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Development and Assessment of an Inquiry-Based Learning Activity in Dynamics: A Case Study in Identifying Sources and Repairing Student Misconceptions

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Abstract

A fundamental question in teaching engineering Dynamics is how to develop pedagogy to repair deeply ingrained student misconceptions about the physical world. This paper documents the development and assessment of an Inquiry-Based Learning Activity (IBLA) used to repair student misconceptions in an introductory Dynamics course. IBLA's consist of presenting teams of students with a physical situation and asking them to predict what will happen. The students next investigate the situation by experimenting with actual hardware that becomes the "authority", thus forcing students to confront their misconceptions. In this study, the authors developed an IBLA based on a question from the Dynamics Concept Inventory (DCI), a validated tool to assess conceptual knowledge in Dynamics. The IBLA was deployed in both an introductory and a second intermediate Dynamics course and assessed through pre-post DCI results, in class quizzes, homework problems, midterm questions and through written student reflections. Next, using videotape and peer prompting, the authors developed and collected a verbal protocol from individual Dynamics students as they worked through the activity using a "talk aloud" approach. Based on analysis of the videotaped transcripts a better understanding of the sources of misconceptions was identified and further refinements to the IBLA are being made. The paper contains the IBLA along with suggestions for implementation and improvements.

Introduction and Background

It is well documented that students enter the classroom with deeply rooted misconceptions.[1-3] This is especially true in STEM disciplines, where the literature contains thousands of studies of students' lack of conceptual understanding.[4] The importance of conceptual understanding for deeper learning has been documented in the National Research Council's How People Learn,[1] indicating that a greater emphasis must be placed on repairing student misconceptions. Unfortunately, identifying and repairing deep-rooted misconceptions is no easy task. One tool developed to identify conceptual understanding in Dynamics is the Dynamics Concept Inventory (DCI).[5] The DCI is similar to other instruments patterned after the Force Concept Inventory.[6] The DCI consists of 29 multiple choice questions that identify 14 common misconceptions in Dynamics. Once identified, however, robust misconceptions can often be difficult to repair. For example, physics students who learn in a traditional lecture format show only limited improvement in conceptual understanding[1,7] with one study indicating that traditional instruction may actually result in a decrease.[2]

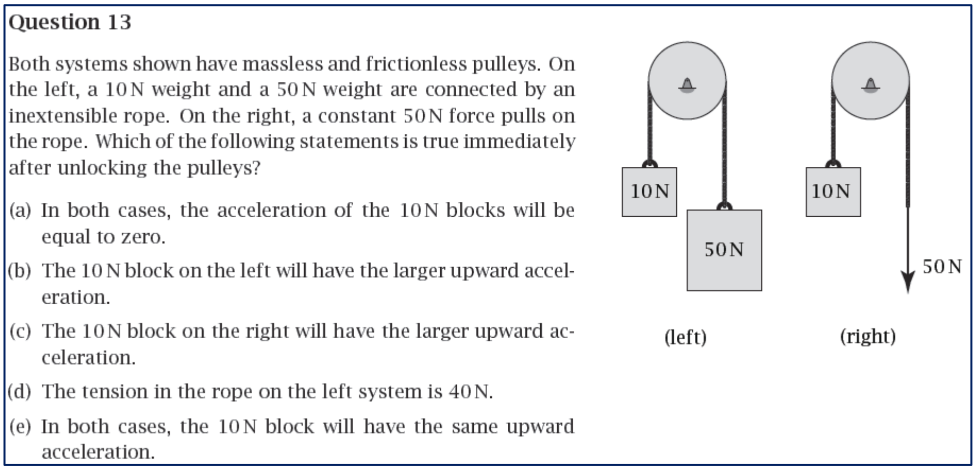
A group of pedagogical techniques known as Active Learning is gaining wider acceptance in engineering classrooms (see Prince[8] for a review). These types of interactive engagement have been shown to help repair student misconceptions.[7,9-10] One type of Active Learning, Inquiry Based Learning Activities (IBLA), are emerging as effective techniques to increase conceptual understanding in Heat Transfer[11,12] as well as in Dynamics.[13] IBLA's consist of presenting teams of students with a physical situation and asking them to predict what will happen. The students next investigate the situation by experimenting with physical hardware that becomes the "authority", thus forcing students to confront any misconceptions. Although the exact definition of inquiry-based instruction varies somewhat between different investigators, this study uses the defining features offered by Laws et al.[14] and highlighted by Prince and Vigeant.[11] The basic content of an IBLA is summarized in Table 1

Table 1: Elements of Inquiry Based Learning Activities.

(a) Use peer instruction and collaborative work
(b) Use activity-based guided-inquiry curricular materials
(c) Use a learning cycle beginning with predictions
(d) Emphasize conceptual understanding
(e) Let the physical world be the authority
(f) Evaluate student understanding
(g) Make appropriate use of technology
(h) Begin with the specific and move to the general

Development of a Dynamics IBLA

The primary goal of this investigation was to develop an IBLA to improve conceptual understanding of how net force and total inertia affect the acceleration of particles. Question 13 (see Figure 1) of the DCI tests understanding of this concept as well as the idea that tension in a rope holding a suspended weight does not equal the weight when it is accelerating.



Question 13

Both systems shown have massless and frictionless pulleys. On the left, a 10 N weight and a 50 N weight are connected by an inextensible rope. On the right, a constant 50 N force pulls on the rope. Which of the following statements is true immediately after unlocking the pulleys?

(a) In both cases, the acceleration of the 10 N blocks will be equal to zero.
(b) The 10 N block on the left will have the larger upward acceleration.
(c) The 10 N block on the right will have the larger upward acceleration.
(d) The tension in the rope on the left system is 40 N.
(e) In both cases, the 10 N block will have the same upward acceleration.

Figure 1: DCI Question #13

Results for this question in the initial testing of the DCI as reported by Gray et al.[5] is given in Table 2. Note that post-class test data indicates that only slightly better than 50% of students can answer this question correctly after completing a first course in engineering Dynamics. The most common incorrect answer in both pre and posttest was (e), namely that both blocks will accelerate identically. The DCI authors state that they believe the primary misconception comes from a “strong student belief that ‘tension = weight’.” Therefore the primary goals of this work were to improve conceptual understanding of how net force and inertia are related to acceleration using an IBLA and an understanding that tension in a cable does not equal the weight of a hanging mass if that mass is accelerating. Table 2 also contains data taken from classes taught by the authors at the authors’ home institution prior to the development of the IBLA. These classes already contained many elements of active learning and a deliberate emphasis on conceptual understanding which results in good performance on this DCI question. Specifically, the problem of dissimilar masses of an Atwood machine was presented in lecture and homework problems in those classes without any hardware implementation. The approach clearly led to post-class DCI averages that were higher than those reported by Gray et al.[5]; however, a significant motivation of this work is to develop an IBLA that can be easily deployed by any faculty member to improve conceptual understanding regardless of their class format. Details of the active approach taken in the existing Dynamics class can be found in Self and Widmann.[10]

Table 2: Reported DCI sample size, *n*, and percent correct results for Question 13

Sample Type	DCI Pre Dynamics Course		DCI Post Dynamics Course		Normalized gain
	n	% Correct	*n*	% Correct	
Large Public Univ.	441	4.6%	457	56.1%	0.539
Small Public Univ.	172	5.5%	166	36.1%	0.324
Cal Poly w/o IBLA	212	14.6%	194	87.1%	0.848

Mass-Pulley IBLA Development Process

In order to develop the most effective IBLA possible, an iterative development process is being employed. An initial mass-pulley demonstration was developed that mimicked question 13 from the DCI (DCI – Q13) and was presented to an Intermediate Dynamics Class as a demonstration. Based on initial feedback, the IBLA was finalized and deployed as a hands-on activity to students in an introductory Dynamics class. Student learning through the IBLA is supported by a homework problem assigned during the same week as the activity. Assessment of effectiveness was provided through pre-post DCI results, in class quizzes, embedded midterm problems and written student reflections. At the same time, the authors videotaped individuals from separate cohorts to better understand and identify sources of student misconceptions and how they might be repaired by the IBLA. This was accomplished through a “talk aloud” approach where students were prompted and encouraged to verbally express all thoughts as they worked through the IBLA. Based on results of the demonstration, initial deployment of the IBLA and the videotapes, a better understanding of the sources of misconceptions are being identified and further refinements to the IBLA will be made

Mass-Pulley Class Demonstration

The basis for the Mass-Pulley IBLA was first presented as a demonstration to students in a second course of “Intermediate Dynamics.” Note that at the test university, the students are on a

10-week quarter system where most engineering students take a first course in engineering Dynamics during their sophomore year after taking a mechanics course in physics during their freshman year. Mechanical Engineering students then take a second course in Dynamics ("Intermediate" Dynamics) early in their junior year. The cohort who witnessed the demonstration was not similar to the cohort of mixed engineering students who are the primary focus of this IBLA development. Also, only a handful of these students had the more active-learning, conceptually focused first course of Dynamics, so the data in the third row of Table 2 did not apply to this group. The demonstration provided insight into logistics and improvements necessary for a complete implementation of an IBLA as well as providing improvement in conceptual understanding for the cohort.

In the Intermediate Dynamics class, the students were asked to predict which of the systems shown in Figure 2 would accelerate more quickly prior to the demonstration. Predictions were collected online using Polleverywhere©[15] and then the demonstration was conducted. Immediately after the demonstration, the instructor led a class discussion concerning the concept of net force and inertia and why the system behaved as observed. At the next class meeting, the students were given a quiz (see Figure 3) which asked them to rank which of the four systems would accelerate the slowest to the fastest. Several weeks later the students were asked a midterm question (see Figure 4) that tested whether the students could transfer the concept to a new situation. Finally, the students took the DCI at the end of the course to assess conceptual gains. Results from this preliminary implementation are given in Table 3.

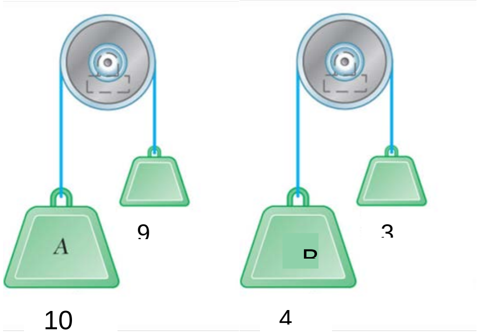


Figure 2: In Class Demonstration Setup

Problem 1. The four different systems (a) – (d) are released from rest in the positions shown. Rank which "Block A" accelerates downwards, from slowest to fastest. Assume the pulleys have negligible mass and friction.

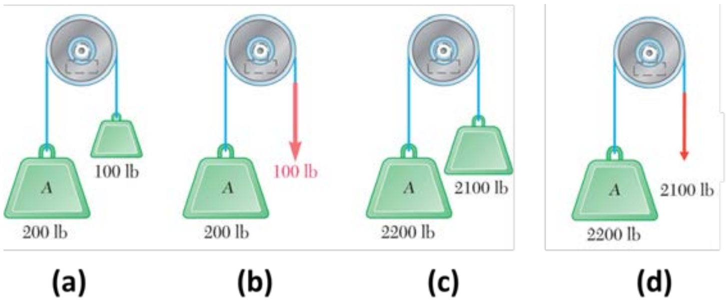
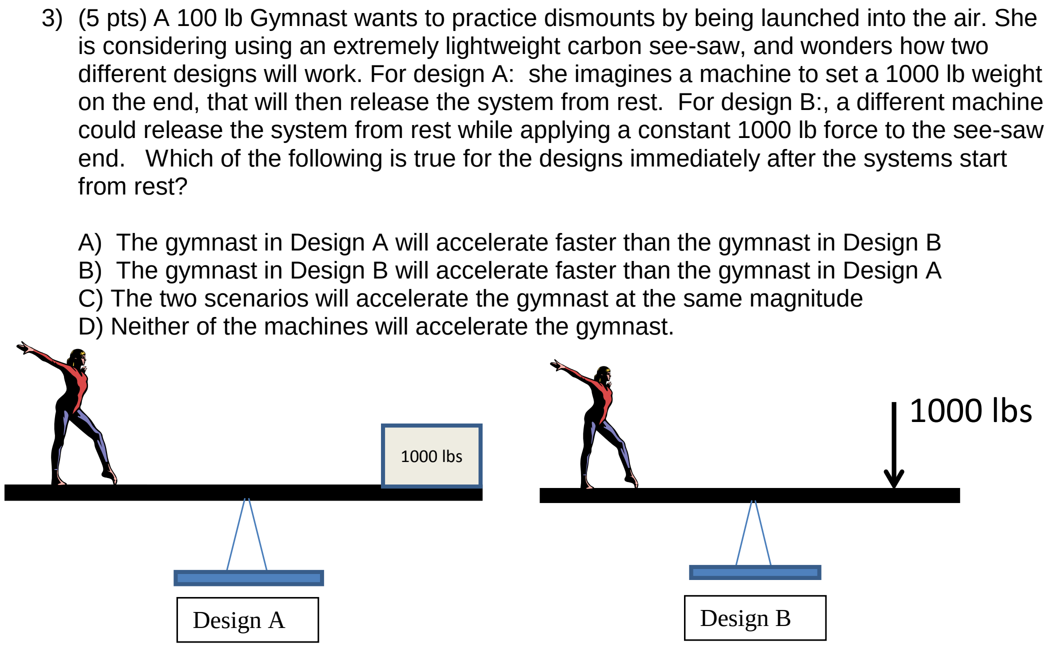


Figure 3: Ranking Quiz



3) (5 pts) A 100 lb Gymnast wants to practice dismounts by being launched into the air. She is considering using an extremely lightweight carbon see-saw, and wonders how two different designs will work. For design A: she imagines a machine to set a 1000 lb weight on the end, that will then release the system from rest. For design B:, a different machine could release the system from rest while applying a constant 1000 lb force to the see-saw end. Which of the following is true for the designs immediately after the systems start from rest?

A) The gymnast in Design A will accelerate faster than the gymnast in Design B
B) The gymnast in Design B will accelerate faster than the gymnast in Design A
C) The two scenarios will accelerate the gymnast at the same magnitude
D) Neither of the machines will accelerate the gymnast.

Figure 4: Midterm Question

Table 3: Results for In-Class Demonstration (*n* = sample size)

DCI- Q13 Pre Class		Individual Pre-Activity Prediction		Team Pre-Activity worksheet		Post Activity Quiz		Midterm Question		DCI- Q13 Post Class		Normalized DCI Gain
n	Correct	*n*	Correct	*n*	Correct	*n*	Correct	*n*	Correct	*n*	Correct	
67	43.3%	68	50%	68	75%	55	60%	68	72%	71	87.3%	0.776

Initial Mass-Pulley IBLA

Although the gains from the in-class demonstration were encouraging, further improvements to the IBLA were made in an attempt to improve its effectiveness. Major changes included having the hands-on activity include three experiments instead of one. This repetition would allow the students to fully explore the concepts and to make sure that they correctly understood how inertia affected acceleration. Thus the students who initially did not understand the concept would have the opportunity to correct their misconceptions and verify their knowledge with physical observations. To accommodate the added experiments and to minimize the amount of hardware, the weight values used in the experiments were changed to 5, 6, 9 and 10 ounces. The three experiments involved using different combinations of the weights hung from the pulleys. The IBLA was deployed in a first course of dynamics run in the spring of 2013 and again to two sections in the fall of 2013. Each class has nominally 36 undergraduates necessitating the creation of nine sets of experimental hardware for the students working in teams of four. The hardware consists of two pulleys attached to a wooden dowel which can be held by a single student. The cord draped over each pulley has a mass attached to each end making up two different mass –pulley systems allowing the motion of the two systems to be compared side-by-side. The students are told that the pulley inertia, rope mass, and friction are negligible. Note that due to the difficulty in constructing an applied massless constant force, none of the tested systems corresponds exactly to the DCI question. When the students have the systems set up, they can release them simultaneously from rest and determine which accelerates faster. Figure 5 shows students conducting these "races."

It took the students about 25 minutes to complete the three experiments. The three experimental weight combinations are shown in Figures 6-8 and the complete IBLA handout is given in Appendix A. For the first two cases, the net force is the same for each system, but the total inertia of each system is different. In Case C, the total inertia of the two systems is the same, but the net force is different. For each case, the students are asked to predict which of the two systems will accelerate faster or whether they will accelerate at the same rate. The students also discuss their predictions with their teammates prior to running the experiments; then they let the physical world be the judge. Afterwards the students were asked to explain the system behavior in writing using Dynamics principles.

Figure 5: Students using the Mass-Pulley IBLA

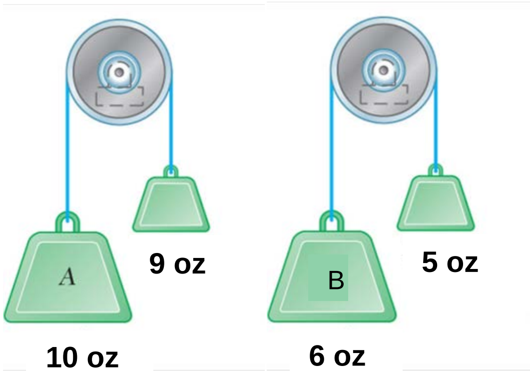


Figure 6: Weight Systems for Case A.

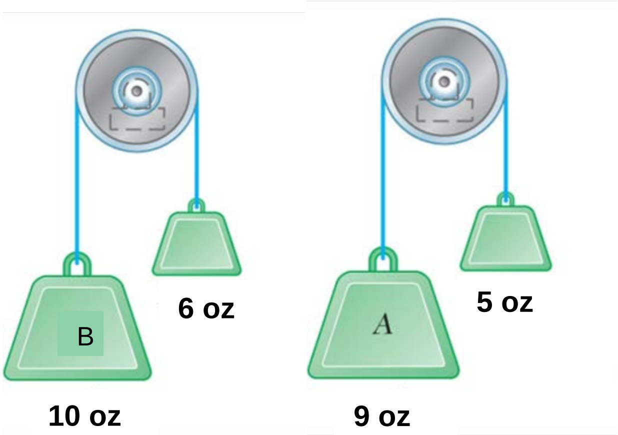


Figure 7: Weight systems for Case B.

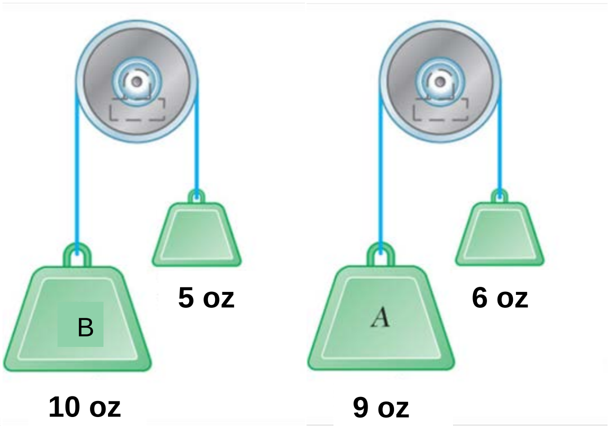


Figure 8: Weight Systems for Case C.

Conceptual gains from the Mass-Pulley IBLA were assessed in a similar way as the class demonstration in the "Intermediate" Dynamics Class. At the beginning of the quarter the students took the DCI to establish a baseline of conceptual understanding. After completing the IBLA, the students were given an analytical homework problem that required them to calculate the accelerations of the blocks. They were also given the conceptual ranking task in the class period following the IBLA and the question on the midterm as previously shown in Figures 3 and 4.

During the last week of class, the students were again given the DCI to measure conceptual gains and finally a survey was given at the end of quarter eliciting feedback on student impressions of the learning process. The results of the initial IBLA implementation are given in Table 4. Note that this table contains only available data from two different quarters and therefore the sample size varies depending on the available data for each category

Table 4: Results for IBLA (*n* = sample size)

DCI- Q13 Pre Class		Team Worksheet Predictions						Post Activity Quiz		Midterm Question		DCI- Q13 Post Class		Normalized DCI Gain
		Case A		Case B		Case C								
n	Correct	*n*	Cor.	*n*	Cor.	*n*	Cor.	*n*	Correct	*n*	Correct	*n*	Correct	
93	14.3%	33	63.6%	33	90.9%	33	96.9%	66	27.3%[*]	96	80.3%	94	90.0%	0.883

[*] Students had difficulty transferring to the applied “massless” load on the post activity quiz. In general however they understood (75.8%) that the higher inertia would result in lower acceleration.

Talk-Aloud Video-Taped Students

In order to further explore the source of student misconceptions and improve the effectiveness of the Mass-Pulley IBLA, individual students were videotaped using a “talk aloud” protocol as they worked through the IBLA for the first time. In this protocol the students were asked to read all questions out loud and talk through their thinking as they attempted to make predictions about the behaviors of the mass-pulley systems. A student researcher acted as the interviewer and reminded the student subject to say out loud what they were thinking. The interviewer also asked for clarification of student statements. Finally the interviewer intervened to explain a concept if the subject become “stuck” and could not continue.

In order to familiarize the subject with the process of “thinking out loud,” a practice problem was provided involving the concept of work-energy. After working the practice problem, the interviewer gave the subject feedback and encouragement to share all their thinking out loud as they went through the Mass-Pulley IBLA. After this, the students performed the IBLA with prompting from the interviewer. An additional case was added to the end of the video-taped session as shown in Figure 9 to assess student understanding of an applied force (similar to the DCI-Q13). All activities were video recorded and analyzed by the researchers to identify stated misconceptions and how they were confronted by the students. After the session, all student questions were answered.

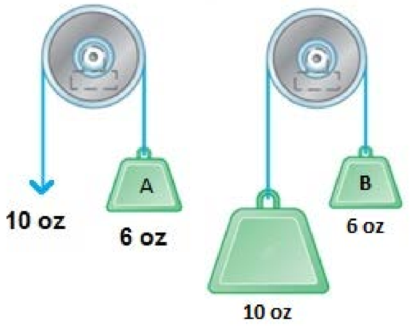


Figure 9: Additional Case D for Videotaped Student Predictions (no experiment involved)

In the fall of 2013, five student volunteers who were taking the first course in Dynamics from a section that did not use the IBLA were videotaped performing the IBLA as individuals. The videotaping occurred towards the end of the course, so the students already had experience with particle and rigid body dynamics. Also, the students from this particular class were given an analytical midterm question where they analyzed an Atwood machine so they had some experience with the question. Analysis of the video indicated a wide variety of student thinking with two of the students exhibiting a similar (and incorrect) pattern of thought. The student predictions for each case are given in Table 5.

Both students #2 and #4 both incorrectly assumed that the total system inertia would determine which accelerated faster with the system having less mass the winner. This allowed them to get both Case A and Case B correct since the net force on the systems was the same, but did not allow them to correctly predict Case C. After confronting their misconception they were able to determine that it is the net force divided by the total mass that determines the acceleration and were able to master case D. Student #1 focused on the fact that the hanging masses caused a net force difference that controlled the acceleration (essentially ignoring the inertia of the systems). This led them to incorrectly predict that the systems in Case A would have identical acceleration. After seeing that their prediction was wrong, the student decided that inertia is the only effect that controlled acceleration. This led to a correct prediction for Case B, but not for Case C. After an intervention the student was able to correctly predict Case D. It is notable that on several occasions the student referred to getting the correct answers by memorizing what they had seen in the past and blamed their inability to predict all cases by the fact that "…all the problems in homework were not like that" indicating a preference to memorize whenever possible.

Student #5 correctly predicted Cases A and B based on lower system inertia, but failed to see the attached blocks as a system. The student exhibited confusion in both Case C and D and failed to see the two blocks tied together as a single system. At one point he accused the interviewer of trying to "trick" him. Finally, student #3 was able to predict all cases correctly with high confidence. This student explained that acceleration was governed by the ratio of the lower mass divided by the higher mass. Whichever system has a lower ratio will accelerate faster. This explanation was also given by several of the teams on the IBLA worksheets during the classroom implementation. This explanation is indeed correct (see Appendix B for details), but without some analytical work it is unclear how the student could arrive at this conclusion unless they had previously conducted the proper analysis. Of course the IBLA confirms through experimentation the validity of the "ratio" explanation.

Table 5 Videotaped student Predictions (**Bold** Represents correct Prediction

Student #	Case A	Case B	Case C	Case D	Misconception(s)
1	Same	**Mass B**	Same	**Mass A**	Inertia has no effect/Inertia is only effect
2	**Mass B**	**Mass B**	Same	**Mass A**	Inertia is all that matters
3	**Mass B**	**Mass B**	**Mass A**	**Mass A**	Unclear
4	**Mass B**	**Mass B**	Same	**Mass A**	Inertia is all the matters
5	**Mass B**	**Mass B**	Same	**Mass A**	Fails to see the blocks as a system

Discussion, Conclusions and On-Going Work

It is evident that the Mass-Pulley IBLA is successful at making clear the concept that acceleration of particles is proportional to the net applied force and inversely proportional to the amount of inertia, with large percentages of students scoring well on post class DCI exams. Less clear is whether the IBLA has a more profound effect than simply exposing the students to an Atwood machine through lectures, homework and/or quizzes. Students who were exposed in this manner also did well on the post-class DCI (see Table 2). Of course the IBLA very closely resembles the DCI question and as one videotaped student pointed out clearly that memorization can be an effective method of “getting the right answer” on the DCI. What is clear is that the use of a team-based, hands-on approach leads to greater student discussion and interaction with the material. The literature[9] generally indicates that this type of active, peer based learning with instructor intervention can lead to deeper and more profound learning.

A five point Likert-scale survey was given at the end of the course (1=strongly disagree | 2=disagree | 3=neither agree nor disagree | 4=agree | 5=strongly agree) with results shown in Table 6. In general students found the activity interesting and motivating and recommended using it in the future. It is interesting that only 75% of the students stated that they fully trusted the results. Like other hardware based IBLA’s, it is best to make the results clear to the students so there is no room for interpretation. For this IBLA, the accelerations of the two systems of Case B are similar. Sometimes the experiment must be run several times before all students are convinced which system accelerates faster. A potential future improvement would be to change the mass values to make the winner for this case more clear.

Table 1. Mass-Pulley IBLA Survey Results

<table>
<tr><td>The mass-pulley lab was interesting and motivating:
4.1 /5.0</td><td>The mass-pulley lab helped me learn about F = ma:
3.9 /5.0</td><td>You should do the mass-pulley lab in future sections of the course:
4.1 / 5.0</td></tr>
<tr><td>Having the professor do a pulley demo at the front of the room would be just as effective as the group activity:
3.0 / 5.0</td><td colspan="2">Did you trust the results of the pulley lab?
• Yes - 75%
• A bit skeptical - 18.75%, with responses:
-“Due to masses hitting each other”
- “Race result seemed to close to call”
• Not there - 6.25%</td></tr>
</table>

For future work, the authors plan to continue with more videotaping of individual students performing the IBLA to gain better insight into common student misconceptions. Changes and improvements to the IBLA will be informed by this information. Of particular interest is how student understanding changes over time and is transferable to new situations. Finally, Table 2 indicates a widespread need for improved conceptual understanding in Dynamics. We plan on making this activity easily adoptable to other faculty in an effort to spread these novel and effective educational activities.

Acknowledgements

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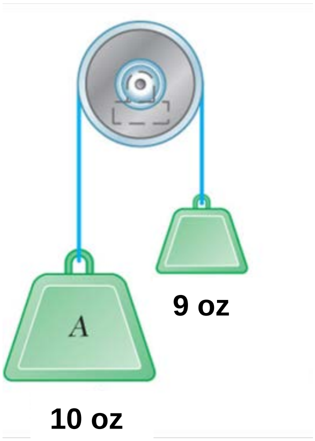
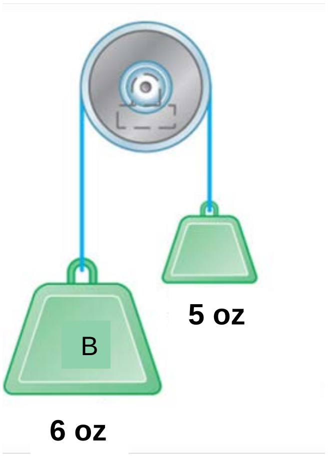
Appendix A: Mass Pulley IBLA Worksheets

When handling the pulleys:
-Release the masses in each case from at least 25 inches above the ground.
-Be careful with the rope because it can twist and tangle easily.
-Wind up the rope in a spiral when you are done with the activity.
-Attach masses at its yarn loop and use metal clasp attached to the main rope.
-To switch the masses around, open the clasps with your thumb (see side picture)

Case A:





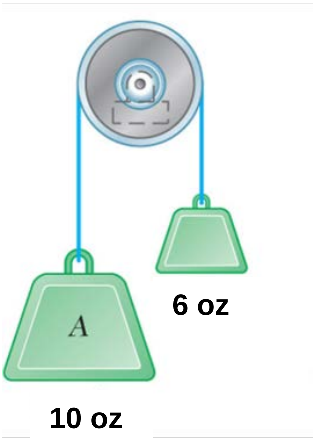
1. Consider the masses A and B with weight as shown. What do you predict about the accelerations of the masses if they are released from rest? Indicate the # of votes on your team of the four give possibilities below.

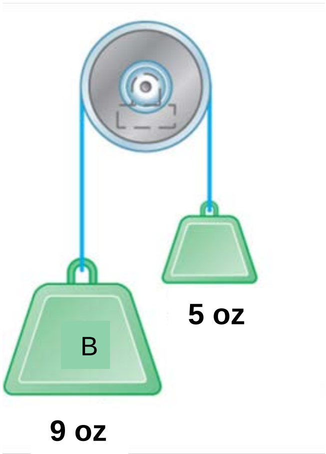
________ Mass A will accelerate downwards faster than mass B
________ Mass B will accelerate downwards faster than mass A
________ Mass A and B will accelerate downwards at the same rate
________ Neither Mass A or B will accelerate downwards

2. What did you observe when performing the experiment?

3. Please explain the results of your experiments using dynamics principles.

Case B:





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________ Mass A will accelerate downwards faster than mass B

________ Mass B will accelerate downwards faster than mass A

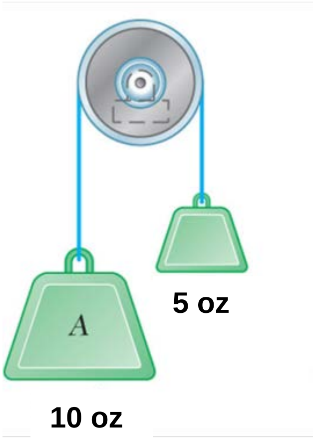
________ Mass A and B will accelerate downwards at the same rate

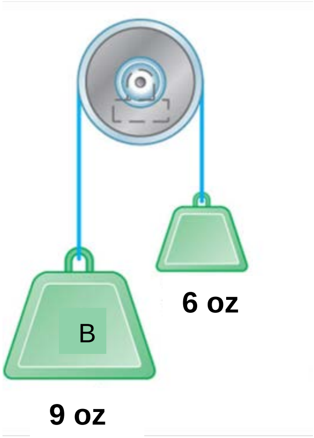
________ Neither Mass A or B will accelerate downwards

2. What did you observe when performing the experiment?

3. Please explain the results of your experiments using dynamics principles.

Case C:





1. Consider the masses A and B with weight as shown. What do you predict about the accelerations of the masses if they are released from rest? Indicate the # of votes on your team of the four give possibilities below.

________ Mass A will accelerate downwards faster than mass B
________ Mass B will accelerate downwards faster than mass A
________ Mass A and B will accelerate downwards at the same rate
________ Neither Mass A or B will accelerate downwards

2. What did you observe when performing the experiment?

3. Please explain the results of your experiments using dynamics principles.

Appendix B: Mass Pulley "Ratio" Explanation

In many of the cases, students using the IBLA used various explanations of dynamics principles to relate the behavior between the neighboring pulley systems. Students responded with such things as *"the bigger ratio between masses in the first system will yield a larger acceleration."* The ratio of masses in a pulley system does positively correlate with block acceleration as seen in the equations below.

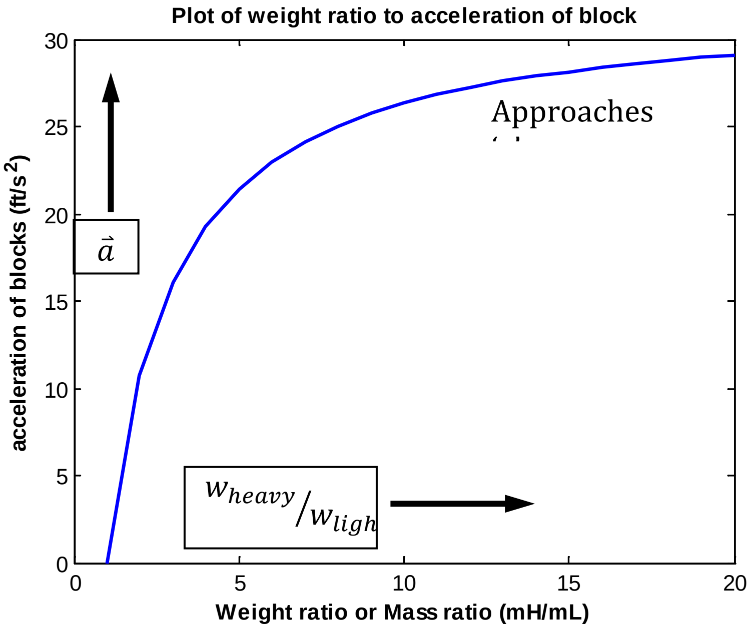
$$\vec{F}_{net} = m \times \vec{a} \tag{1}$$

$$\left(w_{heavy} - w_{light}\right) = \frac{\left(w_{heavy} + w_{light}\right)}{g}\,\vec{a} \tag{2}$$

$$\vec{a} = \frac{g\left(w_{heavy} - w_{light}\right)}{\left(w_{heavy} + w_{light}\right)} \tag{3}$$

$$\vec{a} = \frac{g\left({}^{w_{heavy}}/_{w_{light}} - 1\right)}{\left({}^{w_{heavy}}/_{w_{light}} + 1\right)} \tag{4}$$

Thus, as the ratio ${}^{w_{heavy}}/_{w_{light}}$ or ${}^{m_{heavy}}/_{m_{light}}$ increases, so does the acceleration. (Equation (4) is plotted).



Plot of weight ratios to acceleration of block