Wrapping Your Thread Around the Proverbial Yo-Yo: The Spool Inquiry-Based Learning Activity

Baheej Nabeel James Saoud, Brian P. Self, Jim Widmann, Alexa Coburn, Jeffrey Phillip Georgette

California Polytechnic State University, San Luis Obispo CA

Abstract

Rigid body kinetics, particularly of rolling objects, proves to be one of the most difficult topics for dynamics students to understand. There are complex relationships between moments, forces, linear acceleration, angular acceleration, and friction, with no simple "standard" rules to follow (e.g., the friction force does not vary in a fixed way with the direction an object is rolling). No matter how many times an instructor makes an effort to explain the analysis to the class, students still seem to struggle with the concepts. In an attempt to alleviate this issue and to create a motivating, active classroom environment, we have developed the Spool Inquiry-Based Learning Activity (IBLA). In an IBLA, a physical scenario is presented to students, who are asked to make individual predictions about what is likely to occur. After the students make their individual predictions, they discuss the scenario with their team (3-4 students). This group dialogue introduces the benefits of collaborative learning, in which students are able to help each other understand concepts. The team then performs the experiment, discusses the results, and attempts to explain what occurred and why. Once they reach a conclusion, the students are presented with a second scenario and repeat the process: predict-discuss-observe-explain. The instructor and teaching assistants move throughout the classroom during the cycle and gauge the classes' level of comprehension. Subsequent class discussions led by the instructor depend on how well the class understands the concepts. The process is repeated for a total of four scenarios. Applying this activity plan to the Spool IBLA, we ask questions such as, "If you pull lightly on the string wrapped around the inner diameter of a spool, in which direction do you think the spool will accelerate? In which direction does the friction force act?" The students perform the experiment by pulling on the string and noting the direction of the acceleration. The instructor then discusses the relationship between force and linear acceleration, and between moments and angular acceleration. Results of our initial assessment have found that the students thought the Spool IBLA helped them learn dynamics (4.2/5 on a Likert scale) and that they found the activity interesting and motivating (3.9/5 on a Likert scale). We will also present results from pre- and post-course scores on the Dynamics Concept Inventory and the individual and team predictions for each of the scenarios.

Introduction

While studying to become competent engineers, students are expected to learn course content, which consists of both conceptual and procedural knowledge, to collaborate, and to practice applying their knowledge using homework. Throughout their education, students hone their problem solving and teamwork skills, and ideally, build their conceptual understanding. The Cal Poly Dynamics Research Team is particularly interested in how strong conceptual understanding is achieved and in developing learning activities to support conceptual understanding. Using these activities during class time can effectively engage students in order to yield meaningful learning.

To date, our team has created several hands-on activities to engage students in conceptual learning. 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 overriding goal of this research is to provide students with a coherent framework that pushes them to better conceptual understanding.

Students enter dynamics classes with procedural knowledge gained in prerequisite courses focused on numerical calculations necessary to solve a dynamics problem. However, applying concepts as practicing engineering professionals takes more than being able to plug numbers into an equation and using a calculator to arrive at an answer. Certain dynamics topics are not intuitive or non-observable (i.e., friction between two surfaces or the mass moment of inertia), and do not lend themselves to being fully understood in a more profound way. Our research seeks to allow students to be able to "experience" the phenomena – such as energy or work – to make these concepts relatable by observing objects students can feel and see.

One measure of the effectiveness of these activities is through the use of the Dynamics Concept Inventory (DCI) [1], which is a pre- and post-course instrument developed to track how students' conceptual understanding of important topics changes throughout the class. The DCI contains multiple questions about eleven topics covered in the dynamics curriculum. The concepts covered by the DCI include those targeted by the hands-on activities we have developed, providing us with additional data to assess whether the activities are working as intended.

According to research by Laws et al. [2], students who are taught using the traditional lecture–example problem methods generally have a lower conceptual understanding of course material than those engaged in active learning. The data from Laws et al. given in Figure 1 show a dramatic increase in concept understanding for students engaged in inquiry-based active learning in a physics class.

Both traditional and active teaching methods can also be described as deductive or inductive. In inductive teaching, the direction of learning goes from a specific context to a general concept. The opposite is true for deductive teaching where the learning goes from theory to specific context. Traditional teaching methods take the deductive approach where the concept is introduced and moves toward specific example problems. We use the inductive method in our activities, where the students are given specific problems and are guided towards a more general understanding of the concepts.

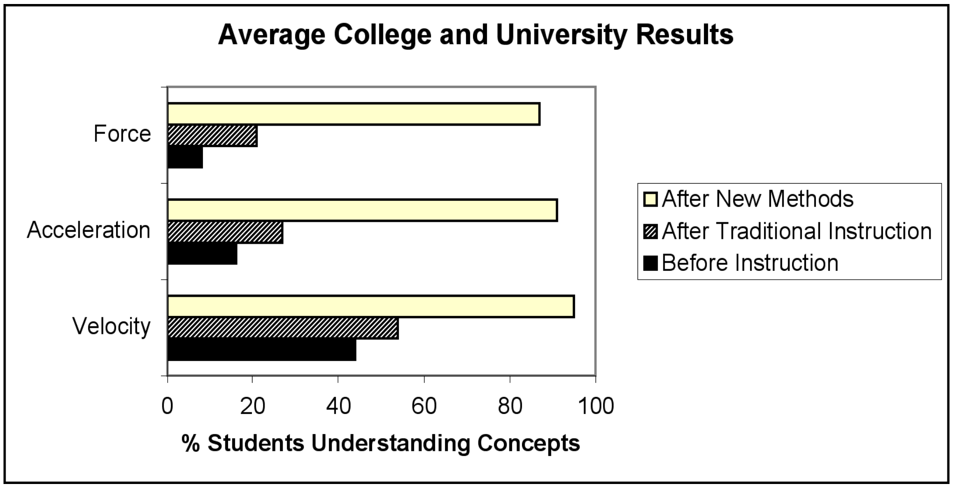

Figure 1. Data show that active learning methods results in dramatically increased conceptual understanding over students engaged in only traditional learning (from Laws et al.).

The Inquiry-Based Learning Activity (IBLA)

Although the exact definition of inquiry-based instruction varies somewhat between different investigators, we will use the defining features offered by Laws et al.[2] and highlighted by Prince and Vigeant[3] in Table 1. A defining aspect of an IBLA is that the physical world is the authority rather than the word of the professor or the calculations in the students' homework. Allowing the results of a physical experiment to communicate information to the student tends to be more effective than having a professor convey the facts. The IBLA procedure has students make a prediction about a physical situation then allows them to witness the result and draw conclusions from that result. The IBLA allows for more independence in learning, as it is not meant to be highly structured as in a laboratory experiment.

(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

Table 1. Elements of Inquiry-Based Learning Activities

Figure 2 shows the IBLA learning cycle that begins with groups of 3-4 students being presented with a physical scenario and a number of choices for the result of that scenario. Each student indicates their individual prediction on a worksheet, then the group engages in a discussion that may result in some of them changing their minds. The group then indicates the number of “votes” for each choice on a group worksheet they fill out together. The purpose of both worksheets is to assess the influence of “group-think” when it comes to individual student understanding. The group goes on to perform the experiment and discuss the results. The cycle begins again when a new scenario is presented to the group that is similar, but differs slightly in a way that either challenges the conclusions drawn in the previous scenario, or presents an opportunity to confirm the methods used to explain the previous results.

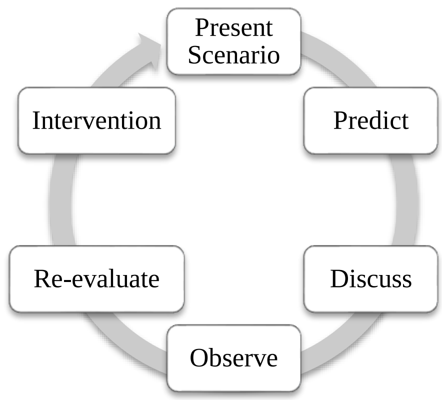

Figure 2. IBLA Cycle

Between subsequent activities, the professor may wish to “intervene” by giving a short explanation and presenting the students with information they can use in the next cycle of the activity.

The Spool IBLA

The Spool IBLA is designed to target the dynamics concepts of Newton’s Second Law, friction, the relationship between net moment and angular acceleration, and the use of Free Body Diagrams (FBDs). In the IBLA, Newton’s Second Law is explored through the interaction of the sum of forces being equal to mass times linear acceleration, and the sum of moments being equal to the moment of inertia times the angular acceleration. The use of FBDs along with Newton’s laws of motion is crucial in making correct predictions because it allows students to visualize the interactions between forces, moments, and accelerations. Additionally, the IBLA is meant to address the common misconception that friction always acts opposite the direction of motion for a moving object. The students are also asked to differentiate between static friction and kinetic friction, especially as they relate to the concept of rolling with or without slip.

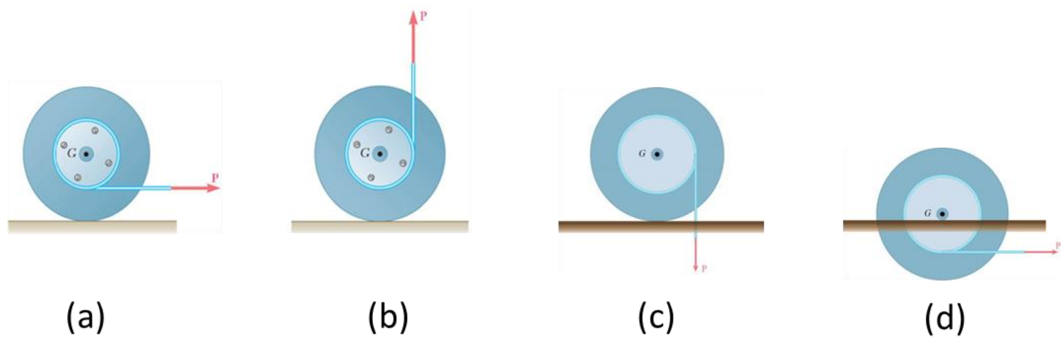

Figure 3. The four cases for the spool IBLA (only results using Cases (a) and (b) are presented here).

In each case of the Spool IBLA, the students are presented with a spool on a surface as shown in Figure 3. The students are tasked with predicting (a) which way the spool will travel when the string is gently pulled in the direction shown and (b) what direction the friction force between the spool and the surface is acting.

When given the first case, most students are observed to not know where to begin and simply use their intuition when making their prediction. After the first case, the instructor performs an intervention. He draws the FBD and Kinetic Diagram (KD), or Mass-Acceleration Diagram (MAD), and discusses the behavior of the rolling spool and how the FBD and KD can help predict that behavior. With this guidance, the students are allowed to continue. In the subsequent cases, we have observed the students using the FBD and KD to make their predictions.

We will discuss our intervention for Case B to provide an example of how we relate force, linear acceleration, moment, and angular acceleration. During the intervention, students are first asked to assume the friction acts to the right, and told to draw the appropriate free-body diagram. As part of a full class discussion, students then talk about the moment about the center of mass – they recognize that the net moment has to be counter-clockwise, which means that the angular acceleration would have to be counter-clockwise. If this is the case, for kinematic consistency, the linear acceleration has to be to the left. Since there is no force to cause this acceleration (assuming the friction is to the right), our assumption must be incorrect.

If we now assume friction is to the left, we see that this is possible; the moment due to the force P is greater than the moment caused by the friction, and the friction force "causes" the acceleration to the left. Similar arguments relating the direction of the friction force, moment, and the linear and angular accelerations can be made for the other cases. We can also discuss the fact that the weight must be greater than P to keep the spool touching the surface. Follow-on activities might discuss how this friction force is analogous to the traction force on the drive wheel of a vehicle, and how the moment caused by P is analogous to the torque caused by the engine.

Through this activity, the students discover that the direction of the friction force on a rolling body is not, in fact, related in any standardized way to the direction of rolling. This conclusion can be drawn from the first two cases where the spool travels in opposite directions, yet the friction force acts in the same direction for both cases.

Assessment

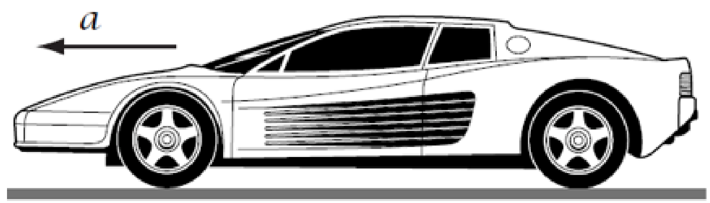

Figure 4. Automobile tire friction question on DCI: Find the friction force direction and expression for the front and rear tires.

The data we have analyzed up to this point spans the Fall 2012, Winter 2013 (2 different classes), and Spring 2013 quarters at Cal Poly San Luis Obispo. In each class, the students took the DCI quiz at the beginning of the quarter. For our research, we looked at the DCI question involving the friction force on the front and rear tires of a rear-wheel drive car (Fig. 4). This question requires the student to apply what they learned in the Spool IBLA and to show that they understand that the friction is not always in the direction of travel. Because it is not explicitly a spool being pulled along by a string, this is really a transfer question that can show whether or not a deeper conceptual understanding has been realized.

Near the middle of the quarter, the IBLA was performed in class. In addition, the students were tested on material involving rolling without slip on an exam. Towards the end of the quarter, the students took the DCI again to record their retention of the concepts. Finally, students submitted a survey to give feedback and compare the IBLA to other activities (homework, lecture, etc.) on whether or not the activity was helpful and interesting.

Results

The results in Table 2 show the percentage of correct answers on the pre- and post-activity DCI for the three dynamics classes evaluated. Only the post-activity scores for the *intermediate* dynamics class in Winter 2013 are available. The students in the intermediate dynamics class were expected to have already learned this material in dynamics, but the activity was performed in their class, and they took the DCI afterwards to provide additional data.

	Friction on Rear Tire		**Friction on Front Tire**	
Class	**Pre**	**Post**	**Pre**	**Post**
Fall 2012 Dynamics	29.0%	57.4%	29.0%	51.1%
Winter 2013 Dynamics	37%	42.9%	33.3%	35.7%
Winter 2013 Inter. Dynamics	N/A	55.9%	N/A	47.5%

Spring 2013 Dynamics	44.4%	59.4%	29.6%	40.6%

Table 2. Percentage of correct answers for DCI questions

The results generally demonstrate a moderate increase in understanding rolling without slip concepts. The only exception is the Winter 2013 dynamics class where less than 10% gains were made. There is no "control" class in which the activity was not run. As a note, the spool concept is not directly tested on the DCI; the friction on the car tires is related to, but not the same as, the spool. Because of these facts, we cannot currently assign any causation from the IBLA in the improvement of DCI scores.

We also tabulated the data from the worksheets filled out during the activity used to mark the individual and group predictions for cases (a) and (b). The data shown in Table 3 through Table 5 show improvement in the individual student's ability to correctly predict the roll direction throughout the activity. It also shows an increase in correct predictions after the students were given a chance to talk with others. There doesn't appear to be a trend in correct predictions of friction directions. We believe that this is because the friction force is not directly observable and is a particularly difficult concept. As a result of this, we have recently altered the intervention that we provide, and added cases (c) and (d) to provide additional practice for the students. We are also working on an interactive simulation to give the students additional practice on rolling scenarios – this will target the friction direction, since this is not easily visualized in the physical hands-on activity.

	Individual Predictions	Team Predictions
Horizontal pull – motion direction	26%	35.7%
Horizontal pull – friction direction	56%	75%
Vertical pull – motion direction	91%	92.9%
Vertical pull – friction direction	32%	42.9%

Table 3. Percent Correct Predictions: Winter '13.

Pre-activity Quiz		Team Predictions	
Horizontal pull – motion direction	52%	Horizontal pull – motion direction	73%
Horizontal pull – friction direction	66%		
Vertical pull – motion direction	86%	Vertical pull – motion direction	84%
Vertical pull –	45%		

friction direction			
	n = 65		n = 63

Table 4. Percent Correct Predictions: Intermediate dynamics, Winter '13

	Individual Predictions n = ~15	Team Predictions n = 30
Horizontal pull – Motion direction	9%	20%
Horizontal pull – Friction direction	44%	46.7%
Vertical pull – Motion direction	59%	76.7%
Vertical pull – Friction direction	72%	60%

Table 5. Percent Correct predictions: Spring '13

The post-activity survey used a Likert scale to assess the students' response to the Spool IBLA. The results in the Table 3 show that the students found the Spool activity helpful and motivating in learning the dynamics concepts. However, the activity was ranked lower on the list of importance relative to some other class activities. In fact, the students reported that lecture was the most important activity to their learning.

Pulling the spools helped me learn dynamics. (Likert scale)	Pulling the spools was interesting and motivating. (Likert scale)	Importance of Activity relative to other activities. (1 is most, 11 is least)	Class session
4.18/5	3.81/5	7.12/11	Fall '12
4.27/5	3.92/5	6.31/11	Winter '13
3.6/5	3.3/5	6.7/11	Spring '13

Table 5. Survey Results

Further Research and Improvement

Several improvements are currently being tested to improve the effectiveness of the Spool IBLA and to gather more data. A newer version of the activity includes the fourth case, whereas the data presented here are from an activity that only included scenarios (a) and (b) in Figure 1 as well as a case where the string was pulled at an angle. We now include all four scenarios with two interventions after case (a) and case (b) and one at the end of the activity. We are still using prediction sheets to track how the students' understanding progresses through the activity. Initial data is showing promising increases in correct predictions through the IBLA.

In addition to continuing the activities in classes with students working in groups, individual students have been video-taped doing the activity using a "think-aloud" protocol[4]. The "think-aloud" involves a one-on-one interview where the student participates in the IBLA in front of a member of our research team. While engaged in the activity, the student is asked to talk through everything they are thinking. The whole process is recorded for analysis at a later date. The purpose of this research is to take the student out of the group setting where they may be influenced by "group-think" in order to pinpoint difficulties the student experiences or misconceptions the student has. This is an effort to make specific changes to the Spool IBLA (i.e., when the professor intervenes and the verbiage used in it) that address these problems and increase its ability to help students grasp the concepts.

One aspect of the Spool IBLA that we think poses the biggest hurdle for students' conceptual understanding is that the friction force is not observable. The potential solution to this would be to visually show the friction force using a computer simulation. There is a question as to whether the simulation would be better than the activity or not due to less credibility or believability of the software. Feedback from students about such a simulation would decide if it would be a beneficial addition to the activity.

Conclusion

The data we have presented in this paper shows little correlation between the Spool Inquiry-Based Learning Activity and a marked increase in scores on the Dynamics Concept Inventory. However, the prediction sheets show more promising results. Overall, the students' ability to correctly predict the direction the spool will roll increases from the first to the second case. The main difficulty students face is predicting the friction force direction, as it is not directly observable. The post-activity survey shows a generally positive attitude towards the use and motivation the IBLA provides for learning concepts related to an object rolling without slip. The Cal Poly Dynamics Research Team is currently conducting more research in order to improve the Spool IBLA.

Acknowledgments

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