Pedagogy Changes Can Improve Concept Application

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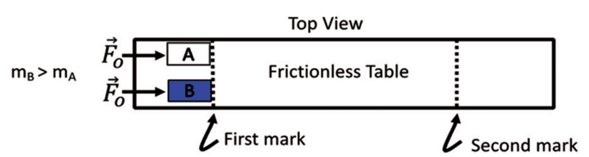
We sought to improve concept application in introductory mechanics by emphasizing causal statements (such as "forces change momentum") instead of laws (such as $\Delta p = F\Delta t$). Using student performance on a well-documented question, this intervention showed modest improvements. However, students in classes using recently introduced "parallel pedagogy" supported by learning assistants did significantly better than conventional pedagogy classes without learning assistants. Parallel pedagogy simultaneously introduces the four concepts (momentum, energy, dynamics, kinematics) and builds complexity in parallel while focusing on concepts, dialogue, and picture drawing. Our results also further confirm the discrepancy between student performance on multiple-choice questions and ability to explain reasoning on those same questions.

Introduction

In 1986, Lawson and McDermott conducted[1] a study on student understanding of the work-energy and impulse-momentum theorems. Lawson held individual demonstration interviews with undergraduate students where they showed two pucks of differing mass being pushed across a table and asked the students to compare the acceleration, energy, and momentum of the pucks (Fig. 1). Lawson and McDermott found that students in both non-calculus introductory physics and honors calculus-based introductory physics "experienced considerable difficulty in a straightforward application of the impulse-momentum and work-energy theorems to this actual one-dimensional motion of an object under constant force."

Two carts, A and B, are initially at rest on a frictionless, horizontal table. A constant force of magnitude F_o is exerted on each cart as it travels from the first mark on the table to the second, after which each cart glides freely. The mass of cart B is greater than that of cart A.



a) Is the magnitude of the acceleration of cart A *greater than, less than, or equal to* the magnitude of the acceleration of cart B while the carts are between the two marks? Explain.

b) Is the kinetic energy of cart A *greater than, less than, or equal to* the kinetic energy of cart B after the carts have passed the second mark? Explain.

c) Is the magnitude of the momentum of cart A *greater than, less than, or equal to* the magnitude of the momentum of cart B after the carts have passed the second mark? Explain.

Fig. 1. Representation of the assessment question given to students. The exact question we gave students had spaces between the lettered questions for responses. The original problem used by Lawson and McDermott was with a puck, which was converted to a cart for this study.

O'Brien Pride et al. gave[2] this question both in multiple-choice and in constructed-response formats to students at the University of Washington almost a decade later and found that there was a significant drop in scores when students had to support their answers with correct reasoning rather than just choose the correct comparison as a multiple-choice question, showing that students were getting "the right answer for the wrong reasons."

Parallel pedagogy, introduced by Schwartz in 2014[3] and adopted by others using free online resources,[4] focuses on learning the four main mechanics concepts simultaneously (or in "parallel") instead of in series. The four concepts (momentum, energy, dynamics, kinematics) are simultaneously introduced in their most basic forms at the beginning of the course and the complexity builds throughout the course. Additionally, students are graded on the *process* of arriving at an answer (including an illustration), not on the correctness of the answer itself. Parallel pedagogy stresses dialogue and is designed to train students to consider the conceptual underpinning of a question before looking for a formula or even thinking about how to get the answer. Parallel pedagogy could be thought of as mixing concepts throughout the course in instruction, homework, and testing. Samani and Pan[5] found that mixing topics in homework alone led to improved retention and problem solving. It should be noted that all the parallel pedagogy classes referred to in this study were taught with in-class learning assistants, the use of which has also been shown to improve student learning.[6] These classes will be referred to as PP/LA (parallel pedagogy with learning assistants).

We gave the assessment (in the same form as Fig. 1, except with space between the questions for responses) to a total of 1080 students in algebra-based and calculus-based introductory mechanics classes at Cal Poly from fall quarter 2018 through fall quarter 2019. The results aligned with those of Lawson and McDermott, and implied that many students had difficulty recognizing the mechanisms through which energy and momentum change. Students would often state the energy and momentum conservation principles inappropriately and fail to apply the work-energy and impulse-momentum theorems.

Lawson and McDermott reported that the cause-and-effect relationship of the work-energy and impulse-momentum theorems is a "subtle, but nevertheless, critical point [that] seemed to elude many participants in their study." In winter 2019, we introduced a change in the parallel pedagogy class intended to increase student understanding of the causal nature of the work-energy and impulse-momentum theorems. This was done primarily through changes to class dialogue. Rather than presenting $dE = dW = Fdx$ and $F = ma = dp/dt$, the causal statements "work changes energy" and "forces change momentum" were adopted and used frequently throughout the quarter.

We found that student performance was enhanced by both PP/LA as well as using the "causal statement intervention." The calculus-based classes that used the intervention and

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PP/LA performed better than those that didn't; the only PP/LA algebra-based class we studied also used the intervention and performed significantly better than the conventional algebra-based classes.

We did not test the effect of parallel pedagogy and learning assistants independently, but each has been shown in other studies to have positive impacts. Pollock has documented that learning assistants improve student learning,[5] and parallel pedagogy without learning assistants has resulted in an overall positive shift in the Colorado Learning Attitudes About Science Survey (CLASS),[7,8] with a large positive shift in Applied Conceptual Understanding.[3] Most introductory mechanics classes result in an overall *negative* CLASS shift.[7] Thus, it is not surprising that the combination of the two (PP and LAs) was effective.

Description of the assessment

The assessment is shown previously in Fig. 1. Part (a) asks for an acceleration comparison and tests student understanding of Newton's second law. Part (b) is an energy comparison; it can be solved in one step by applying the work-energy theorem. Part (c) is a momentum comparison; it can be solved in one step by applying the impulse-momentum theorem once it is noted which puck takes longer to reach the mark. There are other less direct methods to solve parts (b) and (c), which are noted in the "Assessment Results" section.

Parts (a), (b), and (c) of the assessment were scored independently. Three things were noted for each part:

- ***CORRECT COMPARISON:*** The comparison of the two quantities in question made by the student ("less than, equal to, or greater than") was scored as correct or incorrect.
- ***CORRECT REASONING:*** The reasoning behind the comparison was scored as correct, incorrect, or indeterminate. A student would not be scored as giving correct reasoning if they did not arrive at the correct comparison.
- ***THEOREM USAGE:*** It was further noted whether or not the student correctly cited the work-energy or impulse-momentum theorems for parts (b) and (c), respectively, regardless of whether it was applied correctly.

The assessment was given to 13 sections of calculus-based and 11 sections of algebra-based introductory mechanics classes at Cal Poly. One of the algebra-based and three of the calculus-based classes were PP/LA. It was given to all classes as a question on the final exam except in one class, where it was a quiz (for credit) given three weeks before the final.

Description of the "causal statement" intervention

The intervention was a change to class dialogue aimed at emphasizing the causal nature of the work-energy and impulse-momentum theorems. This was done primarily in class through the use of the causal statements "work changes energy" and "forces change momentum" and in the narrative of the textbook. Additionally, an example was added to the textbook (see the appendix) and used as a quiz or class example.

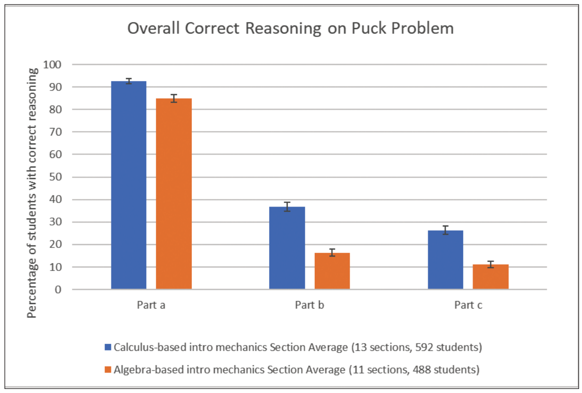

Fig. 2. Correct reasoning by all students, split into class type.

Lawson and McDermott also suggested that "the presentation of both theorems may suffer from a premature emphasis on their application to systems of objects for which momentum or kinetic energy are conserved." This emphasis on conservation can be observed in the following routine dialogue that would take place in class discussions before the intervention:

(***I*** signifies the instructor speaking, ***S*** signifies the student[s] speaking)

- ***I:*** "What do we know about momentum?"
- ***S:*** "It's conserved!"
- ***I:*** "When is it conserved locally?"
- ***S:*** "When there are no outside forces!"

The dialogue above emphasizes the conservation of momentum as its primary characteristic.[9] Part of the intervention was changing it to match the following:

- ***I:*** "How do we change momentum?"
- ***S:*** "With a force!"
- ***I***: "Is there an outside force?"

If there is:

- ***S:*** "Yes."
- ***I:*** "Then what do we know?"
- ***S:*** "Momentum changes."

If there is not:

- ***S:*** "No."
- ***I:*** "Then what do we know?"
- ***S:*** "Momentum is constant."

This new dialogue emphasizes the fact that systems with constant total momentum are a subset of all possible situations and emphasizes the idea that momentum is a quantity that can remain constant or be made to flow to another system by means of a force exerted for some time interval. This differs from the previous dialogue, which emphasized the constancy of momentum in an isolated system as the most important idea. Similar changes were made when discussing the work-energy concept.

Assessment results

As shown in Fig. 2, students performed well on part (a); on average, 93% of students in calculus-based classes and 85% of students in algebra-based classes gave the correct answer that cart A has a greater acceleration and correctly supported their answer. This implies that students had a good understanding of how to apply Newton's second law in this simple one-dimensional scenario, which is expected after a quarter of introductory mechanics. However, matching the observations of Lawson and McDermott, students had significant difficulty with parts (b) and (c). The degree to which they struggled may seem surprising, as both questions only require straightforward applications of two theorems, which are covered in introductory mechanics classes. Calculus-based classes averaged 37% of students with correct answers and reasoning on part (b) and 26% on part (c), while algebra-based classes averaged 16% on part (b) and 11% on part (c).

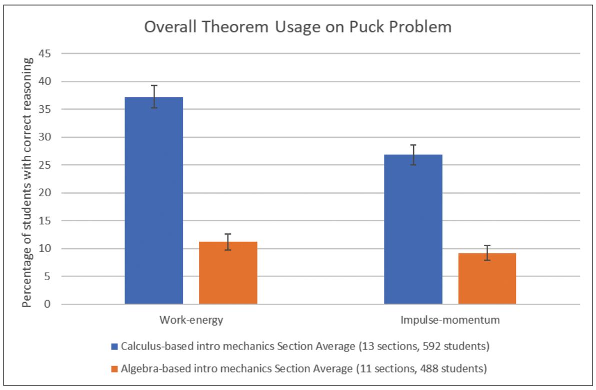

Fig. 3. Usage of the work-energy and impulse momentum theorems in parts (b) and (c), respectively, for all students, split into class type. Part (a) is omitted because it does not require usage of the work-energy or impulse-momentum theorems.

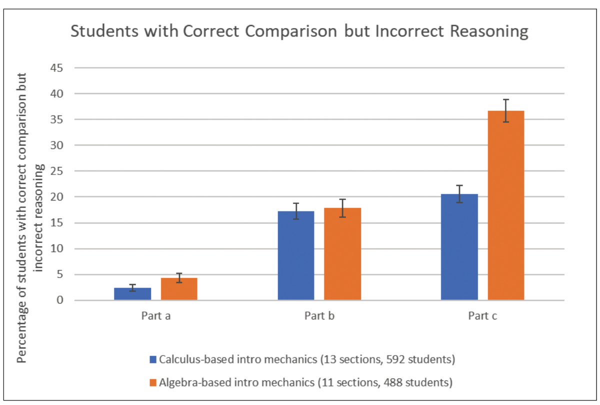

Fig. 4. Students who got the right comparison via incorrect reasoning, split into algebra-based and calculus-based groups.

The following are common ways the students would try to solve the problem without the theorems, similar to those documented by O'Brien Pride et al.:

- They would use simple compensatory reasoning, such as "one cart has more mass but the other has more velocity, so the momenta are equal." A version of this was also seen frequently in part (b): "Cart A has more mass but cart B has more velocity. Since velocity is squared in the kinetic energy formula, cart B has more kinetic energy."
- Many students would assign values to the variables consistent with the problem and solve for energy and momentum, or otherwise manipulate formulas to make a correct comparison of energy and momentum. These processes were sometimes conceptually sound.
- Students would use a comparison of kinetic energies made in part (b) to make a comparison of momenta in part (c). Usually, this would lead to a correct answer only if part (b) was correct.
- Sometimes students would cite the impulse-momentum theorem correctly in part (c), but then not acknowledge that the Δt is different for both carts, perhaps not noticing their acceleration comparison in part (a).
  - In the future, we may change part (a) from "which acceleration is greater" to "which cart arrives first," to try to eliminate this mistake, as it is a mistake that doesn't directly imply a lack of comprehension of the theorem.

Figure 3 shows the theorem usage for parts (b) and (c). As discussed in the previous paragraph, this will be slightly different from students who gave *correct* reasoning, as some students correctly solved the problem without the theorems and others cited the theorems but still made mistakes.

Correct comparison vs. reasoning discrepancy

Figure 4 shows that significant proportions of students made the correct comparison but were unable to support it with correct reasoning. About 17% of students gave the right comparison with incorrect reasoning for part (b). For calculus-based classes part (c) was just slightly higher (21%), but for algebra-based classes 37% of students gave the correct answer for part (c) but supported it with incorrect reasoning.

This discrepancy between correct comparisons and correct reasoning was also described by O'Brien Pride et al. Our results further confirm the inability of a multiple-choice question to measure conceptual competence.

Algebra-based section results: Causal statements and parallel pedagogy

All figures that follow do not include information about part (a). In general, scores on part (a) were all high (see Fig. 2) and part (a) does not test understanding of the theorems in question, so it is not very relevant to this discussion.

Figure 5 shows that the one algebra-based section that used PP/LA and the intervention performed significantly better on both parts than the 10 conventional algebra-based classes. This was the largest discrepancy in correct reasoning observed between the different groups we evaluated, and suggests a positive impact on theorem comprehension due to the use of PP/LA and the intervention.

Figure 6 shows theorem usage for the algebra-based classes. Here, the discrepancy is even larger than it was for answer correctness. The students who gave correct responses in

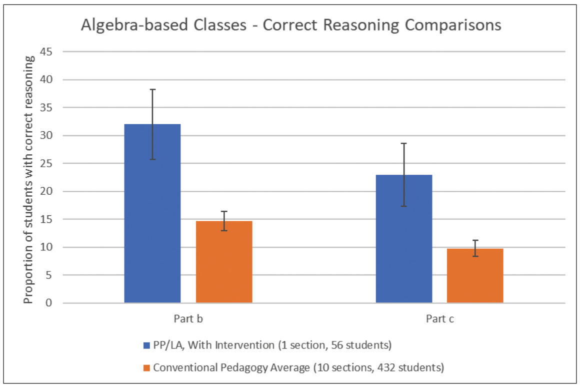

Fig. 5. Answer correctness for algebra-based introductory mechanics classes.

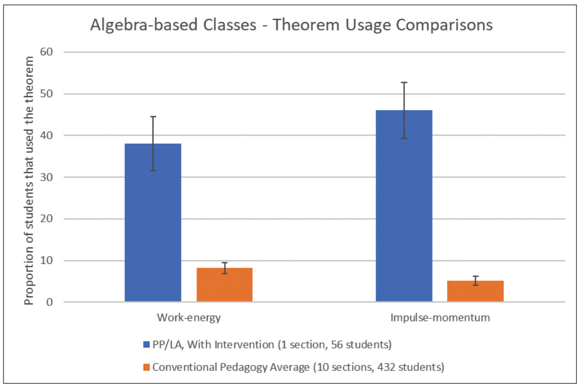

Fig. 6. Usage of the work-energy and impulse-momentum theorems in parts (b) and (c), respectively, for students in algebra-based introductory mechanics classes.

non-intervention conventional classes didn't always use the theorem, and students in the PP/LA class with the intervention sometimes applied a theorem incorrectly, in particular the impulse-momentum theorem on part (c).

It should be noted that because only one section of algebra-based PP/LA was observed, we cannot say that the higher scores shown in Figs. 5 and 6 were not due to characteristics of that specific section that were unrelated to PP/LA.

Calculus-based section results

Figure 7 compares performance of the different calculus-based classes. The calculus-based PP/LA classes outperformed the conventional calculus-based classes, although the semi-intervention PP/LA class was within uncertainty of the conventional classes on part (b). The PP/LA class that used the intervention performed better than the PP/LA class that didn't, but not significantly.

Theorem usage between these classes is compared in Fig. 8. The usage of the impulse-momentum theorem was lower for the "no intervention" PP/LA class compared to the conventional classes, even though their performance on part (c) was better than the conventional classes (see Fig. 7).

Figure 8 shows theorem usage for the calculus-based classes. The outstanding finding was the positive effect of PP/LA, in particular with algebra-based classes.

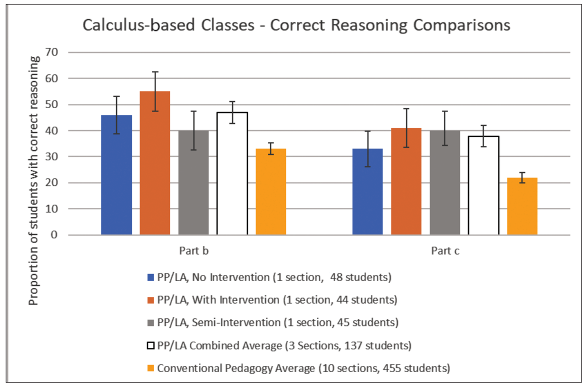

Fig. 7. Correct reasoning for students in calculus-based classes. "Semi-intervention" refers to a class that was not actively trying to use the intervention, but used the same textbook as the intervention class, which included edits made to it for the intervention.

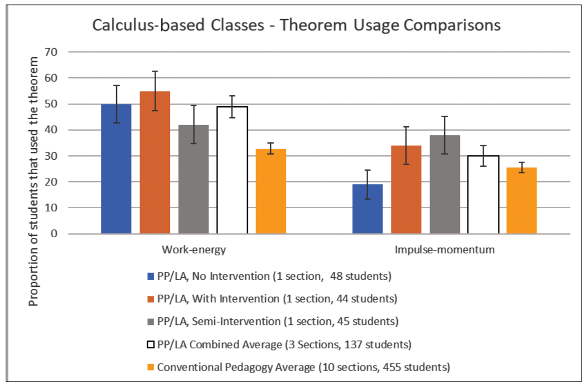

Fig. 8. Usage of the work-energy and impulse-momentum theorems in parts (b) and (c), respectively, for students in calculus-based classes. "Semi-intervention" refers to a class that was not actively trying to use the intervention, but used the same textbook as the intervention class, which includes causal statements.

Discussion

In 1989, David Hammer reported[10] that some students look at physics as a collection of unrelated formulas used to solve problems, whereas other students attempt to relate concepts to their intuition about how the world works. He also proposed that the way the class is taught may support the development of one perspective over the other. For instance, lectures by an expert scientist on how to use formulas may foster the former worldview, whereas student-centered group discussions as to why something happens may develop the latter epistemology.

Herein, we tried casting the conservation laws in terms of "causal statements" intending to help students better apply them, with questionable success. However, it seems that parallel pedagogy, where concept/intuition is placed at the center of the curriculum, results in the development that Hammer suggests. The parallel pedagogy[3] classes introduce all the concepts from the beginning, increasing application complexity during the course, stress dialogue and visualization (with learning assistant support), and require full conceptual support in order to receive credit on assessments.

Conclusion

We evaluated 1080 students on their ability to apply work-energy and impulse momentum theorems and conceptually support their answers. Consistent with Lawson and McDermott, students had significant difficulty in applying the work-energy and impulse-momentum theorems; and calculus-based classes did better than algebra-based classes. Additionally, we further confirmed the difficulty of measuring conceptual competence with a multiple-choice question.

We implemented an intervention focused around causal statements when discussing how energy and momentum change, such as "forces change the momentum of an object," which may have slightly improved student performance. However, we found significant improvement in classes employing concept-focused parallel pedagogy and learning assistants.

Acknowledgment

We are grateful to Stamatis Vokos for suggesting we study this question and providing background and guidance.

Appendix: Addition to Textbook

Starting from rest, two identical cars (but one is full of people) with low-friction wheels are pushed by two friends with the same force. After 10 seconds please compare the momentum and energy of the two cars.

- ***a) Momentum Lens:*** Does conservation of momentum mean that these two cars have the same momentum? Why not?
- **b)** Are the momenta of the cars constant in this example? Why or why not? *
- **c)** How might we compare the change in momentum for each car? So, we ask ourselves, "What's happening with momentum? How do we change momentum?" How do the momenta of the two cars compare after 10 s? Explain how you know.
- ***d) Energy Lens:*** Explain why "conservation of energy" wouldn't mean that the kinetic energies are the same.
- **e)** How do we change energy? How can we compare the change in energy of each of the two cars? How do the kinetic energies of the cars compare after 10 s? Explain how you know.

* This question was recently changed. Previously, during the intervention, the word "constant" was "conserved," which we found to confuse the same concept we are trying to clarify. The textbook exercise presently uses the word "constant" as above.

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9. We recognize that this dialogue misnames "conserved" for "constant." For a discussion of this issue, see Lane Seeley, Stamatis Vokos, and Eugenia Etkina, "Examining physics teacher understanding of systems and the role it plays in supporting student energy reasoning," *Am. J. Phys.* **87**, 510 (July 2019).
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