Increasing Conceptual Understanding and Student Motivation in Undergraduate Dynamics Using Inquiry-Based Learning Activities

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Abstract

To date, our team has created five hands-on inquiry-based learning activities (IBLAs) to engage students in conceptual learning in undergraduate dynamics. The activities allow the students to experiment with physical objects similar to those they might see in a homework problem, i.e. weights on a pulley, hollow and solid cylinders rolling down a ramp, gyroscopes spinning, and strings wrapped around spools pulled gently across a surface. The scenarios are designed to produce non-intuitive results, resulting in cognitive conflict. In this way, the activities intentionally challenge students to rethink their conceptual frameworks.

As part of this research, we identify the concepts used by the students as they piece together their observations in order to understand if meaningful learning is occurring. We also try to pinpoint how they have constructed their understanding and whether it is from observations in the world around them, learned in an introductory course prerequisite to dynamics, or something they have constructed by themselves using the information learned in the dynamics class in which they are currently enrolled. If a misconception is identified, we aim to tailor the activity to address and correct it. The overall goal of this research is to provide students with a coherent framework that pushes them to better conceptual understanding.

Assessment has been done in a variety of ways: analysis of video-taped think-alouds by individual students as they conduct the IBLAs, pre and post scores on the Dynamics Concept Inventory, performance on transfer problems, subjective questionnaires, and performance on their predictions as they walk through multiple cases of the IBLAs.

Introduction and Background

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 misconceptions in the literature[1]. The importance of conceptual understanding has also been highlighted in the National Research Council's study *How People Learn*[2]. 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 formulas[3-5].

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[44,7]. 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%[6]. Over the last three years, the authors' 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[7, 8].

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[9, 10]. One study has shown that traditional instruction may even result in a decrease in conceptual understanding[3].

What Can We Do About It?

A group of pedagogical techniques know as Active Learning is gaining wider acceptance in engineering classrooms (see Prince[11] 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 (IBLAs), are emerging as effective techniques to increase conceptual understanding in Heat Transfer[12, 13] as well as in Dynamics[14]. The term "inquiry" has been used to describe a number of teaching activities and has been used extensively in science education. The NRC[15] identifies five critical features of inquiry that extend across all K-12 levels:

1. Learners are engaged by scientifically oriented questions.
2. Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
3. Learners formulate explanations from evidence to address scientifically oriented questions.
4. Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding.
5. Learners communicate and justify their proposed explanations.

Minner et al[16] developed a framework for inquiry instruction that included the presence of science content, the type of student engagement, and the components of instruction. They then used this framework in a meta-analysis of 138 studies to examine the impact of inquiry based instruction on K-12 student science conceptual understanding. They found "a clear, positive trend favoring inquiry-based instructional practices, particularly instruction that emphasizes student active thinking and drawing conclusions from data."

Although inquiry-based instruction has been utilized extensively in science education, reports on using inquiry activities in engineering education appear to be quite limited. Prince et al.[12] have had success in implementing IBLAs in Chemical Engineering, particularly to look at heat, energy, and thermodynamics. Their work is based on that of Laws et al.[9] and on Workshop Physics (http://physics.dickinson.edu), which defines the elements of IBLAs as 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

Our IBLAs are typically composed of a series of scenarios. For each scenario, the students are first required to make predictions about the physical phenomena of interest, discuss their predictions with teams of students, observe the system experimentally, and then discuss and explain the experimental results on a team worksheet. When appropriate, direct instruction is incorporated together with these Predict-Observe-Explain cycles (Figure 1). With IBLAs, the focus is on conceptual understanding through the integration of hands-on activities in a cycle of predictions, observations, and explanations. In most of the initial scenarios, we hope to create cognitive conflict – challenging the students' current conceptual framework. Doing this with the physical world is much more powerful than just stating the guiding principles to the students. Finally, a homework problem with calculations is usually assigned to the students to further reinforce the primary concepts targeted by the IBLA.

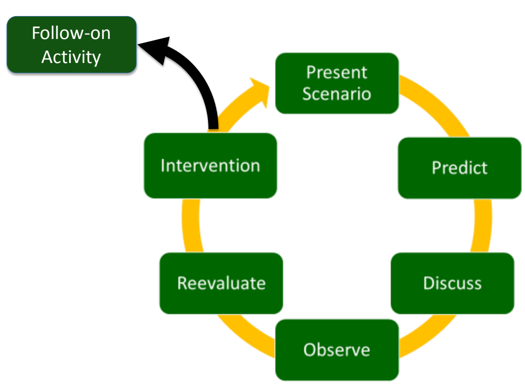


Figure 1. IBLA Learning cycle.

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 or 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.

Developing Dynamics IBLAs

To date we have developed five different IBLAs, as described in Table 2. Each of the IBLAs targets specific principles that students typically find to be difficult. The Pulley and the Impact Pendulum IBLAs are run in the first half of the course when we cover particle dynamics, the rigid body Spool and the Rolling Cylinders IBLAs take place in the second half of the course, and the Gyroscope IBLA is part of our follow-on course *Intermediate Dynamics* (but might be included at the end of a semester course that includes three-dimensional kinetics).

Table 2. IBLAs and their targeted principles.

IBLA	Targeted principle(s)
Pulley	Particle Newton's Second Law
Impact Pendulum	Particle Work and Energy; Impulse and Momentum
Spools	Relationships between (a) net force and linear acceleration; (b) net moment and angular acceleration; (c) linear and angular accelerations
Rolling Cylinders	Effect of mass distribution on rolling; Rigid body work and energy.
Gyroscope	Three-dimensional kinetics; gyroscopic moments; action and reaction

We now discuss the development of each IBLA and some examples of our assessment tools for evaluating IBLA effectiveness at increasing conceptual understanding and student interest.

Pulley IBLA

The Pulley IBLA was our first attempt at developing an activity and has the most research efforts of all our IBLAs. The premise is the Atwood machine[17], which has long been used in physics and dynamics courses to help teach Newton's second law[18, 19]. As shown in Figure 2, two different scenarios are presented, side-by-side, and students are asked to predict which system will have the greatest acceleration – A or B. This is an earlier version of our Pulley IBLA – information from our think-alouds and from Variation Theory prompted us to make updates to the scenarios.

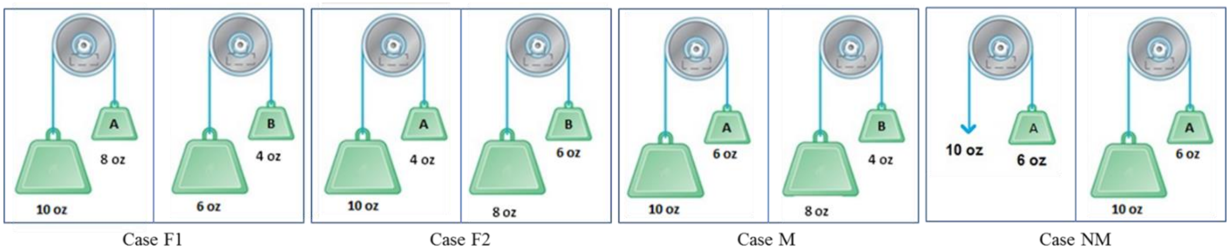


Figure 2. Pulley IBLA cases; F1 and F2 correspond to same net force, M to same system mass, and NM to no mass for one of the pulleys.

In earlier versions of the IBLA, we used Case NM for assessment rather than as an additional scenario. Additionally, we used Question 13 (see Figure 3) on the Dynamics Concept Inventory (DCI)[6] as well as a transfer question on the midterm to assess the effectiveness of the activity.

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.

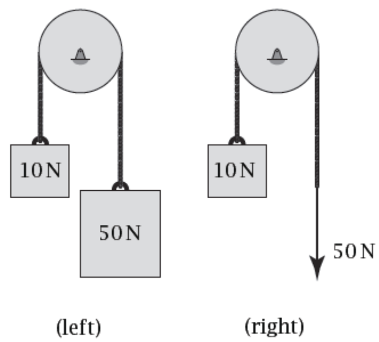


Figure 3. Question 13 on the Dynamics Concept Inventory.

Results from the pre-DCI Q13 (given approximately one week before the IBLA), team worksheet predictions, the post activity quiz (Case NM – that day), a mid-term transfer question (~3 weeks post IBLA), and the post-DCI Q13 (~8 weeks post IBLA) are provided in Table 3.

Table 3. 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 F1		Case F2		Case M								
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.

The think-alouds[20] revealed several alternate conceptions that we needed to address in implementing the Pulley IBLA. Several students focused on only one of the masses during the discussion, while others looked at either the total mass or the net force – and did not recognize the interplay between the two in determining system acceleration. Additionally, we decided that Variation Theory is a useful theoretical framework to use in our development efforts[21]. As a result of these findings, we have added a fifth scenario to examine fusion – where the scenarios have both a different system mass and a different net force. We also decided to change to SI units to hopefully highlight the effects of system mass and to address student confusion over the use of ounces. The current cases of the Pulley IBLA are shown in Figure 4.

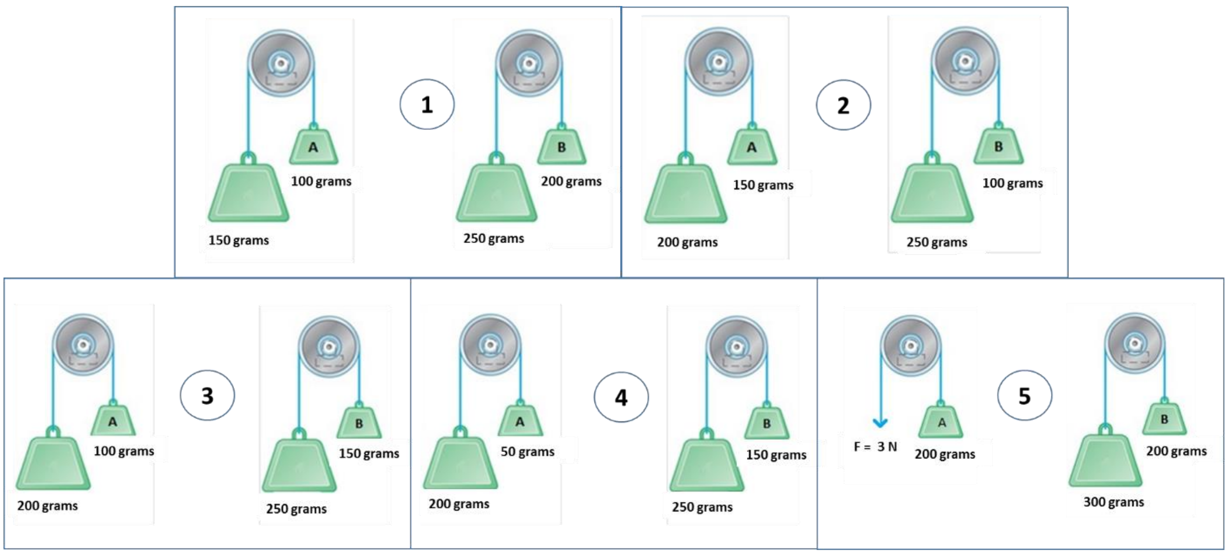


Figure 4. Revised Pulley IBLA, Cases 1-5.

Impact Pendulum IBLA

A commonly held misconception is that mechanical energy is conserved through an impact. Students often attempt to apply the principle of conservation of energy to a system before and after an impact, despite repeated instructor explanations that this is not the case. The Impact Pendulum IBLA was developed to help repair this misconception, and to demonstrate the principles of both work and energy and of the conservation of linear momentum. The five cases in the Impact Pendulum IBLA are shown in Figure 5.

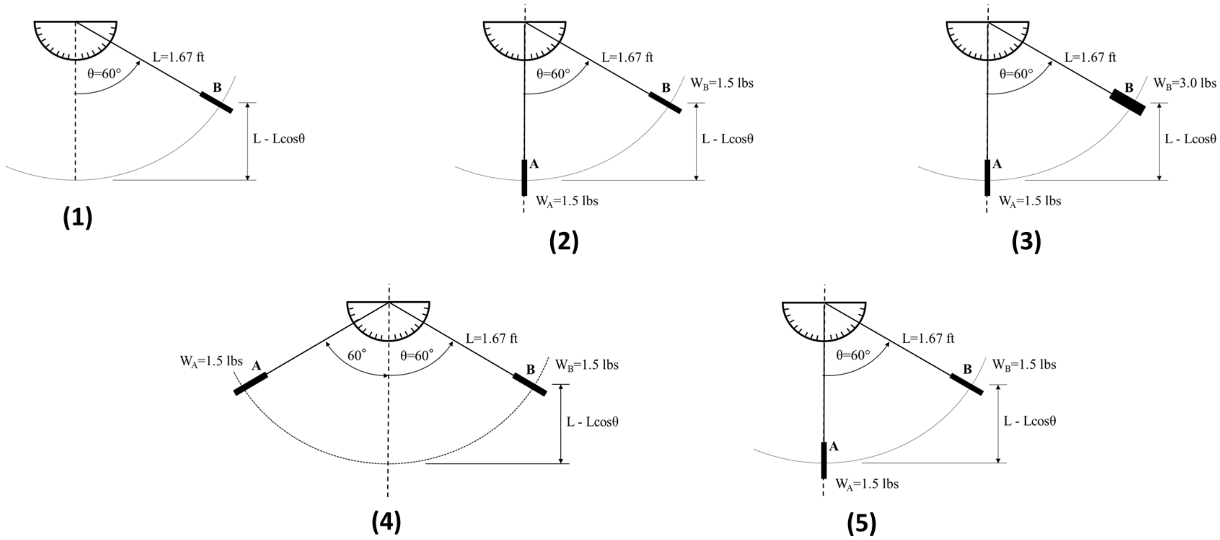


Figure 5. Impact Pendulum IBLA (Cases 1-5).

Case 1 is intended to show students that friction and air resistance really are negligible in a number of cases. This assumption will then be used in the following four cases. Velcro is used in cases 2, 3, and 4 to produce a plastic impact where the weights stick together – Case 5 does not use the Velcro and thus has a non-zero coefficient of restitution. These cases are intended to show the following: Case 2 - energy really is lost in the collision; Case 3 - we can accurately predict the post-impact height by using the principles of both impulse-momentum and work-energy; Case 4 – momentum can be conserved even when all of the mechanical energy is lost; Case 5 – additional information is necessary when dealing with a case that is neither perfectly plastic nor perfectly elastic.

We have only just begun to implement this IBLA on a larger scale, so no assessment data is currently available.

Spool IBLA

The Spool IBLA is based off a fairly common demonstration used by physic and dynamics instructors. The principles involved in understanding this rigid body dynamics problem are more complex than our previously discussed IBLAs, and we have had to increase the amount and improve the quality of our direct instruction, or intervention. An early implementation of the four scenarios is shown in Figure 6.

The phrase "pull on the spring gently" basically indicates that the spool will roll without slip. Knowing this, students should be able to apply three basic principles:

1) the direction of acceleration $\boldsymbol{a}$ of the mass center is in the same direction as the sum of the forces ($\sum\mathbf{F}=m\mathbf{a}$);

2) the direction of angular acceleration (α) is the same as the direction of the sum of the moments about the mass center ($\sum \mathbf{M}_G = I_G * \alpha$)
3) the direction of rolling has to be compatible with the direction of translational movement (the directions of α and $\boldsymbol{a}$ have to be compatible).

A very common pre-conception of students is that the direction of the friction force must oppose the direction of the translational motion. Although some students can correctly predict the direction of friction by examining the relative displacement of the wheel on the floor, our intervention attempts to explain the motion of the spool and the direction of friction in the larger context of principles (1) – (3) above. For instance, in Scenario 2, force ***P*** causes a counterclockwise (CCW) moment about G, which would tend to angularly accelerate the spool CCW. If we assume the friction force is to the right, this would also angularly accelerate the spool CCW – but it would be the only horizontal force in the system and cause a linear acceleration ***to the right***. This is impossible – we cannot "alpha" CCW and linearly accelerate to the right! If we assume friction is to the left, then the laws of physics can apply – the spool linearly accelerates to the left, and the moment due to ***Pr*** is just bigger than that due to ***FR***. Therefore, the friction must act to the left. Similar arguments can be made for the other scenarios.

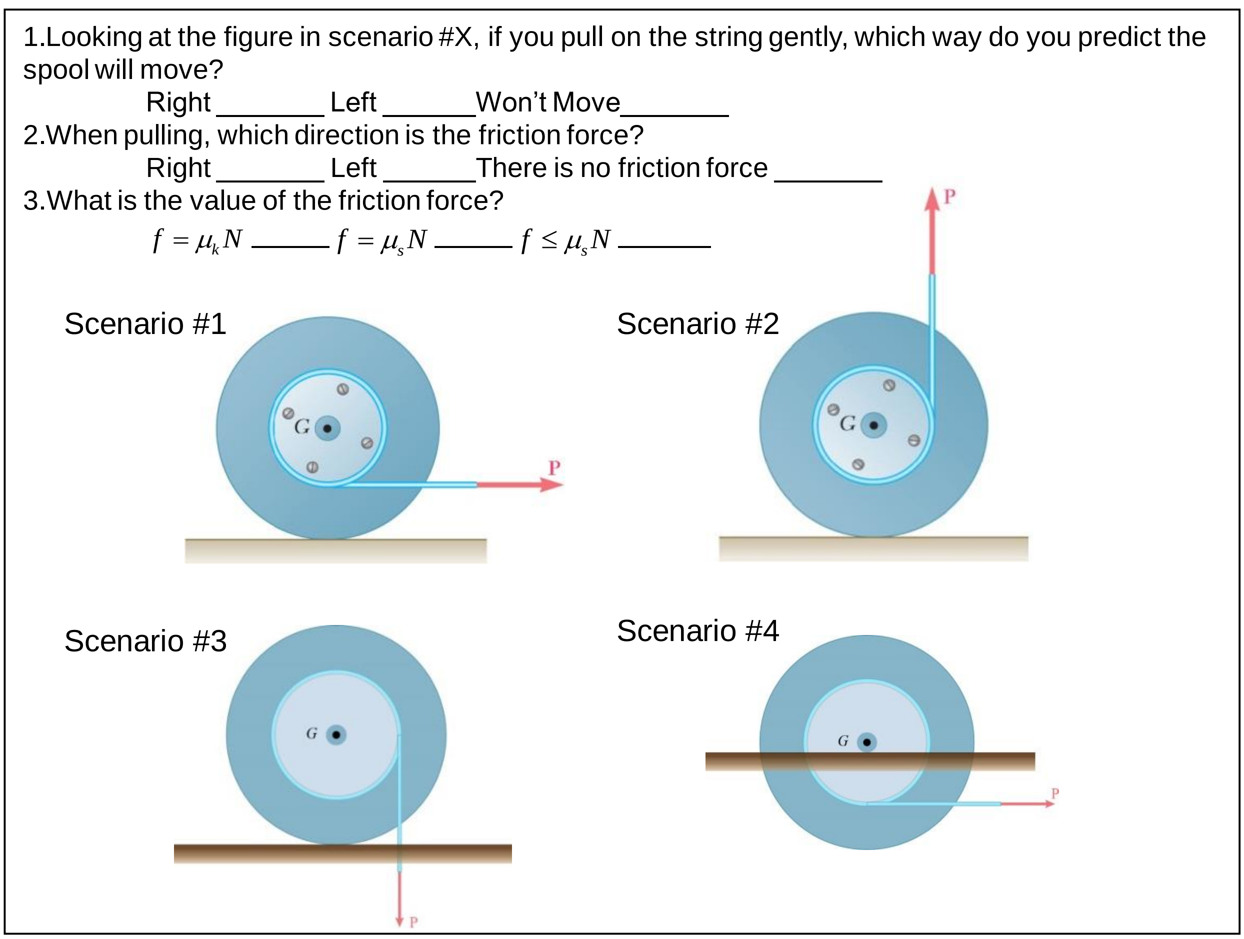


Figure 6. Spool IBLA (Cases 1-4).

We have reported results from our think-alouds, as well as some quantitative data elsewhere[22]. In one of our post-surveys, students 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….)?".

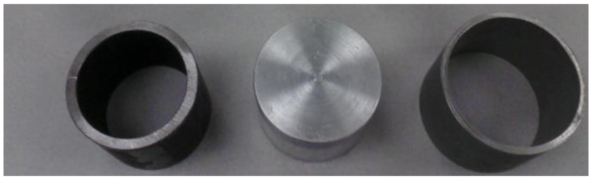
Table 4. Student responses as to when they understood the concepts in the IBLA.

	Spool IBLA
Understood beforehand	10
During/after pre-quiz	10
During activity	36
Talking with team	42
After activity	6
Discussion in class	37
Studying it later	5
Still confused	22

The responses revealed that participating in the IBLA and then discussing the concepts with their teammates and the entire class seemed to be beneficial for the majority of students. A substantial number, however, continue to be confused about the direction of the friction and the dynamics of the spool. As a result of these surveys and the think-alouds, we have altered the sequence of the scenarios, increased the frequency of direct instruction, and improved the delivery of that instruction.

Rolling Cylinders IBLA

A second IBLA dealing with rigid body motion focuses on the relationship between translational and rotational kinetic energies and the effect of mass distribution on a rolling object. As in the Spool IBLA, rolling objects provide compelling visual evidence of dynamic principles and are often used in classroom demonstrations. By following our predict-observe-explain cycle along with the benefits of collaborative learning, we feel that our IBLAs offer unique hands-on learning experiences in dynamics. A number of different objects (see Figure 7) were created for the IBLA.



Black Metal Pipe
Big metal Solid Cylinder
Grey Metal Pipe

Big PVC pipe
Small metal Solid cylinder
Wood Solid cylinder
Small PVC pipe

Figure 7. Test objects for the Rolling Cylinders IBLA.

The specific “races” and their targeted concepts are provided in Table 5, and a picture of the students testing different objects is shown in Figure 8.

Table 5. Cases and targeted concepts for the Rolling Cylinders IBLA.

Case	**Targeted concept**
Big metal cylinder vs Black metal pipe (same m, same R, different shape)	Distribution of mass – larger mass moment of inertia results in smaller translational velocity
Small metal solid cylinder vs Big metal solid cylinder (different m and R, same shape)	Work energy principles – the translational velocity is independent of mass and outer radius when the shape is the same
Small metal solid cylinder vs Black metal pipe (different m, R and shape)	Work energy principles and effect of mass distribution – the solid cylinder always beats the pipe
Small PVC pipe vs Big PVC pipe vs Grey metal pipe	Rolling object with the same shape will tie, regardless of mass and outer radius

This IBLA is typically run at the same time as a catapult project, so past interventions have been conducted somewhat randomly by teaching assistants as questions arose. We have collected DCI data as well as subjective response data, and also analyzed responses from the team worksheets. On the worksheets, students were asked to explain their observations using the principles of dynamics. Worksheet responses were analyzed and grouped thematically, then responses were recorded in Table 6. Note that many of the targeted concepts were mentioned by the students, even in the absence of an intervention.

Figure 8. Students doing Rolling Cylinders IBLA.

Table 6. Concepts mentioned by teams during the Rolling Cylinders IBLA.

Concepts mentioned on Team Worksheet	**Groups**
Moment of Inertia based upon mass distribution	38.8%
Moment of Inertia relates to rolling acceleration or translating velocity	67.4%
Potential Energy at top of ramp converts to Kinetic Energy at the bottom of ramp	75.5%
Kinetic energy distributes into linear and angular components	44.9%
Work-Energy equation or principle	59.2%
Solid cylinders always beat hoops (regardless of m and R)	2.1%
All solid cylinders roll with the same translational velocity (regardless of m and R)	22.5%

Gyroscope IBLA

Gyroscopic motion is one of the most non-intuitive in all of dynamics principles. The Gyroscope IBLA involves predictions when using a precision gyroscope as well as cases with a bicycle wheel. As in previous IBLAs, several iterations have occurred with the Gyro IBLA – mainly trying to reduce the number of predict-observe-explain cycles to provide students more time to think about what they are observing. One sample question from the precision gyroscope and from the bicycle wheel are shown in Figure 9 (further details can be found in Bohn et al.[23]).

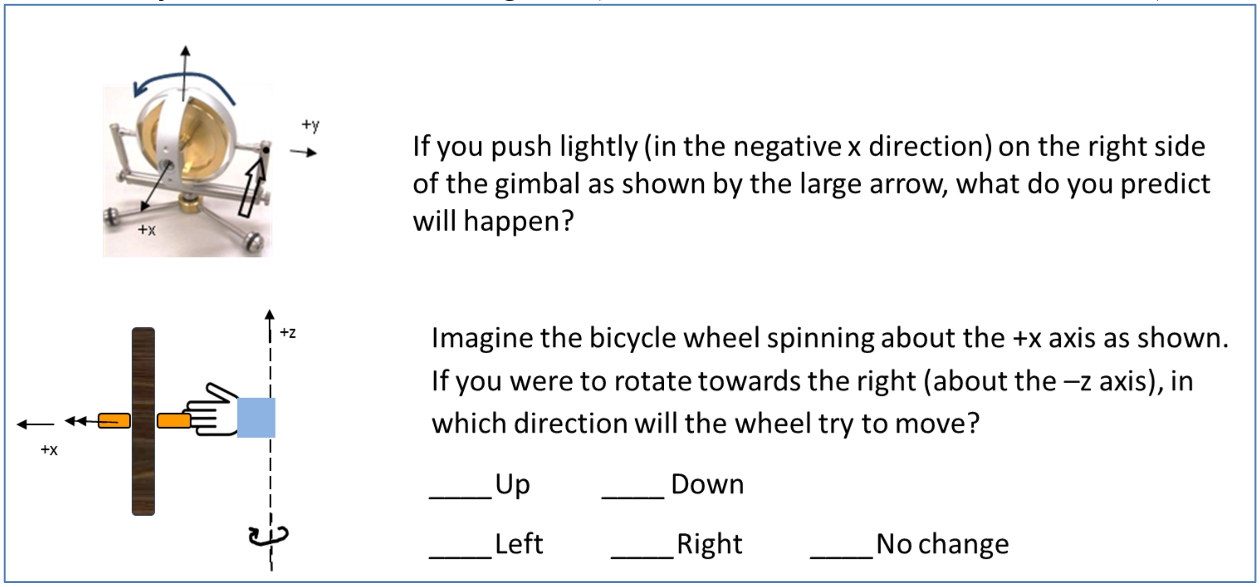


Figure 9. Sample cases from the Gyroscope IBLA.

As with the other IBLAs, our team has collected individual prediction data and team worksheets, as well as subjective survey data from the students. A summary of responses is shown in Table 7, and some examples of open ended responses are provided below.

Some selected responses from students on the survey:

> *"Gyros are really cool and aren't intuitive."*
>
> *"Gyroscopic motion confused me the most. Partly because it was at the end of the quarter and everything felt rushed. I always confused the moment and the precession."*
>
> *"Gyroscopic motion: It was a difficult concept to grasp because I hadn't seen anything like it before."*
>
> *"Working through the activity definitely helped and it all seemed to click once I saw the bike wheel demonstration."*

Table 7. Response to statements using a Likert scale (1=strongly disagree, 5= strongly agree)

The gyroscope lab was interesting and motivating	The gyroscope lab helped me learn about angular momentum and 3D kinetics	You should do the gyro lab in future sections of the course
4.2/5	4.0/5	4.3/5

Conclusions

Our iterative development of IBLAs has been informed by the use of test trials, think-alouds, and the use of variation theory as a theoretical framework. We have found that direct instruction at key points of the learning cycle is critical – just a single intervention or letting the students conduct the IBLA without any intervening explanations is not effective. Creating cognitive conflict is also quite useful at generating curiosity and interest.

We have presented our five IBLAs and provided examples of assessment techniques for each. Our team has utilized a mixed-methods approach, including (a) individual prediction data for each scenario, (b) team worksheets and team predictions, (c) pre- and post Dynamics Concept data, (d) short term transfer questions on quizzes and tests, (e) longer-term transfer questions from final exams, (f) think aloud interviews, and (g) subjective surveys. Our results support the use of IBLAs for both student learning and student motivation.

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