c) 120 N/m
- (d) 240 N/m

28. Which graph best represents the relationship between the gravitational potential energy of an object near the surface of Earth and its height above Earth's surface?



29. As shown in the diagram below, a child applies a constant 20.-newton force along the handle of a wagon which makes a 25° angle with the horizontal.



How much work does the child do in moving the wagon a horizontal distance of 4.0 meters?

- (a) 5.0 J
- (b) 34 J
- (c) 73 J
- (d) 80. J

30. As a block slides across a table, its speed decreases while its temperature increases. Which two changes occur in the block's energy as it slides?

- (a) a decrease in kinetic energy and an increase in ΔE_{th}
- (b) an increase in kinetic energy and a decrease in ΔE_{th}
- (c) a decrease in both kinetic energy and ΔE_{th}
- (d) an increase in both kinetic energy and ΔE_{th}

APPENDIX F

PHYSICS STUDENT LIKERT SURVEY

Student Survey -- Physics

Choose the response that best describes how you feel about the statement

1. I often think about the 'physics' I experience in everyday life

Mark only one oval.

- ☐ Strongly Disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly Agree

2. Learning physics changes my ideas about the way the world works

Mark only one oval.

- ☐ Strongly Disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly Agree

3. I am not satisfied until I understand why something works the way it does

Mark only one oval.

- ☐ Strongly Disagree
- ☐ Disagree
- ☐ Neutral
- ☐ Agree
- ☐ Strongly Agree

4. I can usually figure out a way to solve a physics problem*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

5. When I solve a physics problem, I locate the equation and variables given in the problem and plug them in*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

6. Nearly everyone is capable of understanding physics if they work at it*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

7. It is possible to explain physics ideas without the use of mathematical formulas*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

8. There is usually only one correct approach to solving a physics problem*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

9. To understand physics, I discuss it with friends and other students*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

10. I cannot learn if the teacher does not explain things well in class*Mark only one oval.*

- ☐ Strongly Disagree
☐ Disagree
☐ Neutral
☐ Agree
☐ Strongly Agree

APPENDIX G

PHYSICS STUDENT INTERVIEWS AND TRANSCRIPT

Can you tell me about how you go about solving a physics problem?

What are your strengths in physics class? What do you find easy? Why?

What are your weaknesses in physics class? What do you find difficult? Why?

Me: Can you tell me how you go about solving a physics problem?

Student 1: I read the question and I put it in like a real-world situation and I draw diagrams from that and just plug in numbers, then solve.

Student 2: Usually I start with going about the process of what you taught us and start with diagrams and move on to plugging in and stuff like that.

Student 3: I think about the problem by listing everything that is important and trying to find formulas or anything, then using the diagram.

Student 4: I list the information that I have in the problem and then when I see what I have, I compare it to the equation. That's how I solve it.

Student 5: I do pretty much the same thing and highlight key parts that will help me figure out what I need so far.

Me: It sounds like we all use diagrams as a part of solving problems. Can you tell me how you go about choosing diagrams and how they are helpful for you when solving problems? Or how are they not helpful in solving problems?

Student 5: Yeah so the diagrams usually help when they apply to the problem. But when you add numbers to the problem you have to use an equation as a part of it too. But they are really helpful in helping you think about problems.

Me: What is one way that diagrams are helpful in helping you think about problems?

Student 5: Like with the LOL diagrams, when you have to think about the initial of the situation, with a car or something, thinking about it changes in motion. It helps me think about what is happening in the situation and then apply it back to the problem.

Student 6: I agree.

Student 4: Like he said, the LOL diagram, they help, but sometimes if you did something wrong the equation might be messed up and I sometimes get that happening.

Student 3: Using the position versus time graphs are easy. They help you know which way the direction of the object is going.

Student 2: I think the diagrams just help you break it down to a different level to where you can see it. It just helps you figure out where you have to go from there.

Student 1: So when I put something into a force diagram it helps me see if an object will do something and then the LOL diagrams are helpful because they help you come up with an equation and then plug in variables and solve for it. So it makes it easier.

Me: One thing that you are all saying is that these diagrams help people see or are able to help carry people through the problem.

Student 1: Imagery

Me: Yes, that's a good word for it... So in general, what is a strength or weakness of your own in physics? Or for the class in general?

Student 1: Cause I like math, one of my strengths is plugging in and solving for the one variable that is not there.

Student 2: I guess one of the weaknesses I have is that sometimes there is so much going on and I get confused on what formulas to use and I plug in the wrong formula.

Student 3: Strength I have is that as a visual learner, if you show all the steps it takes, I can see it and get the answer.

Student 4: Yeah, I agree with what he said, about being visual, but I think that one of my weaknesses is forgetting what to do with an equation.

Student 6: I agree with her too. That I sometimes forget how to do things with equations.

Student 5: I think one of my strengths is graphs, but I do also get confused with the formulas. Like the red one and the blue one I get confused with each other.

Me: One more question, when I give you a goal-less problem, what do you find hard or easy about it?

Student 5: It is confusing because you don't know when to stop. Like you might think you are done but you are not. You can be done with one answer, so that makes it easy.

Student 4: For me sometimes I look at my answer I think it looks wrong. So I over-think it sometimes.

Student 1: So if there are multiple answers, I would just want you to show us what we need to have if I am going to get credit for the answer.

Me: So it seems we all agree with these types of questions, we are able to solve for a lot, but if there is going to be credit given, you want to know the correct number of answers.

All: Yes.

Student 1: I think that some of the problems we do are simple math, but if you have a big problem with multiple things that people could get confused.

Me: Any other comments overall?

Student 5: I just think you should let us know when it is a goal less problem and give us a guide.