Evaluating the Effectiveness of a Virtual Pulley Inquiry-Based Learning Activity on Increasing Student Understanding of Newton’s Second Law

Megan N Phillips, California Polytechnic State University, San Luis Obispo

Megan Phillips is a fourth-year student at California Polytechnic State University, San Luis Obispo pursuing a Bachelor of Science in Biomedical Engineering with a concentration in Mechanical Design. She is minoring in German and Entrepreneurship and expects to graduate in March 2022. She has been working as a learning assistant for the Department of Mechanical Engineering at California Polytechnic State University since September 2019, where she works to assist student learning in undergraduate dynamics classes and participates in research to improve student understanding of complex dynamics concepts.

Maggie Nevrly, Cal Poly SLO

Mechanical Engineering student interested in engineering education and social justice.

Dr. Brian P. Self, California Polytechnic State University, San Luis Obispo

Brian Self obtained his B.S. and M.S. degrees in Engineering Mechanics from Virginia Tech, and his Ph.D. in Bioengineering from the University of Utah. He worked in the Air Force Research Laboratories before teaching at the U.S. Air Force Academy for seven years. Brian has taught in the Mechanical Engineering Department at Cal Poly, San Luis Obispo since 2006. During the 2011-2012 academic year he participated in a professor exchange, teaching at the Munich University of Applied Sciences. His engineering education interests include collaborating on the Dynamics Concept Inventory, developing model-eliciting activities in mechanical engineering courses, inquiry-based learning in mechanics, and design projects to help promote adapted physical activities. Other professional interests include aviation physiology and biomechanics.

Michaella Ochotorena, California Polytechnic State University, San Luis Obispo

Michaella Ochotorena is currently pursuing her B.S. in General Engineering with an individualized course of study in Sustainable Energy from Cal Poly, San Luis Obispo. She has been helping to develop interactive and inquiry-based learning activities for mechanics courses. Additionally, she is working in the Cal Poly Mechanical Engineering Department researching thermal comfort and its relationship to energy usage and student success.

Nathalia De Souza, California Polytechnic State University, San Luis Obispo

Nathalia De Souza is a second-year Aerospace Engineering student (B.S.) at California Polytechnic University, San Luis Obispo. She obtained her A.A. in Math and Science at West Hills College, Lemoore in 2019. Nathalia currently works as a research assistant for the Cal Poly Mechanical Engineering Department and is also pursuing a minor in Ethnic Studies. Her engineering education interests include researching the gap in performance and between white students and students of color. Her professional interests include aerospace design and manufacturing as well as space policy.

Ms. Eileen W. Rossman P.E., California Polytechnic State University, San Luis Obispo

Eileen Rossman has a worked in various industries for over 14 years before starting a career teaching engineering. Here industry experience includes field support for Navy Nuclear refueling with Westinghouse, analysis and programming of pipeline flow solutions with Stoner Associates, and design of elevator structures and drive components with Schindler Elevator.

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Introduction

Newton’s Second Law, $\Sigma F = ma$, is notorious in STEM education and poses difficulties for students when they apply it to complex problems in undergraduate engineering courses. When five dynamics classes consisting of a total of 205 engineering students were asked to use Newton’s Second Law to evaluate three relatively complex conceptual questions, only 40% answered the first question correctly, 50% answered the second question correctly, and 70% of students answered the third question correctly. These scores show a large gap in student understanding of Newton’s Second Law, as these students had been instructed on Newton’s Second Law prior to the test.

To increase students’ ability to apply Newton’s Second Law to complex problems, inquiry-based learning (IBL) can be utilized. There are “two pillars” shown to be results of IBL that are consistently acknowledged by educators: a deep engagement in rich mathematics and opportunities to collaborate¹. IBL is a student-centered approach to increasing student understanding of typically STEM-related subjects because it allows students to engage with the material and approach it from their individual perspective. IBL uses guiding questions to lead students to correct reasoning on their own, which has been shown to increase student confidence and learning in areas such as scientific literacy and research skills².

Inquiry-based learning activities (IBLAs) have been growing in popularity since the shift toward student-centered IBL in the recent years. Undergraduate students who underwent inquiry-based learning in an IT class reported high satisfaction with the program and high approval of the methods used. Teachers also reported higher satisfaction in using these methods in their teaching³. This increase in student and teacher satisfaction makes IBL a promising candidate for increasing student understanding of Newton’s Second Law.

Coupled multiple-response questions (CMRs) allow professors to evaluate student reasoning behind answers to conceptual questions. These CMRs consist of multiple-pronged conceptual questions aimed to identify alternate conceptions of students⁴. Understanding how student reasoning changes based on IBLAs helps us identify the effectiveness of this activity, as we want students to answer the question correctly and to apply scientific reasoning to arrive at these answers. This paper evaluates the effectiveness of a pulley IBLA in increasing student understanding of Newton’s Second Law in undergraduate dynamics classes, as well as student perceptions of the IBLA as a learning tool.

Methods

Initial analysis of the need for creative solutions to increase student understanding of Newton’s Second Law was completed in five undergraduate dynamics classes in Fall 2020 using the Concept Warehouse (http://jimi.cbee.oregonstate.edu/concept_warehouse/CW.php), an open
Two hundred and five students were asked to answer three complex conceptual questions regarding Newton’s Second Law. Each of these three conceptual questions was followed by a free-response follow-up question asking students to explain their reasoning.

Three undergraduate dynamics classes consisting of 107 total students participated in this study in Winter 2021. The students were first given three concept questions about Newton’s Second Law before they participated in the IBLA, with a free-response follow-up question asking them to explain the reasoning behind their answers. These questions were also administered using the Concept Warehouse. The first question they were given is shown in Figure 1.

![Figure 1](image)

In system A, a small block weighing 5 lb and a small block weighing 10 lb are placed on either side of a see saw. In system B, the 10 lb block is replaced by a concentrated force of 10 lbs. Which system will have the highest acceleration at the given position?

- System A has greater acceleration than System B
- System B has greater acceleration than System A
- They accelerate at the same rate
- Neither system accelerates

Explain why you predict this.

Figure 1: Question 1 - See saw question used to evaluate student understanding of Newton’s Second Law, followed by a free-response explanation.

Next, the students were given the following question, seen in Figure 2, to assess how they apply Newton’s Second Law in a different context.
The final question given to assess student understanding involved ranking the acceleration of masses given pulley systems with different masses and applied forces as is seen in Figure 3. Each dropdown menu on the left of the answers included options for students to select rankings from 1 to 4.

![Figure 3: Pulley ranking question used to evaluate student understanding of Newton’s Second Law, followed by a free-response explanation.](image)

The full answers given by students for each question are included in the Appendix.

After the pre-IBLA assessment, students participated in the IBLA, which consisted of five different “Cases” involving Newton’s Second Law. These cases were created from the “pulley IBLA,” one of five hands-on inquiry-based learning activities designed to use non-intuitive results to challenge students to rethink their conceptual frameworks. The goal of the IBLAs is to increase...
student conceptual understanding of dynamics without heavy reliance on equations. We transformed the pulley IBLA, created to conceptualize Newton’s Second Law, into an online learning format using videos and simulations to demonstrate each of the five cases.

First, to encourage students to think about the questions in a conceptually relevant way, a warm-up question was given, as seen in Figure 4.

![Warm Up](image)

**Figure 4:** Warm-up question to assess students’ ability to identify contributors to the motion of a pulley system.

In Case 1, students were asked to predict the acceleration of two masses relative to one another, followed by a free-response explanation. Case 1 is seen in Figure 5.

![Case 1](image)

**Figure 5:** System analyzed in Case 1 of the pulley IBLA
Each case was followed by a YouTube video showing the actual motion of the pulley system when demonstrated in person, as previewed in Figure 6.

![YouTube video](image)

**Figure 6:** Demonstration video showing the pulley system’s actual motion when done in person

The students were then directed to a simulation in a new window, showing the same system as well as graphs of the motion and summary tables. The end of the simulation for Case 1 is seen in Figure 7.

![Simulation](image)

**Figure 7:** Simulation for Case 1 of the pulley IBLA

Figure 8 below shows the corresponding graphs and motion summary tables for Case 1, produced by the simulation.
After the students participated in the simulation corresponding with Case 1, they were prompted to answer the following questions seen in Figure 9.

**Figure 9:** Post-simulation reflection questions for Case 1 of pulley IBLA

Finally, as seen in Figure 10, students were provided with a YouTube video explaining the logic and correct answers for Case 1, narrated by an undergraduate learning assistant.
The same series of steps – prediction with explanation, video of the physical system’s motion, simulation of the motion with graphs and summary tables, reflection regarding the simulation, and explanation video narrated by a learning assistant – was repeated for each following case. However, the fourth question in the reflection was only asked for Case 1 since it introduced students to the correct conceptual understanding of the pulley problems. The systems in Cases 2 through 5 are included in Figures 11.a, 11.b, 11.c, and 11.d below.

**Figure 10:** Explanation video for Case 1 of pulley IBLA, narrated by learning assistant Michella Ochotorena

**Figure 11.a:** System analyzed in Case 2 of the pulley IBLA
Case 5 included a constant applied force. Since this is difficult to recreate with a low-cost physical demonstration, there was no video for Case 5—only a simulation.

To assess how student understanding of and reasoning patterns associated with Newton’s Second Law changed as a result of the IBLA, the same pre-IBLA questions were given in a
coupled-multiple response format as a post-IBLA quiz. These CMRs were developed as a learning evaluation tool to test student reasoning associated with answers to conceptual questions about Newton’s Second Law. The team used qualitative analysis tool Dedoose to identify student reasoning patterns associated with student answers to each conceptual question. The most prevalent reasoning patterns among students were categorized into a multiple-response, multiple choice follow-up questions with correct reasoning elements and distractors representing the most common misconceptions among students. Additional details regarding the development of and results from these CMRs can be found in Nevry et al., 2021⁴. The conceptual questions paired with follow-up reasoning questions are shown in Figures 12.a, 12.b, and 12.c.

Figure 12.a: See saw coupled-multiple response question used to evaluate student understanding of Newton’s Second Law post-IBLA

Figure 12.b: Block coupled-multiple response question used to evaluate student understanding of Newton’s Second Law post-IBLA
Figure 12.c: Pulley ranking coupled-multiple response question used to evaluate student understanding of Newton’s Second Law post-IBLA

Following the activities and post-IBLA quiz, students were asked to reflect on their own learning and how effective each aspect of the activity was in increasing their learning of dynamics. Students were asked to respond on a five-point scale including options for ‘strongly disagree’, ‘disagree’, ‘neither agree nor disagree’, ‘agree’, and ‘strongly agree,’ unless otherwise noted. The following questions were asked regarding the effectiveness of the activity’s videos and simulations:

1. Seeing the video (no simulation) would allow me to understand the phenomenon and would result in the same learning (e.g., I don’t really need the simulation).
2. Seeing only the simulation (no video) would allow me to understand the phenomenon and would result in the same learning (e.g., I don’t really need the video).
3. Both the video and the simulation contributed to my understanding of the phenomenon and contributed to my learning (e.g., I prefer having both the video and simulation).
4. (Free response) - Please explain your answers above and differentiate between how the video and the simulation helped your learning.

The following questions were asked regarding overall learning, attitudes, and opinions of the students:

5. This activity helped me learn about dynamics.
6. This activity was interesting and motivating.
7. (Free response) - If you have any comments as to how to improve this activity, or any other comments, please write them below.
Results

The percentage of the students who answered each of the three pre- and post-IBLA quizzes correctly, along with correct reasoning of the post-IBLA quiz are included in Table 1 below. The percentage of students who correctly answered each pre-IBLA question is shown in the second column and the percentage of students who correctly answered each post-IBLA question is shown in the third column.

Table 1: Percentage of students who correctly answered each pre- and post-IBLA question regarding Newton’s Second Law correctly, along with the percentage who correctly answered the post-IBLA CMR reasoning question correctly

<table>
<thead>
<tr>
<th>Question</th>
<th>Pre-IBLA Answer</th>
<th>Post-IBLA Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 1</td>
<td>23.4%</td>
<td>81.3%</td>
</tr>
<tr>
<td>Question 2</td>
<td>62.6%</td>
<td>82.24%</td>
</tr>
<tr>
<td>Question 3</td>
<td>16.8%</td>
<td>72.9%</td>
</tr>
</tbody>
</table>

Figure 13 below shows the results of the students’ survey answers for questions 1, 2, 3, 5, and 6. Questions 4 and 7 were omitted because they were free-response questions.

Figure 13: Summary of student responses to survey questions regarding the IBLA’s effectiveness and student attitudes toward the IBLA

The fourth survey question was an open response question asking students to explain their answers for questions 1 through 3. This provided us reasons the students liked each method of learning as well as arguments for having both. The following reasons were found to be the most common for students who agreed the video provided them with quality learning:

- The video provided them with a “real life” example of how the systems would act
- The video provided a visual representation of the systems’ motion
- The video was simpler and more straightforward than the simulation
The following reasons were most commonly given for students thought the simulation provided them with quality learning:

- The graphs and summary tables provided them with data to mathematically justify the resulting motion of the systems
- The simulation made it easier to see the motion of the systems
- The simulation provided them the opportunity to slow down the resulting motion
- The simulation clarified what was seen in the videos

Many of the students who thought they could have gotten the same level of learning from just the video or just the simulation said the combination was redundant and provided them with the same conceptual understanding of the systems.

The final survey question number 7 asked student students for feedback regarding the activity. The most common responses across all students, despite their response to the previous survey questions, was that the activity was long and repetitive after the first few cases. A significant few also mentioned they would like to see whether their post-IBLA quiz answers were correct.

**Discussion**

In the pre-IBLA quiz administered to students, 23.4% answered Question 1 correctly, 62.6% of students answered Question 2 correctly, and only 16.8% of students answered Question 3 correctly. In the context of previous classes, these numbers are as expected, as Question 2 resembles questions the students had seen in previous courses. When applying Newton’s Second Law to a slightly more complex problem like the see saw problem (Question 1), students performed worse initially. This is likely due to the added complexity of rotational acceleration as well as the presence of multiple blocks in the system. Question 3 yielded the lowest initial correct responses, likely due to its complexity in nature. This question asked them to compare the acceleration of four different systems with multiple blocks and analogous applied forces.

The post-IBLA questions yielded significantly higher results after students had interacted with Newton’s Second Law in the pulley IBLA. 81.3% of students answered Question 1 correctly, which showed that approximately 3.5 times as many students understood Newton’s Second Law better when applying it to multiple blocks accelerating in a rotational motion. Question 2 was answered correctly by 82.2% of students after the pulley IBLA. This was a smaller increase due to the higher number of students who initially answered Question 2 correctly, but still showed that a fifth of students were able to correctly answer Question 2 who had not before. A lower overall percentage of students answered Question 3 correctly after the IBLA with 72.9% of students correctly ranking the four systems. However, this question posed the most difficulty to students and had the greatest increase in the number of students who answered it correctly post-IBLA. About 4.4 times as many students answered Question 3 correctly post-IBLA compared to pre-IBLA.

Student survey questions showed that more students disagreed (strongly or normally) that the IBLA with videos only would have resulted in the same level of learning at 38.3% than students
who disagreed that the IBLA with simulations only would have resulted in the same level of learning at 32.7%. While the same number of students agreed (normally) that the video or the simulation would have provided them with the same level of learning, 18.7% of students strongly agreed that just the simulation would have provided the same level of learning as having both but only 8.4% strongly agree the video would have done the same. This leads us to believe that the simulation was more effective in increasing their learning than the demonstration videos, but less than half of the students in both cases agreed just having one would have been as effective.

Overall, 68.2% of students agreed (strongly or normally) that the video and the simulation contributed to learning. This shows that although some students agree that one or the other would have provided them with the same level of learning, most students agree that they were both valuable in increasing their understanding of dynamics.

When analyzing student reasoning behind their answers to the first three survey questions mentioned above, the pros they gave for the video and the simulation differed greatly from one another. The students who praised the video demonstrations explained they liked the “real life” examples the most, and the students who praised the simulations mostly spoke about the value of the data/graphs and ease of viewing. It was also common for students to acknowledge the benefits of both the videos and the simulations in their explanations, showing the benefit of having both available to students.

A minor, but significant number of students mentioned the redundancy in having both the video and the simulation show the resulting motion. This is difficult to address since most students agreed both the videos and the simulation contributed to their learning. Because additional exposure to and hours spent interacting with dynamics concepts typically solidifies student understanding, the overall learning of the students who felt like the video or the simulation solely would have solidified their learning of the material will not suffer from more exposure to these dynamics concepts.

A large majority of students, 90.6%, agree (strongly or normally) that the IBLA increased their understanding of dynamics and 60.7% agree the activity was interesting and motivating. The main focus of the IBLA is to increase student understanding of Newton’s Second Law, which the vast majority of students agreed to be true. It is difficult to develop engaging and effective learning tools for students, but 2/3 of students who learned from this activity also thought it was engaging. This number is high, considering this was a virtual homework activity, which often has low engagement and low student interest.

**Conclusion**

Overall, the IBLA increased student understanding of Newton’s Second Law, as shown by the increase in correct responses to all three conceptual evaluation questions. The undergraduate students who participated in the IBLA slightly preferred the simulation over the video due to its mathematical justification and ease in watching, but many students also praised the video for providing a “real life” example of the motion. A slight majority of students agreed both the
simulation and video were valuable for their learning, and the vast majority agreed the IBLA increased their understanding of dynamics. Students also mildly agreed that this activity was interesting and motivating for them.

The pre-IBLA question’s coupled explanation was free response for this experiment, so we could collect additional data for the CMR reasoning question. In the future, we will give the CMR pre- and post-IBLA to allow us to compare the changes in student reasoning due to the IBLA. We will also use the survey responses to modify the IBLA and consider making the activity shorter for students. In the future, we also plan to analyze the performance of students in relation to their ethnicity, gender, etc. to identify possible correlations between student performance and feelings of belonging in the classroom.

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Bibliography


