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3, 2, 1 … Discovering Newton's Laws

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"For every action there is an equal and opposite reaction." "Except when a bug hits your car window, the car must exert more force on the bug because Newton's laws only apply in the physics classroom, right?" Students in our classrooms were able to pick out definitions as well as examples of Newton's three laws; they could recite the laws and even solve for force, mass, and acceleration. However, when given "real world" questions, they would quickly revert to naive explanations. This frustration led to an examination of our approach to teaching Newton's laws. Like many, we taught Newton's laws in their numerical order—first, second, and then third. Students read about the laws, copied definitions, and became proficient with vocabulary before they applied the laws in a lab setting. This paper discusses how we transformed our teaching of Newton's laws by flipping the order (3, 2, 1) and putting the activity before concept, as well as how these changes affected student outcomes.

Background

The traditional instructional methods that we previously used failed to facilitate a deep understanding of the laws of motion. Students could recite classic definitions but, when faced with real world situations, failed to apply them correctly.[1,2] As part of the Target Inquiry (TI) professional development program,[3] we were encouraged to examine the science education literature for alternate methods that could be used to address the student misconceptions we were seeing. The following findings from the literature informed several changes in our approach.

1. The order of the laws encouraged students to misapply the second law of motion to the objects involved in a third law interaction.[4]
2. The vocabulary for the third law (action-reaction forces) implied a sequence to the forces, when, in fact, they happen simultaneously.[5]
3. Traditional instruction with verification labs allowed students to hold their misconceptions, instead of forcing them to confront and revise those misconceptions.[6]

Based on this research, we decided to make changes to our force and motion unit.

1. ***Order of Instruction:*** Teaching the laws in the 3, 2, 1 order seemed to make a difference for science teachers who were not physics majors.[4] We took this idea and used it to reorganize our sequence. In doing so, we could avoid the misapplication of the "newly discovered" relationship between mass and force from Newton's second law to imply that somehow more massive objects can then apply larger forces in a third law interaction. Moreover, during third law investigations, students often notice different reactions to equal forces, based on mass. This observation of equal forces having unequal results provides a perfect segue into Newton's second law.
2. ***Action/Reaction Vocabulary:*** Here, instead of identifying and naming the forces specifically, we talk about "the force by the bat on the ball, and the force by the ball on the bat." This allows students to identify force pairs correctly without an implied delay or cause-effect relationship between the two forces.[5] Discussions about type of force, such as gravity or normal force, are eliminated because it really does not matter at this point. This also sets students up for recognizing the often overlooked "unseen forces" such as friction and air resistance.
3. ***Activity Before Concept[7]:*** This was a direct result of the insight we gained from participating in the Target Inquiry (TI) program. This teacher development program gave us the resources and support we needed to feel safe while implementing these changes to our approach to these concepts.

Classroom activities

Both Newton's third and first law concepts were taught by: (1) students rotating through a series of stations where they experienced the phenomena, followed by a whole class discussion to pull ideas together; and (2) an Interactive Lecture Demonstration[8] (ILD) where students' common misconceptions were further challenged with real-time data. Examples of station and ILD activities are described below. Detailed descriptions, material lists, sample student data, and facilitation tips are available on the TI website (https://www.gvsu.edu/targetinquiry/). In between, Newton's second law was developed through students' use of cars, tracks, and photogate timers (CPO Science®) to explore the motion of cars under conditions of different applied forces and varying masses.

Starting with Newton's third law, students rotated through four active learning stations. Two activities examined direction of forces, and two explored magnitude of forces. In the end students put their ideas together to form one coherent thought about force pairs. To explore the direction of forces, pairs of students sat on skateboards and pushed against each other's outstretched arms. In another activity, students sat on skateboards and pushed against a bowling ball. During the direction activities, some students observed that the effects of the forces on large vs. small students was very different. Students were encouraged to note this and bring it up in class discussions later in the unit as a springboard into Newton's second law. The magnitude of the forces was explored using tube-style spring scales and pairs of bathroom scales. In both activities, one person kept their scale stationary while the other student pushed or pulled on their scale. Both scales were read simultaneously by other students.

Students' common misconceptions about force pairs were further challenged with real-time data using the ILD procedure. The ILD employed low-friction carts with force probes on a track system. The teacher first described and demonstrated the interaction and asked students to predict the direction and magnitude of forces on the carts, including the shape of the force/time graph. The demonstration was then repeated, this time in data collection mode so that the graphs of the forces were created and displayed in real time during the interaction.

Figure 1 shows the results when a massive double cart "truck" and a single cart "car," both with force probes, collide head on. The truck is loaded with 500 grams of mass and is pushed toward the "car," which is stationary, until the truck collides with it. The key concept of this scenario is that size, mass, and speed have no effect on the magnitude of the forces in a force pair. This scenario created significant cognitive dissonance. Although students had seen several interactions before this, where in each case the forces on the carts were equal and opposite, many students still thought the truck would apply a greater force on the small car. This resulted in many debates within groups. Seeing the graphs in real time, as seen in Fig. 1, caused students to recognize that the forces were equal in magnitude and helped to solidify an accurate understanding of the forces. After these experiences, students read about Newton's third law and were assessed on understanding.

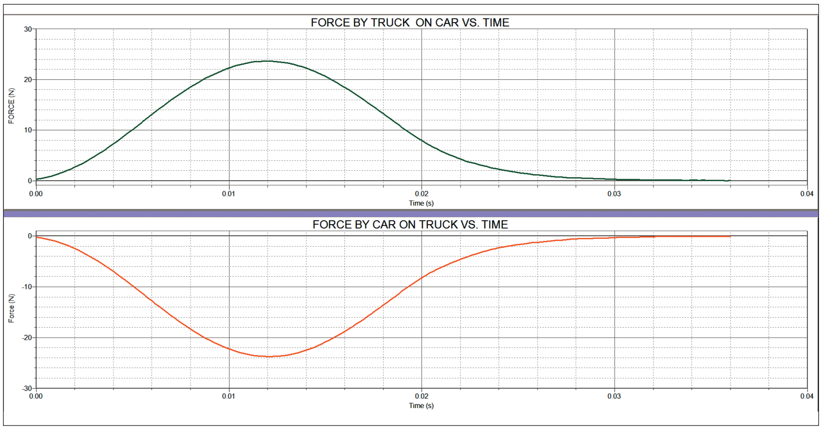

Fig. 1. Force vs. time graphs of a loaded truck colliding with a stationary car. Notice the forces are equal in magnitude but opposite in direction.

Newton's first law was taught using the same model as the third law. Students conducted a series of hands-on activities to develop key ideas. An example of these activities is the sail car and fan. A low-friction car with a half sheet of paper attached to the top like a sail was rolled toward a box fan. The fan speed was varied (including having the fan off). The effect on the car was observed and discussed. The key concept was that air resistance is a force that affects motion.

This was again followed by a series of ILDs using a track setup similar to that used for Newton's third law but with a motion sensor added. For each scenario, the students were asked to predict the shape of the velocity/time, acceleration/time, and force/time graphs, as shown in Fig. 2. An example scenario for Newton's first law: a string was attached between the right end of a low-friction cart and a mass hanging over the right end of the track. The cart was pushed toward the left. After release, the force of gravity on the mass steadily slowed the cart to a stop. Gravity then accelerated the cart away to the right. The key concept of this scenario was that constant force caused an object to slow down, change directions, and speed up in the opposite direction. This scenario was designed to address the common misconception that a constant net force results in a constant velocity rather than zero net force resulting in constant velocity. Of course, it is also possible to take numerical data from this ILD scenario to reinforce Newton's second law ($F = ma$).

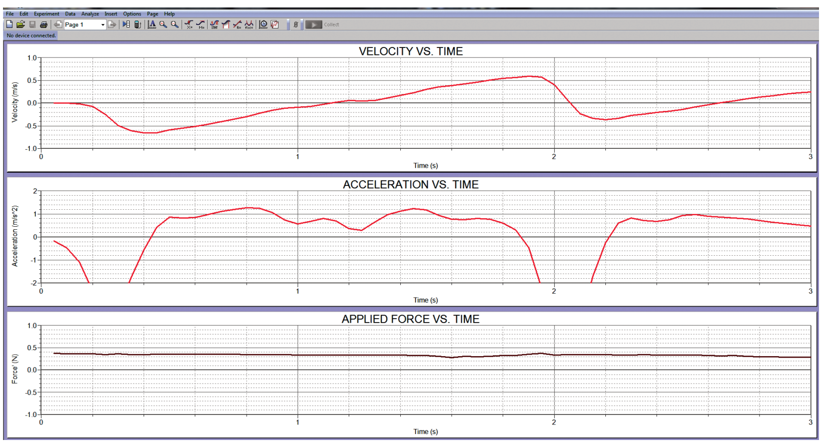

Fig. 2. Graphs of velocity, acceleration, and applied force vs. time for a car that starts moving to the left but is being accelerated to the right. The velocity and acceleration graphs show motion during the push, while the cart is moving on its own, and while it is being stopped as it returns to the end of the track. The applied force is constant because it is from a hanging mass on the end of the track.

This scenario was the most challenging for students to predict because the initial velocity was in the negative direction, but the force and resulting acceleration are in the positive direction. The students' predicted graphs for acceleration and force created great discussions within lab groups, between lab groups, and, finally, with the whole class. Students did not reach consensus about the graphs. Seeing the graphs formed in real time triggered great conversations about the meaning of each graph and why their shapes made sense. These conversations revealed that many students still confused velocity, acceleration, and force as well as their graphs. Improved success in predicting the graphs of scenarios like this will require more practice with these terms and their graphs.

Impact on students

We found that the activities had a positive effect on student misconceptions. Students' ideas were assessed using the first 21 questions of the Force and Motion Concept Evaluation (FMCE).[9] Pre- and post-tests were compared and 66% of students made gains, with the average normalized gain 17.23%. Though many students successfully confronted their misconceptions, some misconceptions were more easily overcome than others. On the 10 questions from the FMCE that related to Newton's third law, 98.6% of students showed gains from pre- to post-test. The average normalized gain was 88%. The misconceptions most difficult to correct involved Newton's first and second laws. The three flawed ideas that were most prevalent after instruction included: constant force yields constant velocity, force is always in the same direction as the motion, and acceleration only occurs with changing forces. These ideas are common and deeply ingrained. However, it should also be noted that in comparing two years of student scores on the Force Concept Inventory (FCI),[10] using a using a t-test for two independent samples with unequal variances, students participating in these activities were found to score significantly higher (39.2%) than students from the previous year (34.12%), who were taught Newton's laws without these activities ($p = 0.002$, with a small effect size as measured by Cohen's $d = 0.37$). It is reasonable to assume that students showed greater gains on the FMCE because the questions from the FMCE were directly related to concepts taught, while the FCI includes many questions that fall outside the scope of our middle school physics program, including projectile motion and vectors.

More convincing than the test scores were the students' discussions as they robustly debated their predictions as part of the ILD process. As students drew predicted graphs on marker boards and presented and defended their analysis to their peer group, student disagreements led to a deeper understanding. As each group presented a summary of their predictions to the class and defended their predictions, critical reflections helped refine key ideas. One moment that stands out is when a group was sharing their incorrect ideas and a fellow student could not contain his enthusiasm to persuade them with his analysis. He came to the front of the class and showed on the marker board how the graph must look for the motion observed. This took the classroom discourse to a new level. Throughout this process, students showed great shifts in understanding and developed confidence in their views as they explained them to peers. An ongoing goal of the authors is to have the FCI scores reflect the higher level of understanding that was clearly and broadly expressed during classroom debate.

Conclusion

This restructuring of our curriculum helped students confront their misconceptions with Newton's third law. While gains were achieved with Newton's first and second laws, the gains were not as large. We feel that further gains in student understanding of Newton's first and second law could be achieved by incorporating additional practice interpreting force graphs and with situations where force and motion are not in the same direction. Requiring students to draw free-body diagrams for each question may help students more accurately analyze the forces affecting motion. Adding space to the FCI answer sheet for each question and requiring students to create a free-body diagram in that space may help show the gains that were observed in classroom discourse.

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