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CourseSource

Lesson

A Momentum-First Approach to Newton's Second Law

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Abstract

Students frequently struggle with seeing the connection between forces and motion in introductory physics. This lesson is part of a combined momentum and kinematics unit that first teaches Newton's second law as a statement of conservation of momentum. Drawing on prerequisite knowledge of calculus, Newton's first and third laws, and static equilibrium, students are prompted to graphically represent the relationships between forces (sometimes non-constant) and the momentum of an object, as well as calculate changes in momentum as the result of a non-zero net force.

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Learning Goals

Students will:

◊ describe the motion of an object subjected to a force for a specified period of time.

◊ explain how changes in momentum are related to the net force on an object.

Learning Objectives

Students will be able to:

◊ graph the motion of an object subjected to a force for a specified period.

◊ calculate the change in velocity of an object under the action of a constant net force.

INTRODUCTION

This lesson was designed to introduce Newton's second law as a description of changes in momentum of an object. In a traditional university or college introductory physics course or textbook, students learn about constant-force motion (kinematics) first, and therefore may have trouble understanding the more fundamental relationship between (net) forces and the motion of an object—particularly when forces are no longer constant. Indeed, student misconceptions regarding kinematics, graph reading, and momentum are well-documented (1–3). This activity comes from a course which teaches static equilibrium (including both force and torque balances) first. The lesson described below is the first lesson where students encounter a scenario where the net force is not zero and must make mathematical predictions about the behavior of objects in this case. We introduce Newton's second law as $\sum F = dp/dt$ to address the idea that a net force changes the velocity of an object and set them up for future lessons about the Rocket Equation in which the mass of an object is also changing. Students apply this equation to graphing the motion of an object under the action of different forces, and then use this equation to calculate changes in velocity of an object.

Intended Audience

The intended audience for this lesson is first-year STEM students enrolled in calculus-based physics.

Required Learning Time

50 minutes.

Prerequisite Student Knowledge

Students should have a basic understanding of differential calculus, static and kinetic friction, and Newton's first and third laws. Students should be able to work with imperial and metric units in combination. In addition, students will complete a pre-reading on momentum (not collisions) and impulse before class and be asked to answer a brief qualitative question on the magnitude of a force on two different objects hitting a wall to gauge their understanding (4).

Prerequisite Teacher Knowledge

The teacher should have a solid understanding of Newton's laws, graphical representations of motion, and conservation of linear momentum.

SCIENTIFIC TEACHING THEMES

Active Learning

This lesson is highly interactive and relies on collaborative small-group problem-solving (5) and clicker questions (6). This is best done in a flat active-learning style classroom (*e.g.,* SCALE-UP), but can also be facilitated in a lecture hall with students working with nearest neighbors. Students work together in small groups on a worksheet that carefully scaffolds the application of key physics principles to different scenarios and draws on prior lessons on forces. The instructor and learning assistants circulate around the room answering questions and monitoring before bringing the class back together to discuss the worksheet solutions, test student understanding using clicker questions, and give a brief lecture on the physics and mathematical explanation of the results. Students are accustomed to this teaching style by this point (fifth week) of the semester. They are introduced to this teaching style by first experiencing it on the first day, being asked for their feedback, and then addressing the feedback and literature on the effectiveness on the second day (7).

Assessment

Assessment of these learning outcomes was achieved through a combination of in-class clicker questions, pre-class quizzes, and homework problems. The clicker questions test conceptual understanding of graphical representations (1), a quiz is administered before the second class on momentum to give students a chance to apply the equation, and the homework tests whether students can apply the ideas of conservation of momentum to real-world scenarios (8).

Prior to the next class period, students were asked to transfer the knowledge from the car sliding on flat ground to a truck sliding up a hill, requiring them to break forces into components but still probing the second learning outcome:

> A large truck that weighs 10,000 kg is traveling on flat ground at a speed of 25 m/s. Its brakes suddenly fail, and it turns off onto a runaway truck ramp that is angled upward at an incline of 30 degrees. The runaway ramp is filled with sand, which has a kinetic friction coefficient of 0.5. How long (in seconds) does it take for the truck to come to a stop? You can neglect air resistance.

We then placed two questions about Newton's second law and calculating times for an object to come to a stop on the following homework assignment.

> For a school woodshop project, you are to make a toy car out of a block of wood, which will be propelled by a little canister of carbon dioxide. You are graded on how quickly the car goes a certain distance.
>
> a. The friction due to rolling is very small, so what is the most important physics principle governing how the car moves (3 points)?
> b. If everyone has the same amount of carbon dioxide available, what are the features of the car you can change to maximize its velocity? (4 points)
> c. If air resistance is not important and each canister contains 16 grams of carbon dioxide that is expelled at a speed of 100 m/s, what is the maximum speed of a 1 kg car? (8 points)

> You are driving your electric car to work one morning and forget your coffee cup on the roof. As you leave your driveway, you speed up to 10 mph and then remember your coffee cup and decide you need to stop. If you stop too fast, the cup could go flying and hit a pedestrian. How long should you take to come to a stop to be sure the cup doesn't fly off the roof? (20 points)

Inclusive Teaching

The lesson incorporates several inclusive teaching practices (9). This includes encouraging the participation of all students by randomly calling on students to provide answers, active monitoring of student participation, having students work in small groups, asking open-ended questions, and establishing classroom norms. We also structured our small groups such that women and students of color were never in the minority, which is considered best practice (10). Group work was supported using Learning Assistants (11) who identified which groups were struggling the most and focused on them. In total, there were four personnel for a class of 198 monitoring the group work. There is no explicit discussion of diverse contributions to science, but we explicitly avoid placing Newton on a pedestal throughout the course, so we don't communicate implicit messages of what a scientist looks like (12). The design of the course also relies on assessment methods that are independent of students' high school physics preparation, which promotes equity (8). By asking them questions (*e.g.,* above) which require them to make their own assumptions and reason with limited information, we are challenging students with prior physics experience to think in new ways while simultaneously supporting students who are new to physics by scaffolding this kind of thinking in class.

LESSON PLAN

The complete materials required for the lesson are in the Supporting Materials: Supporting File S1 is the worksheet students use and Supporting File S2 is the slides that accompany the lesson to provide explanations. The timeline for the activity is given in Table 1.

Set-Up

This lesson is part of a whole curriculum, so by this point, students are already familiar with working together in groups, completing worksheets, answering clicker questions, and doing invention activities. Students are asked to complete a brief pre-reading on momentum, Newton's second law and impulse. They are then asked a comprehension question online before class, which asks them whether a ball of putty or a tennis ball, thrown against a wall with the same velocity, experiences a greater force. This draws on intuitive knowledge (that the tennis ball is 'bouncier' and therefore in contact with the wall for less time), and the newly gained knowledge that the force is proportional to change in velocity over change in time.

Part 1

Students start working together almost immediately after a brief review of the statement of Newton's second law. Note that the activity is situated in a real-world context in which some students may be able to imagine themselves—*i.e.,* an automotive engineer at a local electric car manufacturing facility. Students are first asked to apply the momentum equation (for a constant mass scenario) to create velocity versus time sketches for different kinds of net forces from the motor: a constant force (linear velocity versus time graph) and a linearly increasing force (quadratic velocity versus time graph). They are also asked to sketch the motor force as a function of the car's mass (which is linear if you ignore air resistance). These answers are probed using clicker questions and peer instruction (6).

Part 2

In the second part of the activity, students are now asked to apply Newton's law in two contexts: calculating the force the motor would have to deliver for a certain 0–60 mph time, and calculating how long it would take the car to skid to a stop (on locked wheels) from 60 mph. They are explicitly told to use Newton's second law. In these calculations we explicitly mix imperial and metric units, as this is an important skill for students to learn as engineers. As can be seen in Supporting File S2, even though the force is assumed constant, we illustrate the solution with integral calculus to lay the foundation for non-constant forces in future homework or quiz problems. We also illustrate the answer using symbolic algebraic forms to show how the issue of converting units can be almost entirely avoided. After students have worked on these two problems, we have a brief conceptual clicker question about what forces slow down the car (to acknowledge the complexity of the situation in reality), and then go over the answers to the questions. We ask this question about the forces responsible for slowing the car down to connect back to physical intuition and real-world experiences. This also creates an opportunity to explain why ignoring air resistance (compared to friction) might be a reasonable assumption. The inclusion of engine braking opens an opportunity to explain why this is not relevant when the car is skidding along a surface and addresses prior knowledge some students may have. Finally, we ask students to apply Newton's second law to calculate how long it takes a car to come to a stop using friction. This requires them to look up, or assume, values for kinetic friction, which they are typically already familiar with (they have been pointed to a table of friction values in the textbook).

TEACHING DISCUSSION

The lesson appears to be effective in teaching principles of momentum conservation and Newton's second law for students. On the pre-class reading quiz, approximately 30% of students got the correct answer on the first try, and 65% of the remaining students got the correct answer on the second try, meaning 76% of students got the correct answer before they were shown the correct answer in the online quiz. For the follow-up transfer question before the next class, 74% of students got this question correct after 3 tries. The scores on the homework questions were 82% and 93%, respectively, indicating an overall improvement.

One notable difficulty for the students during the lesson was the translation of the differential statement of Newton's second law into a graph, even for a constant force. Part of this difficulty was with proportional reasoning (13), which has been documented and which we encountered earlier in the semester. However, once we established that a constant derivative corresponded to a linear plot, students had no trouble extending this idea to a non-constant force.

One modification we would suggest is not to explain the calculation of the 0–60 force of the motor using calculus without more scaffolding. Students had quite a lot of difficulty applying concepts from their calculus course to physics, and this likely resulted in unnecessary cognitive load during the learning process. Indeed, it likely interfered with being able to solve the question about the 0–60 stopping time at the end of class. This derivation could be saved for a follow-up activity, or omitted entirely depending on the extent to which calculus is used in the course.

We believe that this lesson would transfer quite well to other university contexts. Indeed, the use of calculus for this lesson is not necessary for teaching the underlying concepts, so the clicker question about a non-constant force could be omitted for teaching an algebra-based course. We acknowledge that faculty members might struggle to adapt this lesson, as it presumes understanding of Newton's first and third laws in static equilibrium first, however there is an activity published in *The Physics Teacher* that could be paired with this (14) to teach Newton's three laws in a relatively short time span.

SUPPORTING MATERIALS

- S1. Momentum-First-Approach – Momentum worksheet
- S2. Momentum-First-Approach – Momentum lesson 1 slides

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Table 1. Timeline of activities for the lesson.

Activity	Description	Estimated Time	Notes
Logistics			
Review of Newton's second law and pre-reading	Lecture	5 min	
Students Working Together: Part 1			
Students complete parts 1.1–1.2 of the worksheet	Students complete parts 1.1–1.2 of the worksheet	5 min	
Go over answers and lecture	Students answer two clicker questions to see the answers to 1.1 and 1.2, connecting what they know back to calculus	5 min	
Test understanding	Students answer a clicker question that requires them to use the content just presented (1.3)	3 min	This tests their understanding of Newton's second law for a non-constant force
Students Working Together: Part 2			
Students complete parts 1.4–1.5 of the worksheet	Students work together to solve simple problems using Newton's second law	15 min	Students are already familiar with friction at this point
Go over answers and lecture	Lecture and walk slowly through derivations	15 min	

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