Is There a Correlation Between Conceptual Understanding and Procedural Knowledge in Introductory Dynamics?

Lora Goodwin, Brian P. Self, and James Widmann
California Polytechnic State University
San Luis Obispo

Abstract

Engineering professors are usually quite successful at teaching their students to choose an appropriate equation and then substitute appropriate numbers into that equation. This procedural knowledge is practiced on homework problems, quizzes, and tests. By the end of their collegiate careers most students become reasonably skillful at these types of tasks. What is more uncertain is if these students actually graduate with a deep conceptual understanding of their course material.

Students tend to struggle with the course content in Introductory Dynamics. This is often the first rigorous course in engineering that a student takes, and much of the content seems counter-intuitive. Many students continue to talk about the force that "throws you outward" when you are travelling in a curve, and struggle to understand that a rotating mass has more kinetic energy than one that is translating. We have assessed student conceptual understanding by administering the Dynamics Concept Inventory (DCI) before and after the course. The scores on the DCI will be correlated to scores on a midterm test and a final exam to see if there is a correlation between student conceptual knowledge and procedural knowledge.

Background: Procedural Knowledge versus Conceptual Knowledge

Procedural knowledge typically classifies knowledge of processes, algorithms or specific steps involved in completing a problem or task. This type of knowledge plays a very important role in completing tasks which require hands-on experience, or in solving problems which may arise often or need to be completed quickly without time for thought or analysis [1]. Procedural knowledge, however, has limitations and does not necessarily correspond to a strong conceptual understanding of the concepts at hand. It is typically applicable to one specific situation and cannot be extended easily beyond equivalent problems.

Typically, the development of conceptual knowledge in students is advantageous in engineering academia in order to help them gain a deeper understanding of the fundamental concepts. Conceptual knowledge is a rich understanding of the underlying concepts involved in a topic. Streveler, Litzinger, Miller and Steif describe this type of knowledge as necessary in the development of 'engineering judgement' or 'heuristic thinking' [2]. A conceptual understanding of kinetic energy, for example, would include an understanding of the different types, translational, rotational and vibrational, along with the ability to apply them to a given problem. A student with only a procedural knowledge of kinetic energy may be familiar with the types of kinetic energy that they have used before to solve a problem, and may only be able to apply their knowledge to problems similar to those they have previously seen, but may not be able to adapt their techniques to new problems or scenarios. It is often difficult for teachers to succeed at producing full conceptual understanding in students so in the interest of student development it is necessary to research how this challenge can better be met [3].

The relationship between conceptual and procedural knowledge has been a topic of research within the math and physic communities for some time, but has only recently emerged in the engineering community, specifically in the topic of introductory dynamics at California Polytechnic State University in San Luis Obispo. Introductory dynamics is a beginning level core engineering course which contains a wide array of concepts that students often struggle to fully understand. With a better understanding of how conceptual and procedural knowledge are related, instructors in this field could adapt their teaching styles to better provide their students with the opportunity to gain deeper understanding of the introductory dynamics concepts [4].

According to Rittle-Johnson and Wagner Alibali, a relationship clearly exists between conceptual and procedural knowledge in the subject of mathematics, but it is not yet clear as to which type of knowledge influences the other. Evidence shows that conceptual and procedural knowledge may feed off of one another and develop iteratively for most students. This would imply that both procedural knowledge and conceptual knowledge are required to gain full understanding of a concept, and teachers must cater to both to ensure their students have the opportunity for success. On the other hand, some studies suggest that procedural knowledge does not encourage the growth of conceptual knowledge, implying that proper conceptual instruction in the classroom is critical to student's growth in the subject [5]. It is difficult to accurately test for an iterative relationship with existing tools, but it is possible to further test the general relationship and the order of influence between the two knowledge categories. To relate this to the instruction and learning process in introductory dynamics, a concept inventory was developed to measure conceptual understanding.

The Dynamics Concept Inventory (DCI)

The development of the Dynamics Concept Inventory (DCI) began in 2003 and was first publicly released in January of 2005. The purpose of the DCI is similar to that of the Force Concept Inventory (FCI) which is already widely used as a teaching aid in the physics community [6]. Since its release, the DCI has been used at a series of universities to determine how much conceptual knowledge is gained through an introductory dynamics course. It consists of 29 conceptual multiple choice questions relating to the fundamental concepts presented in the course, which students often struggle to grasp. These concepts range from conservation of energy to direction of friction forces, and to velocity and acceleration magnitudes at different points on a moving rigid body. All questions and multiple choice options in the inventory were carefully selected after discussion between a selection of experienced engineering professors and in depth testing on and with students (for further discussion on the development and content of the DCI, see [7]).

Testing Gained Conceptual Knowledge in Introductory Dynamics

Data has been collected at California Polytechnic State University, San Luis Obispo, in a selection of introductory dynamics courses in an attempt to measure how well students learned the key concepts presented in the course. The DCI was given on the first day of the class, then again on the last day of the class, to obtain pre and post scores for each individual who completed the course. This was done in 8 different course sections with 3 different instructors to gain a wide spread of data. Two different styles of dynamics instruction were used in these courses. We will call the first group the Active Learning (AL) sections taught by two different instructors and the second group the Traditional (Tr) sections taught by a single instructor. The AL sections utilized collaborative learning and Model Eliciting Activities (MEA's), where the Tr sections were taught in a more traditional lecture format.

The AL sections were specifically given MEA's as a part of their coursework to see if they would have an impact on student's gained conceptual knowledge throughout the quarter. MEA's are new teaching tools being developed which use project-oriented assignments that aim to promote real-world application of engineering principles. Their focus is to use student's conceptual knowledge to solve problems outside of the typical textbook procedural problem range (for further description of the purpose and development of MEA's, see [8]). The change in DCI scores between pre and post scores of the students in the AL sections who used MEA's were compared to that of the classes who did not use MEA's. More specifically, the MEA given to AL sections involved applying work energy methods and conservation of linear momentum to accident reconstruction cases. Students completing this MEA were required to develop a model to aid police in determining the cause of accidents given any amount of data which could be collected from the crime scene. Four police cases involving different types of car accidents were then given to students to solve using the model they developed. Work energy and conservation of linear momentum were the fundamental concepts which needed to be applied to find initial velocities of the cars involved in the impact in order to solve the cases.

The data were analyzed in two ways: first by comparing average pre and post DCI scores of the different classes to see if any MEA impact was evident, and secondly by comparing each individual's post DCI score and final exam score to find any relationships between gained conceptual knowledge (post DCI and conceptual portion of final exam) and gained procedural knowledge (procedural portion of final exam) both in terms of average normalized gain. These comparisons can reveal whether or not there is any sort of correlation between DCI scores and final exam scores, as well as if any impact is shown concerning the use of MEA's. Comparisons of normalized gains were used in analyzing DCI scores as used by Hake in his analyses of the Halloun–Hestenes Mechanics Diagnostic test as well as the Force Concept Inventory [3].

All data was collected at California Polytechnic State University in fall 2008 quarter. In total, the scores of 154 unnamed dynamics students in the AL sections who completed both the Pre and Post DCI exams, as well as the final exam, were used in the analysis. Additionally, the pre and post DCI scores of 80 students in the Tr sections with unknown final exam scores were used in the MEA analysis.

Results: Comparison between Pre and Post DCI Scores

The overall results given in Table 1 show a larger percent improvement and a larger normalized gain from pre to post DCI scores for the students who participated in MEA's compared to those who did not complete any MEA's in their coursework. The definition of average normalized gain which was used in this analysis was popularized by Hake as a means to accurately evaluate learning levels. In words it is the ratio of the average gain to the maximum possible average gain [7].

$$\text{Average Normalized Gain} = \frac{\%\text{Post} - \%\text{Pre}}{100\% - \%\text{Pre}} \tag{1}$$

Table 1. Total pre and post DCI scores for all MEA and non-MEA participants.

	N	Value	Pre DCI Results [%]	Post DCI Results [%]	Overall Average Normalized Gain [%]	Overall Average Percent Improvement [%]
MEA in Coursework	149	Mean	29.85	49.97	29.6	20.11
		Median	27.59	48.28		
		Standard Deviation	14.55	17.20		
No MEA's in Coursework	80	Mean	32.97	46.64	21.1	13.66
		Median	31.03	44.83		
		Standard Deviation	14.19	18.33		

To further and more accurately compare DCI results to the completion of MEA's, the topic of the MEA which the students completed was compared to the scores on only the DCI questions directly related to that topic in terms of normalized gain. Questions 18 and 20 were selected from the DCI as the most conceptually related questions to the tools students should have learned by completing the Accident Reconstruction MEA. Specifically, questions 18 and 20 in the DCI test for conceptual understanding of what happens after an impact. These questions are shown below in Figures 1 and 2 respectively. The results, when only considering these two DCI questions, are shown in Table 2.

Question 18

An impact occurs between two identical wooden balls that are sliding on a frictionless horizontal surface. The impact is non-ideal, that is, the coefficient of restitution is greater than zero and less than one. Which of the following statements is *always* true.

(a) The sum of the kinetic and potential energy for each individual ball, before and after the impact, stays the same.

(b) The sum of the kinetic and potential energy for each individual ball, before and after the impact, decreases.

(c) The potential energy of each ball decreases during the impact.

(d) The kinetic energy of each ball decreases during the impact.

(e) The sum of the potential and kinetic energies for the balls taken together decreases during the impact.

Figure 1. Question 18 of the DCI testing students' understanding of an impact.

Question 20

A wooden block *A* is released from rest, slides down the incline and hits an *identical* wooden block *B* at the bottom. After impact, the blocks do not stick together and both have non-zero speed. The surface on which the blocks slide is frictionless. After they separate, how far up the second hill will block *B* travel?

(a) Block *B* will stop somewhere on the horizontal section.

(b) Block *B* will go higher than the initial height of block *A*.

(c) Block *B* will go exactly the same height as where block *A* started.

(d) Block *B* will go to a lower height than the original height of Block *A*, then start sliding back down the hill.

(e) Impossible to tell without knowing the mass of the two blocks.

Figure 2. Question 20 of the DCI testing students' understanding of an impact.

Table 2. Pre and post DCI scores for MEA and non-MEA participants considering only the DCI questions directly related to MEA topic (questions 18 and 20).

	DCI Question Number	Mean DCI Pre Score [%]	Mean DCI Post Score [%]	Normalized Gain [%]	Average Normalized Gain [%]
MEA in Coursework	Q 18	26.7	45.6	25.74	41.1
	Q 20	47.6	77.2	56.48	
No MEA's in Coursework	Q 18	19.1	32.2	16.18	14.8
	Q 20	50.9	57.5	13.37	

Students in the AL sections who completed the Accident Reconstruction MEA in their dynamics course showed an average normalized gain of 41.1% improvement in their scores on the DCI questions relating to impact. These same students showed an average normalized gain of 29.4% on all remaining DCI questions which were not related to the MEA. Students in the Tr sections who did not complete the accident reconstruction MEA showed only a 14.8% normalized gain on the same DCI questions relating to impact. The same group of students showed an average normalized gain of 19.3% on all remaining DCI questions. These results show that the students who completed the MEA had a 25% higher normalized gain on the DCI questions relating to the MEA than on all other DCI questions. This is significantly different from the group of students who did not complete the MEA and showed a 25% lower normalized gain on the DCI questions relating to the MEA than on all other DCI questions.

Results: Comparison between Post DCI Scores and Final Exam Scores

The final exam for the dynamics course was made up of five questions. Questions 1-4 were typical procedural type questions which were based off of the following topics respectively: rigid body kinematics, particle work energy and kinetics, rigid body kinetics, rigid body work energy and angular impulse momentum. Question 5 was comprised of a series of conceptual type questions which could be compared to the content of the DCI. The final exam scores were evaluated in three ways as shown in Table 3: total exam score (%), conceptual portion of exam score (%), and procedural portion of exam score (%).

The data in Table 3 show the grade breakdown for the 154 AL students taught by two separate professors during the same quarter, both of which incorporated MEA's into their coursework. The results were broken into four categories based on the student's score on the post DCI test: 0%-25% correct, 25%-50% correct, 50%-75% correct, or 75%-100% correct. The final exam results were then analyzed overall and within each category.

Table 3. Post DCI scores compared to final exam scores.

	N	Value	Total Final Exam Score [%]	Conceptual Portion of Final Exam Score [%]	Procedural Portion of Final Exam Score [%]
0% - 25% on Post DCI	8	Mean	67.52	58.57	69.76
		Median	67.33	60.00	70.83
		St. Deviation	12.09	16.37	13.36
25% - 50% on Post DCI	72	Mean	64.17	63.80	64.26
		Median	63.33	66.67	62.92
		St. Deviation	12.48	15.14	14.39
50% - 75% on Post DCI	56	Mean	74.61	75.60	74.36
		Median	76.33	76.67	74.58
		St. Deviation	12.42	11.96	14.93
75% - 100% on Post DCI	18	Mean	82.15	87.22	80.88
		Median	85.00	88.33	85.00
		St. Deviation	13.48	7.25	16.64

A trend can be seen between conceptual scores on the final exam and post DCI scores. On average, students who scored high on the post DCI also scored high on the conceptual portion of the final exam. Additionally, the same trend can be seen between post DCI scores and procedural final exam scores, as well as between post DCI scores and total final exam scores. Due to these multiple trends, these data alone cannot support any type of relationship purely between post DCI scores and conceptual final exam scores.

However, by looking at a linear regression involving each of the comparisons previously described, a stronger correlation can be seen between post DCI score and conceptual exam exists than between any other combination of scores. The linear regression results are summarized in Table 4.

Table 4. Linear regression results from post DCI and final exam scores.

Score Comparison	Correlation Coefficient
Post DCI - conceptual final exam	0.576
Post DCI - procedural final exam	0.353
Conceptual final exam - procedural final exam	0.313

The correlation coefficient between post DCI scores and conceptual final exam scores suggests medium correlation strength between the two scores. This is higher than the resulting correlation between post DCI scores and procedural final exam scores as expected, since the DCI is intended to test only conceptual knowledge. The typical assumption that the top students will excel in all areas, in both procedural and conceptual areas in this case, is not supported by these correlations. A much higher correlation than the resulting 0.313 would be required in order to claim that students tend to do well in all areas or no areas. This suggests that there may be a level of independence between student's gain in conceptual knowledge and their gain in procedural knowledge in a course.

Possible Further Research

To further develop this research, more DCI scores as well as corresponding final exam scores must be collected. The use of MEA's at California Polytechnic State Universities will also be continued in introductory dynamics, intermediate dynamics, thermodynamics and heat transfer courses. With this additional data, similar analyses can be preformed to verify and expand results.

Conclusion

As would be expected, there was a strong correlation between the DCI scores and the conceptual scores on the final exam. We would also have expected a strong correlation between the procedural and conceptual scores; students who do well on problem solving should also have a strong grasp of dynamics concepts. This correlation, however, was much weaker. Future studies could also examine if students who did well on certain conceptual problems (eg. work-energy) needed that conceptual understanding to complete their corresponding procedural exam problems.
Without further investigation, the results remain ambiguous as to whether or not a correlation exists between procedural and conceptual knowledge. It appears from the data that conceptual and procedural knowledge may have separate developments paths but further research is required to gain more insight before a concrete conclusion may be reached.

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Acknowledgements

This work was funded by the NSF CCLI Grant #070607: *Collaborative Research: Improving Engineering Students' Learning Strategies Through Models and Modeling.*

Author Information

Brian Self, California Polytechnic State University
Brian Self has been an Associate Professor at Cal Poly for the last three years. Before that, he taught at the Air Force Academy for seven years. He is the ASEE Campus Rep and the Zone IV Chair. Besides his pedagogical research, Dr Self is actively involved in aerospace physiology and biomechanics research. He has worked extensively to involve undergraduates in his research, taking students to present at national and international conferences. By involving students in solving ill-defined projects and problems that don't have a "correct answer", Dr Self hopes to further advance their intellectual curiosity and problem solving skills.

James Widmann, California Polytechnic State University
Jim Widmann is an Associate 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 design optimization, machine design, fluid power control and engineering education.

Lora Goodwin, California Polytechnic State University
Lora Goodwin is an undergraduate mechanical engineering student at California Polytechnic State University, San Luis Obispo. Her interests lie in the fields of math and science. She plans to complete her graduate work in mathematics in order to teach math at the college level.