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Inquiry-Based Learning Activities in Dynamics

Dr. Brian P. Self, California Polytechnic State University

Dr Self has taught in the Mechanical Engineering Department at Cal Poly, San Luis Obispo since 2006. Prior to that, he worked in the Air Force Research Laboratories before teaching at the U.S. Air Force Academy for seven years. During the 2011-2012 academic year he participated in a professor exchange, teaching at the Munich University of Applied Sciences. His engineering education activities 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. Dr 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.

Dr. James M Widmann, California Polytechnic State University

Jim Widmann is a Professor of Mechanical Engineering at California Polytechnic State University, San Luis Obispo. He received his Ph.D. in 1994 from Stanford University. Currently he teaches mechanics and design courses. He conducts research in the areas of machine design, fluid power control and engineering education. He is a past Chair of the ASEE-DEED Division and a U.S. Fulbright Scholar.

Dr. Michael J. Prince, Bucknell University
Jeffrey Georgette

Jeffrey Georgette is a masters student in mechanical engineering at Cal Poly San Luis Obispo.

Inquiry-Based Learning Activities in Dynamics

Abstract

Inquiry-based learning activities (IBLA) consist of presenting teams of students with a physical situation and asking them to predict what will happen. They can then investigate the situation by experimenting with the laboratory materials. In this way the physical world is now the "authority" rather than the instructor. IBLAs, which have been shown to be extremely successful in the physics community[1], have been developed for an engineering dynamics course. Two initial IBLAs, involving a spool (or yo-yo) and rolling cylinders, were implemented in the Fall of 2012. Assessment of the IBLAs includes pre- and post- Dynamics Concept Inventory data, targeted quiz and final exam questions, and subjective responses from students.

Introduction

Although engineering professors are often successful in teaching students how to choose and apply an appropriate equation, we are typically less successful at producing true conceptual understanding in our students. The problem is widespread through STEM disciplines, with nearly 7700 reported studies of student misconception in the literature[2]. The importance of conceptual understanding has also been highlighted in the National Research Council's study *How People Learn*[3]. Two of their three key findings concentrate on conceptual understanding: one is the need to identify and engage student conceptual knowledge (and later challenge misconceptions), and the second is the need for students to organize new facts and knowledge within a unifying conceptual framework. To truly learn, students must master engineering concepts, not simply memorize facts and correctly choose and apply correct formulas[4-6].

In order to progress through the engineering curriculum, it is imperative that students have a strong *conceptual* understanding of the material. This understanding serves as a framework that students can use to organize new information and facts; otherwise, their learning will consist of a loose assortment of new facts and knowledge (which is much more easily forgotten). While these students can often solve problems similar to what they have seen (typically through algorithmic substitution), it is much more difficult for them to transfer their new knowledge to different situations without a strong conceptual framework

It is often disconcerting for instructors to find out how poorly their students perform on conceptual based tests[4,7]. Many professors assume that students show mastery of the concepts by performing satisfactorily on homework-type problems. Performance on the Dynamics Concept Inventory at the end of a dynamics class show students average anywhere from 32.1% to 63.9%[8]. Over the last three years, the PI's experiences have shown that students typically average between 50-60% on the DCI after completing a quarter's worth of dynamics. It is evident that simply learning the correct equations to apply does not mean a student has mastered the conceptual content of a course[9,10].

There is also evidence that simply telling a student about a misconception does not necessarily "repair" that misconception. Traditional lecture methods have been shown to have limited effectiveness on improving student conceptual understanding in basic physics courses[1,11]. One study has shown that traditional instruction may even result in a decrease in conceptual understanding[4].

What Can We Do About It?

Research has shown that students enter classrooms with persistent, strongly-held misconceptions that can be extremely difficult to identify and to repair [3,4,12]. It is difficult to change a student's conceptual framework by simply telling them that their robust view of the physical world is incorrect when everyday experience has reinforced this framework. Students know that heavier objects such as books drop more quickly than lighter objects such as paper, and instructors may reinforce this idea by teaching that the force due to gravity on heavier objects is greater than that on lighter objects. Although students may correctly choose appropriate equations to apply to homework-type problems, they may still leave courses with an insufficient conceptual understanding necessary for subsequent courses.

The physics educational community has shown that this situation can be improved. In a study involving 6,000 students, Hake[11] showed that instruction that involved active learning and that stressed conceptual understanding resulted in much larger conceptual gains than traditional lecture-based approaches. There is a growing body of literature supporting active learning in engineering education (see Prince[13] for a review), and it appears that this message is being heard. In a pilot study, we found that active-learning based courses resulted in an 8.5% larger normalized gain on the DCI than traditional instruction (see Table 1). Additionally, active engagement methods of instruction may not only result in higher conceptual understanding, but have also been shown to result in equivalent or sometimes better quantitative problem solving skills[14-16].

Table 1. Total pre and post DCI scores for Active Learning and Traditional classrooms.

	# of Students	Value	Pre DCI Results [%]	Post DCI Results [%]	Overall Average Normalized Gain [%]	Overall Average Percent Improvement [%]
Active Learning	149	Mean	29.85	49.97	29.6	20.11
		Median	27.59	48.28		
		Standard Deviation	14.55	17.20		
Traditional Instruction	80	Mean	32.97	46.64	21.1	13.66
		Median	31.03	44.83		
		Standard Deviation	14.19	18.33		

An approach that shows great promise is that of inquiry-based instruction. This consists of presenting teams of students (also introducing the benefits of collaborative learning) with a physical situation and asking them to predict what will happen. They can then investigate the situation by experimenting with the laboratory modules. In this way the physical world is now the "authority" rather than the instructor. As shown in Figure 1, Laws et al.[1] have shown that using inquiry-based active learning instruction (identified as "New Methods") dramatically increases student performance on questions relating to force, acceleration, and velocity.

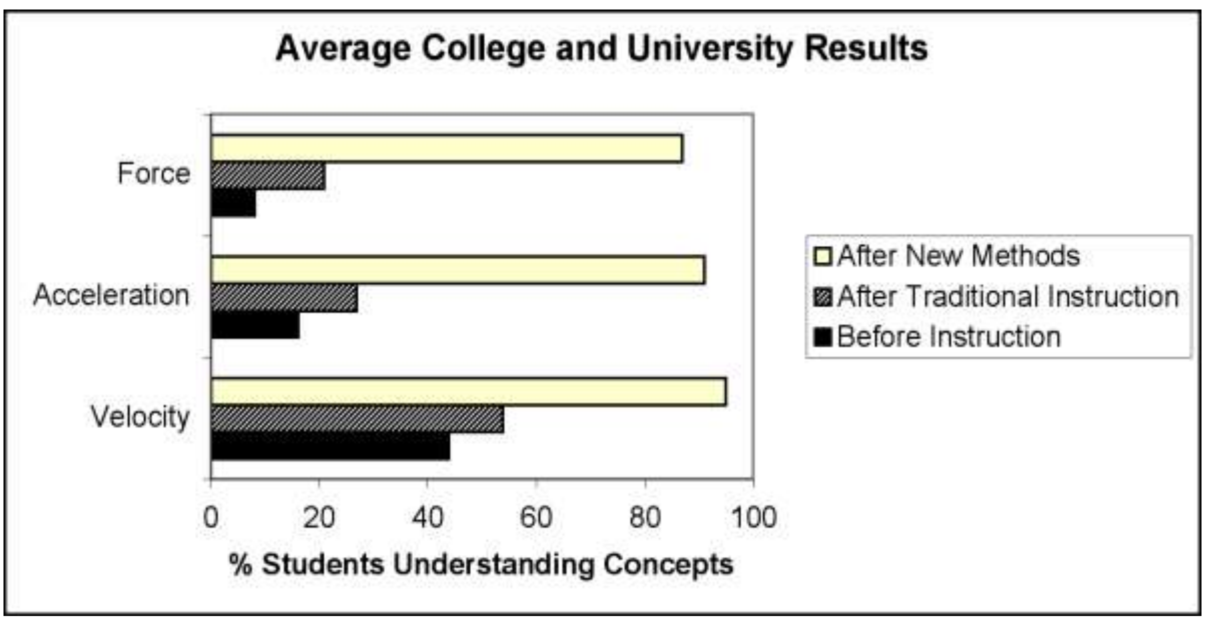


Figure 1. Active-engagement vs. traditional instruction for improving students' conceptual understanding of basic physics concepts (taken from Laws et al.,[1]).

Although the exact definition of inquiry-based instruction varies somewhat between different investigators, we will use the defining features offered by Laws et al.[1] and highlighted by Prince and Vigeant[17] and summarized in Table 2.

Table 2: Elements of Inquiry-Based Activity Modules

(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

While prevalent in the physics educational community, inquiry-based activities have only just begun to be used in engineering education. Steif and Dollár [18] have had teams of students use physical demonstrations to investigate statics (see example in Figure 2) but did not follow all of the guidelines set forth in Table 2. The work of Prince and Vigeant has shown great promise in the fields of heat transfer and thermodynamics, as can be seen in Figure 3. Our goal is to achieve similar gains in the field of dynamics.

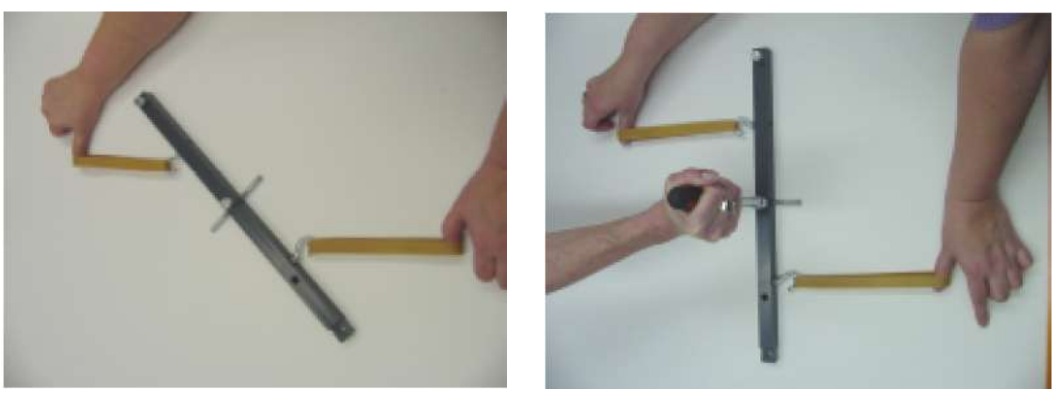


Figure 2. Physical demonstrations showing the idea of a force couple and a moment (from Steif and Dollár [18]).

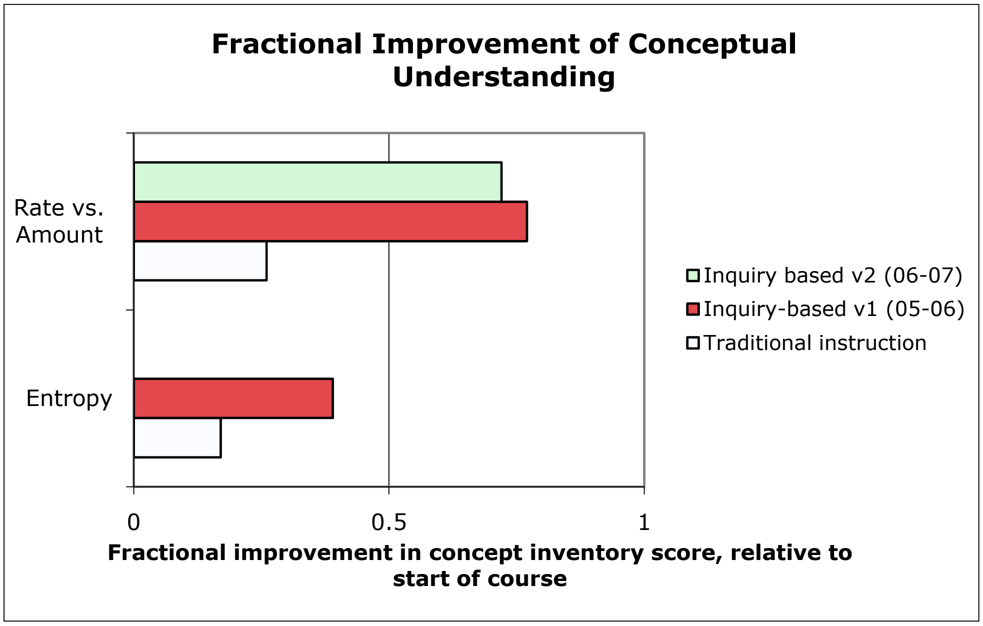


Figure 3. Improvement of conceptual understanding using traditional and inquiry-based instruction methods in heat transfer (unpublished results from Prince and Vigeant).

Dynamics

Undergraduate dynamics is often cited as one of the most difficult courses that engineering students must take (in a recent survey of our classes, 95% of students reported that it was either *the* hardest of one of the hardest courses they had so far). It is typically the first truly challenging engineering course in the curriculum, and many of the topics are in direct conflict with their perception of the world around them (e.g., there is no such thing as centrifugal force). As discussed previously, these students often hold many robust misconceptions. These have been extensively studied through the use of the Force Concept Inventory, which indicates that many misconceptions are not corrected during introductory physics courses. For example, students often forget about Newton's third law when asked about the forces involved when a large SUV hits a motorcycle. Students also frequently assume that energy is conserved during such an impact. Additional misconceptions are elicited when dealing with rigid bodies (e.g., students often do not understand that bodies have both translational and rotational kinetic energy). These rigid body misconceptions are in addition to the list of misconceptions developed for the FCI.

Spool Inquiry-Based Learning Activity

The first IBLA developed for Dynamics involves the direction of friction and motion for a rolling object. An online quiz, shown in Figure 4, was assigned the day before the activity. In this way, students are required to think about the situation before coming to class, and to make predictions about the behavior of the system. The primary concepts addressed are that the directions of the linear and angular accelerations have to match the directions of the net force and moment, respectively. During class, students are given spools and told to basically perform the "experiments" from the quiz the night before (see Appendix A for the Spool IBLA worksheet).

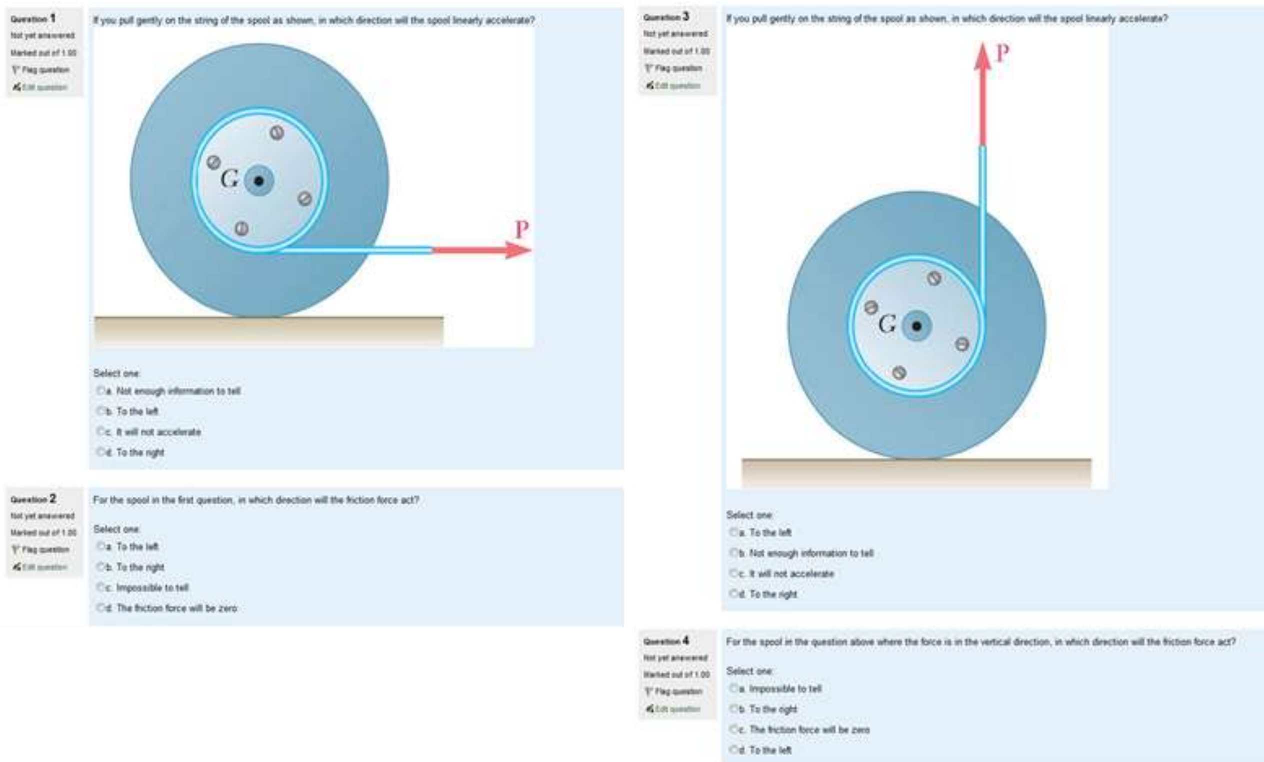


Figure 4. Online quiz given before the Spool IBLA.

An example of the student activity is shown in Figure 5. As the instructors circulated throughout the classroom, we occasionally probed the teams with pertinent questions, asked them the relevant dynamics principles, and encouraged them to draw free-body diagrams to help them think about the situation. After approximately 20 minutes, the class discussed the results and then took a "team quiz" (see Appendix B). This quiz involved a slightly different shape to see how well the teams could transfer the information learned during the activity.

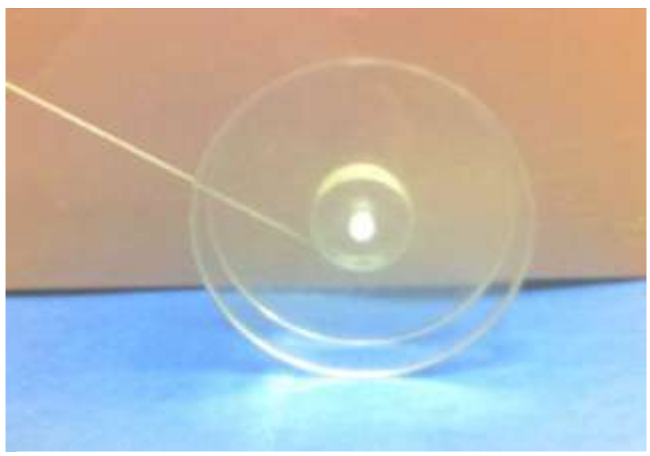
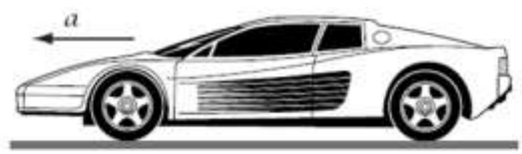


Figure 5. Testing during the Spool IBLA.

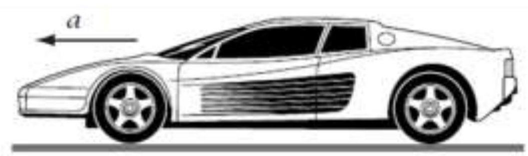
Another Dynamics concept associated with the Spool IBLA is the direction of friction acting on a rolling object. The direction of friction can be difficult for students when dealing with particles – it can become even more confusing with rigid bodies. When accelerating without slip, the friction of the drive wheel of a car acts forwards, while the friction on the non-drive wheel acts backwards. The Dynamics Concept Inventory (see www.ciHUB.org) has two questions which involve this, as shown in Figure 6. A final assessment was done on the final examination for the class, as shown in Figure 7.

For the *rear* wheel drive car, consider a situation in which the car starts from rest and accelerates to the left. The tires do not slip on the road. Assume the normal force on the rear tires is N_{rear} and the coefficients of static and kinetic friction are μ_s and μ_k, respectively. The friction force, F_{rear}, on the *rear* tires is given by what expression and what is its direction?



(a) $F_{\text{rear}} = \mu_k N_{\text{rear}}$ to the right.
(b) $F_{\text{rear}} = \mu_k N_{\text{rear}}$ to the left.
(c) $F_{\text{rear}} \leq \mu_s N_{\text{rear}}$ to the right.
(d) $F_{\text{rear}} \leq \mu_s N_{\text{rear}}$ to the left.
(e) Not enough information is given.

For the *rear* wheel drive car, consider a situation in which the car starts from rest and accelerates to the left. The tires do not slip on the road. Assume the normal force on the front tires is N_{front} and the coefficients of static and kinetic friction are μ_s and μ_k, respectively. The friction force, F_{front}, on the *front* tires is given by what expression and what is its direction?



(a) $F_{\text{front}} = \mu_k N_{\text{front}}$ to the right.
(b) $F_{\text{front}} = \mu_k N_{\text{front}}$ to the left.
(c) $F_{\text{front}} \leq \mu_s N_{\text{front}}$ to the right.
(d) $F_{\text{front}} \leq \mu_s N_{\text{front}}$ to the left.
(e) Not enough information given.

Figure 6. DCI questions dealing with friction and acceleration without slip.

You pull gently on the spool with a force T and cause it to roll without slip. Which way will the friction force act?

a. To the left

b. To the right

c. Upwards

d. Not enough information to tell

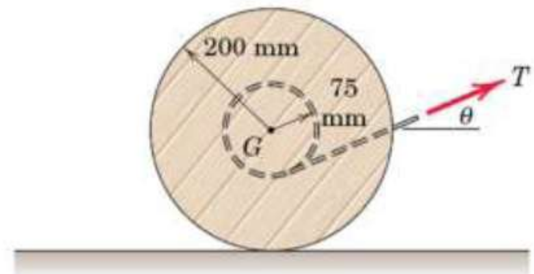
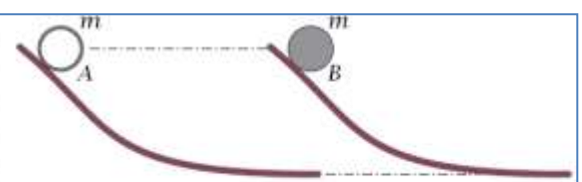


Figure 7. Final exam question assessing the Spool IBLA.

Cylinder-Pipe Inquiry-Based Learning Activity

A second IBLA created for Dynamics involves the rolling of Cylinders and pipes down a ramp. This IBLA directly addresses one of the questions in the DCI as shown in Figure 8. The test contains distracters that were generated from student answers to conceptual problems. The most commonly selected distracter for this problem is choice A, followed by B. This problem addresses the inertia of the two rolling objects – the thin hoop has more mass located away from the center of rotation, and therefore has a higher mass moment of inertia. The forces and moments are the same for both wheels; therefore, the cylinder on the right side will roll down the hill more quickly than the hoop. An inquiry-based module was created to help teach students concepts of mass distribution and work-energy (see Appendix B for the full worksheet). Several different metrics were collected to assess the usefulness of the IBLA: (a) DCI scores at the beginning and end of the course, (b) an in-class quiz immediately before the IBLA, (c) an assigned a homework problem that was based on the activity, and (d) a multiple choice question on the final exam. Both (c) and (d) can be found in Appendix B.

The two objects in the figure at the right are released from rest at the position shown and roll without slipping down identical hills. Both objects have the same mass m and same outer radius. Object A is a thin hoop whose mass is concentrated in its outer edge. Object B is a uniform solid cylinder. Neglecting air resistance, how do the speeds of the two objects compare when they reach the bottom of their respective hills?



(a) A and B will have the same speed.

(b) The speed of A will be greater than that of B.

(c) The speed of B will be greater than that of A.

(d) Knowledge of the friction forces is required to answer the question.

(e) Knowledge of the shape of the cross-section of the thin hoop is required to answer the question.

Figure 8. DCI question related to the Cylinder/Pipe IBLA.

The Cylinder-Pipe IBLA addresses the effects of distribution of mass with the first exercise (large metal solid cylinder and the black metal pipe with same radius, length, and mass). The IBLA then goes on to explore different concepts of work and energy. It ends up that as long as there is rolling without slip, all solid homogeneous cylinders will have the same linear velocity at the end of the ramp, *independent of mass and radius*. Furthermore, all solid cylinders will get to the bottom of the ramp before all pipes, regardless of the radius and mass. This is demonstrated by examining the work-energy equation: $T_1 + V_1 = T_2 + V_2$, where T and V are kinetic and potential energy, respectively. If the cylinder starts from rest, then $T_1 = 0$. For a given ramp, the change in height will be same for all circular objects. Therefore, we can rewrite the equation as:

$$mgh = \frac{1}{2} I_G \omega^2 + \frac{1}{2} m v_G \tag{1}$$

We now set the mass moment of inertia equal to cmr^2, where c is a scaling factor. For a thin ring, $c= 1$, and for a solid cylinder, $c= ½$. If we also substitute the roll without slip condition, $v_{center}= r\omega$, we obtain:

$$mgh = \frac{1}{2} cmr^2 \left(\frac{v_{center}^2}{r^2} \right) + \frac{1}{2} m v_{center}^2 \tag{2}$$

Solving for v_{center}, we see that the mass and the radius both cancel.

$$v = \sqrt{\frac{2gh}{1+c}} \tag{3}$$

Examining Eq (3), it can be seen that the linear velocity only depends on the mass moment of inertia factor, c. Therefore, a round object with a higher mass moment of inertia will get to the bottom of the ramp more slowly than an object with a smaller I_G. Many students realized that this really indicates a distribution of the translational and rotational kinetic energy of the objects. A cylinder will have greater translational energy than a pipe of identical radius and mass when released from identical locations on the ramp, and therefore will reach the bottom fastest.

Students performing the Cylinder/Pipe IBLA can be seen in Figure 9.

Figure 9. The Cylinder/Pipe IBLA.

Assessment

Spool IBLA. Table 3 shows (a) the pre- and post-DCI results of the rear and front wheel friction force questions, (b) the online quiz results from the day before the Spool IBLA, and (c) the results from the final exam question.

Table 3. Assessment of Spool IBLA; percentage of students answering the question correctly.

DCI (Fig 6)		DCI (Fig 6)		Online Quiz Problems (pre-IBLA) (Fig 4)				Exam
Friction on Rear		Friction on Front		Horizontal Pull		Vertical Pull		(Fig 7)
Pre	Post	Pre	Post	Motion	Friction	Motion	Friction	Friction
29.0%	57.4%	29.0%	51.1%	37.6%	69.5%	78.4%	70.5%	65.9%

Cylinder-Pipe IBLA. Table 4 shows (a) the pre- and post-DCI results of the ramp question, (b) the quiz results from the day before the IBLA, and (c) the results from the final exam question.

Table 4. Assessment of Cylinder/Spool IBLA; percentage of students answering the question correctly.

DCI (Fig 8)		Quiz (pre-IBLA) (App B)	Exam (App B)
Pre	Post		
31.3%	89.8%	43.4%	84.5%

Subjective Assessment

Students were asked a number of questions on an end-of-course survey. The first set used a Likert scale to determine if different course components (a) helped the students learn the material and (b) thought it was interesting and motivating. Averages for the responses are shown in Table 5, where 1= strongly disagree, 2= disagree, 3= neutral, 4= agree, and 5= strongly agree.

Table 5. Comparison of two IBLAs and a course project.

The ____ helped me learn the material.			**The ___ was interesting and motivating**		
Catapult project	Spool IBLA	Cylinder/Pipe IBLA	Catapult project	Spool IBLA	Cylinder/Pipe IBLA
3.93	4.11	4.38	3.96	3.83	4.12

Additionally, they were asked "When did the behavior of the spool finally make sense to you (e.g., in the middle of the activity, after you talked to your team about it, after it was discussed in class, when you took the quiz, after you saw the quiz solution, it still doesn't make sense….)?". The same question was asked about the behavior of the different rolling cylinders. Responses were coded and are tabulated in Table 6.

Table 6. Student responses as to when they understood the concepts in the IBLAs.

	Spool IBLA	Cylinder-Pipe IBLA
Understood beforehand	10	10
During/after quiz	10	2
During activity	36	52
Talking with team	42	36
After activity	6	7
Discussion in class	37	19
Studying it later	5	11
After homework	N/A	22
Still confused	22	7

Finally, we asked students if they had any suggestions to improve various course components. Only six students targeted the IBLAs – in the future we will ask more directed questions immediately after the activity and not at the end of the quarter.

Several of the comments requested more guidance during the activities, as shown below:

> *Tell us how the cylinders should behave and have us experiment to prove that that's true.*
>
> *Have teacher explain more or give hints to why before the spool and cylinder. We already get what you are trying to do, and don't want to sit there not understanding what is going on.*
>
> *Maybe have them do the math out for the rolling cylinders, then test to see it work, rather than try to guess on which one looks like it rolls faster, because it's pretty impossible to tell. We ended up just doing the math anyway to make sure because our visual results varied each time.*

Discussion and Conclusions

It is evident that the Cylinder/Pipe IBLA was more successful at clearing up the targeted misconceptions than the Spool IBLA. Even after the Spool IBLA, over a tenth of the students were still confused about the direction of the friction force. Our final exam question was slightly more in-depth (at an arbitrary angle) than the initial pre-activity quiz, but it is still disappointing that the students did not perform better on it. It should also be mentioned that the Spool IBLA targets more difficult topics than the Cylinder/Pipe one. The direction of the friction force cannot be visualized – only the direction of the motion can be explicitly seen. In the future, we plan to have a more in-depth discussion after the first horizontal pull, then have them complete the second portion with the vertical pull. We are also planning on developing a simulation module that would indicate the direction of the friction under different forces. Additionally, we will assign a homework problem, including some conceptual questions, to help solidify their learning.

The Cylinder/Pipe IBLA was successful, but we did encounter some difficulties during implementation. It is important to make the ramp angle shallow – otherwise small differences are exacerbated as the objects "race" to the bottom. As noted in student comments, the results are also somewhat dependent on the release of the objects. This may end up reinforcing student misconceptions – if the heavy steel cylinder beats the lighter, smaller wooden cylinder by even an inch, some students will decide that heavier cylinders will always beat the lighter ones. In the future we will experiment with an inexpensive "starting gate" to help alleviate this situation.

By carefully constructing inquiry-based activities where students must make predictions, experiment with a physical artifact, and explain the results, we can force students to confront their misconceptions head-on. Initial testing revealed that we must carefully craft the IBLAs in order to maximize conceptual conflict, and to develop proper conceptual understanding. Our engineering students seemed motivated by the experiments, and a great deal of good discussion could be heard as we walked around the room. In future work, we hope to ascertain exactly when students seem to understand the concepts, and the exact components necessary to make an effective inquiry-based learning activity for dynamics.

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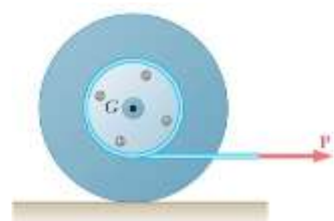
APPENDIX A

Spool Laboratory

1. Discuss the question from last night (pull on the string gently, which way will the disk move?

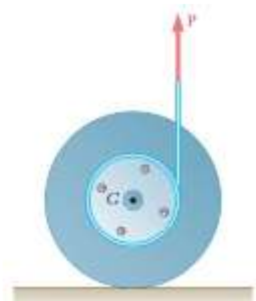
(Indicate # of votes): Right _______ Left ______Won't Move_______

2. Pull gently on the string in the configuration shown. Which way does it move? Which direction is the friction force?



Now pull on the string a bit harder so that it isn't rolling without slip. Which way do you think the friction force acts? It is probably in the same direction as above, but now it will be equal to what value?

3. Now pull gently on the string vertically. Which way does it go? Which way does the friction go?

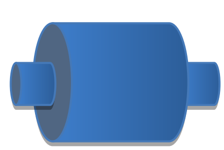


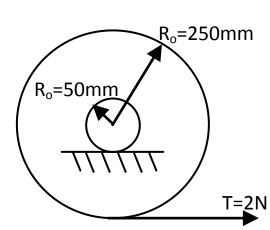
4. Try varying the angle of your pull, and how hard you pull on the string. When is the friction force equal to $\mu_s N$? $\mu_k N$? Explain your answers.

Post Spool IBLA Quiz

1. The spool shown has a cable wrapped around its OUTER diameter and rolls on its INNER diameter. Note that this is the opposite of the spools you have been playing with in class. This spool has an outer radius of 250mm and INNER radius of 50mm. The cord wrapped around the OUTER diameter is subjected to a pulling force of 2 Newtons. The spool has a mass of 1 kg and can be modeled as a uniform disk. If μ_s=0.3 and μ_k=0.2, determine the acceleration (magnitude and direction) of the center of the disk. Also determine the friction force and in your reflection, compare it to the Tension force.

Note for a uniform disk: $I_G = \frac{1}{2}mr^2$





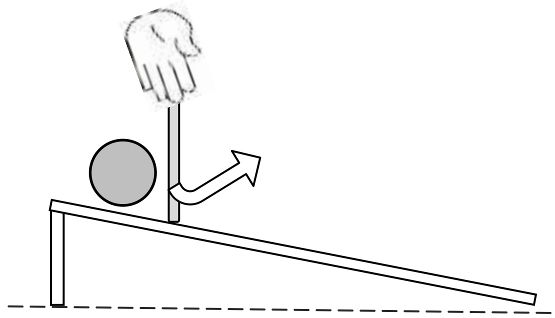
Appendix B: Cylinder-Pipe IBLA

Cylinder vs Pipe Laboratory

Setup

Create an incline with the ramp with a height of several inches using a book or steps.

Experiment



Place the rolling objects close to the top of the ramp and side by side. Create a 'starting gate' with the clipboard. To initiate the race, flip up the clipboard with both hands. When the objects roll to the bottom of the ramp catch them or use a cushion to stop them. Run the following scenarios and respond to the prompts.

Exercises

- Roll the **big metal solid cylinder** and the **black metal pipe.** (Same radius, length, and mass). State your prediction. State the post-race result. How do you explain the race result using principles of Dynamics?

- Next, roll the **small metal solid cylinder** and the **wood solid cylinder**. (Same radius and length, but different mass).
  State your prediction and state the post-race result. How does mass influence rolling behavior?

- Roll the **big metal solid cylinder** and **wood solid cylinder**. (Same length and shape, different mass and radius).
  State your prediction and state the post-race result. How do the cylinders compare to each other?

- Roll the **small PVC pipe** and **big PVC pipe** and **grey metal pipe**. (Same length and shape, different radius and mass).
  State your prediction and state the post-race result. What is the rolling behavior of pipes?

- Which has bigger Kinetic Energy when it reaches the bottom, the *big metal solid cylinder* or *black metal pipe*? (same mass and radius)

- Which has bigger Kinetic Energy when it reaches the bottom, the small metal solid cylinder or the wood solid cylinder big metal solid cylinder?

<u>Quiz Question Before the Cylinder/Pipe IBLA</u>

In the picture above, the cylinder (A) and the pipe (B) above have the same outer radius and the same mass. If they are released from rest and roll without slipping down identical ramps, which of the following statements is true?

a) The cylinder A will get to the bottom of the ramp first

b) The pipe B will get to the bottom of the ramp first

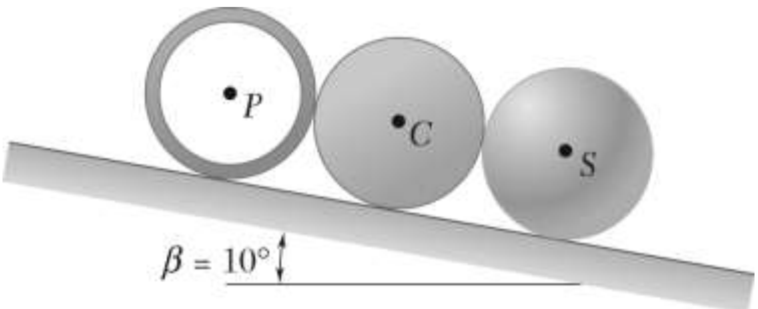
c) The cylinder A and the pipe B will get to the bottom of the ramp at the same time

d) There is not enough information to tell

Homework Due After the Cylinder/Pipe IBLA

1. Use the Work-Energy Equation to show that a cylinder will always reach the bottom of the ramp faster than a pipe with a small thickness, ***independent of mass or radius***.

2. A homogeneous sphere S, a uniform cylinder C, and a thin pipe P are each released from rest on the incline shown. Knowing that all three objects roll without slipping. Each has the same outer radius of 10 cm and the same mass of 1 kg. After rolling for 3 meters, calculate the linear velocity of each rolling object.



Final Exam Problem Assessing the Cylinder/Pipe IBLA

The thin disk (a) and ring (b) both have the same mass and radius. They are both released from rest in the horizontal position shown. Which will have the higher angular acceleration when they are released?

a. The thin disk (a) will have the higher angular acceleration

b. The ring (b) will have the higher angular acceleration

c. The disk and ring will have the same angular accelerations

d. Not enough information to tell