AP Physics 1 Investigation 5: Impulse and Momentum

How are force and impulse related to linear momentum and conservation of momentum?

Central Challenge

In this multipart investigation, students investigate concepts of impulse and momentum both qualitatively and quantitatively. After they explore the basic concepts of momentum, they gather the data needed to calculate changes in momentum and impulse, make predictions about motions of objects before and after interactions, and determine whether momentum is conserved.

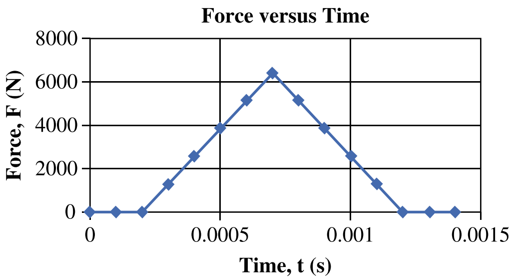
Background

Linear momentum describes the translational motion or motion of the center of mass of an object or system in terms of its mass and velocity ($\vec{p} = m\vec{v}$). Momentum is a vector quantity that has the same direction as the velocity. A net external force exerted on a body or system will change its momentum; this change in momentum is called impulse ($\Delta\vec{p}$). The rate of impulse, or impulse divided by time of interaction, is equal to the net force exerted on the object or system. Newton's third law of motion, then, arises from the conservation of momentum and describes interactions in terms of impulse and force: the impulse one object or system exerts on another is equal in magnitude and opposite in direction to the impulse the second object or system exerts on the first object or system.

$$\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$$

The area between the plot line and the *x*-axis for a graph of force exerted on an object as a function of time is the change in momentum of the object. For example, if a force is exerted by a tennis racket while serving a tennis ball, the force exerted by the racket on the ball is forward, and the increase in momentum of the ball is also forward. The force exerted by the ball on the racket is equal in magnitude to the force exerted by the racket on the ball, and the impulse delivered by the ball to the racket is equal and opposite to the impulse delivered by the racket to the ball.

In Graph 1 below, the area between the graph line and the time axis (a triangular shape here) represents the change in momentum ($\Delta\vec{p}$) of the object on which the force is exerted. If this area is divided by the mass (m) of the object, the change in velocity ($\Delta\vec{v}$) of the object can be determined.



Graph 1

Linear momentum is always conserved. This means that if no net external force is exerted on the system, the linear momentum of the system cannot change. So, total linear momentum of objects within a system prior to an interaction of those objects is equal to the total linear momentum of the objects after the interaction when there is no external force acting on the system during the interaction. For example, if two carts on a level, frictionless track collide, the total momentum of both carts prior to the collision ($m_{1o}\vec{v}_{1o} + m_{2o}\vec{v}_{2o}$) is equal to the total momentum of both carts after the collision ($m_{1f}\vec{v}_{1f} + m_{2f}\vec{v}_{2f}$). In isolated collisions, momentum is constant and if the collision is elastic, kinetic energy is also restored, so that the final is equal to the initial for momentum and kinetic energy.

Real-World Application

Sports provide a lot of real-world applications regarding momentum and impulse. In boxing or karate you can talk about the differences between a quick jab, which produces a large change in momentum over a short time and so a large force, or a follow-through punch, which may deliver the same change in momentum, but over a longer time so a smaller force. In baseball, you can talk about how the bat changes the momentum of the ball.

Seatbelts and airbags are designed to increase the amount of time it takes a body to stop, thus decreasing the amount of force exerted on a body by the car, since the impulse exerted on a body is always equal to its change in momentum. Similarly, crumple zones in cars are also designed to increase the amount of time over which a collision occurs, thus reducing the amount of force being exerted on objects as they come into contact during the collision.

Inquiry Overview

In this lab students first pursue a qualitative examination of interactions between objects, making predictions and observations about the motions of objects before and after interactions in response to these three questions:

- How do forces exerted on an object by another object change the linear momentum of the object?

- What is impulse?
- How are force and impulse related to conservation of linear momentum?

Depending on equipment selected (or available), students design their investigations to include collisions of two moving carts of equal and of unequal mass — both elastically and inelastically. If possible, they include an "explosion" where two carts connected by a spring and at rest are released so that the carts move apart. They use the terminology that includes linear momentum, force, impulse, and conservation of momentum to write their observations. They then share those observations with the larger group, refining their descriptions in readiness for the quantitative part of the lab.

The quantitative portion of the lab is guided inquiry, where the teacher provides the recommended equipment and sets some parameters, such as providing the purpose and setting the requirement that the analysis should include at least one graph. Students then meet in small working groups to decide how to gather and record data for the same situations they have observed qualitatively. Students decide how to make the necessary measurements of the speeds of the carts, set experimental controls, and process the data in order to answer the central question: How are force and impulse related to linear momentum and conservation of linear momentum?

Connections to the AP Physics 1 Curriculum Framework

Big Idea 5 Changes that occur as a result of interactions are constrained by conservation laws.

Enduring Understanding	Learning Objectives
5.D The linear momentum of a system is conserved.	**5.D.1.1** The student is able to make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. (Science Practices 6.4 and 7.2)
	5.D.1.6 The student is able to make predictions of the dynamical properties of a system undergoing a collision by application of the principle of linear momentum conservation and the principle of the conservation of energy in situations in which an elastic collision may also be assumed. (Science Practice 6.4)
	5.D.2.1 The student is able to qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. (Science Practices 6.4 and 7.2)
	5.D.2.4 The student is able to analyze data that verify conservation of momentum in collisions with and without an external friction force. (Science Practices 4.1, 4.2, 4.4, 5.1, and 5.3)

[**NOTE:** In addition to those listed in the learning objectives above, Science Practice 4.3 is also addressed in this investigation.]

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Skills and Practices Taught/Emphasized in This Investigation

Science Practices	Activity
4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.	Students meet in advance of the experiment to determine the data they need to collect in order to calculate change in momentum and impulse. They also decide what data they need to determine whether linear momentum is conserved. They may decide, for example, to collide carts moving on a track, measuring cart velocities before and after the collision and measuring the carts' masses to determine change in momentum in order to determine impulse.
4.2 The student can *design a plan* for collecting data to answer a particular scientific question.	Students make decisions in their small working groups about how to conduct the experiment to gather the necessary data to answer the question. They decide how many trials are appropriate and the method(s) they will use to gather data. For example, students may decide to use motion sensors at each end of the track to record and plot velocities.
4.3 The student can *collect data* to answer a particular scientific question.	Students collect the data they have determined they need, using the collection method(s) available to them. If motion sensors are available, students may decide to use them to plot velocities. If a camera and computer analysis tools are available, they may use this method to find velocities and changes in velocity. In the absence of these tools, students may need to use distance–time measurements to directly calculate velocities.
4.4 The student can *evaluate sources of data* to answer a particular scientific question	From the results of their experiment, students may compare momenta before and after a collision, with the goal of demonstrating that linear momentum is conserved. If the results are different, students examine sources of uncertainty in the experiment. For example, if momentum seems to have been lost or gained due to the collision, students may consider how carefully they derived values from motion sensor graphs or may re-evaluate whether friction played a role in exerting an external force on the system.
5.1 The student can *analyze data* to identify patterns or relationships.	In the quantitative portion of this lab, students answer the experimental questions by calculating impulse, force, changes in momentum, and whether momentum is constant for the system. They also determine what data can be used to create a plot that reveals meaningful results. If they have used motion sensors or video analysis, they have to use the velocity–time plots to determine changes in momentum and to assign correct signs to the quantities measured, based on direction of motion.
5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.	After calculating and graphing data, students compare results to predictions to determine whether the data produced reasonable results. For example, in making calculations related to conservation of momentum, students need to decide whether differences between original and final momentum are within reasonable limits and uncertainties to conclude that momentum is constant.

6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.	From the qualitative portion of the lab, students gather observations and are introduced to terminology that they will use to make predictions about results from the quantitative portion. They then evaluate their predictions, comparing the qualitative data to their predictions.
7.2 The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	In the final analysis, students should extrapolate their findings to other experiments that might be performed to gather further data. As a required part of each analysis they also discuss practical applications of the lab. For example, students might decide to discuss how the collision of carts on a track reveals information about how cars collide on a road, particles collide in a cloud chamber, or meteorites collide with planets.

[**NOTE:** Students should be keeping artifacts (lab notebook, portfolio, etc.) that may be used as evidence when trying to get lab credit at some institutions.]

Equipment and Materials

Per lab group (three to five students):

- Two spring-loaded carts
- Track
- Bubble level
- Known calibrated masses (three to four per station, in the range of 200–500 g) and at least two objects with unknown mass (also in the range of 200–500 g)
- Calculator
- Meterstick
- Stopwatch
- Computer with Internet access
- (Optional) Video camera and analysis software
- (Optional) Force sensor
- (Optional) Motion sensor with calculator or computer interface

Most schools have access to spring-loaded carts, but a simple substitution can be contrived using any two similar objects with wheels on a track or level surface. The wheeled carts can be launched by constructing a rubber band launcher (similar to a sling shot) at each end of the track area. By pulling each cart back and releasing, the carts will move toward each other and collide. Moving carts on an air track will also work for this experiment.

Timing and Length of Investigation

- **Teacher Preparation/Set-up:** 15 minutes

  Setting up the equipment for Parts I–III should take about 15 minutes.

- **Student Investigation:** 70 minutes

  Prelab should take under 5 minutes if you choose to talk about each section of the lab individually. You can have students work on the entire lab and turn it in when completed, at which time it will take about 10 minutes to go over the lab, or you can have them all work on Part I, then stop, discuss it, and move on to Parts II and III.

  Part I: 10 minutes (Qualitative Construction of Momentum)

  Part II: 30 minutes (Collisions of Carts)

  Part III: 20 minutes (Explosions of Carts)

- **Postlab Discussion:** 25 minutes

  Student presentation time after Part I (the qualitative section) should take about 25 minutes. If you have eight groups, each group should have about 2–5 minutes to present their findings. After Parts II and III, the postlab presentation of results might take about the same: 2–5 minutes per group. It will most likely be necessary to split the lab up over two or three days, at which time Part I and the postlab discussion might take one full class period, and Parts II and III could be done the next day with their presentations on the third day.

- **Total Time:** 85 minutes to 2 hours

  [**NOTE:** This lab could be split into two class periods, with the setup, collisions, and qualitative analysis on the first day and the explosions of carts and postlab discussion on the second day. Of course, the amount of time spent depends on how you choose to setup the prelab, quantitative report-out, and postlab discussions.]

Safety

Safety is of minimal concern with this lab. Make sure students do not have the carts going excessively fast. The biggest risk may be to equipment; students should be warned not to allow carts to hit the motion sensors or the camera, or to allow carts to roll onto the floor from a raised track. The carts should NOT be considered skateboards by students trying to ride on them.

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Preparation and Prelab

Prior to this lab, students should have an introduction to linear momentum, with definitions and equations related to linear momentum, force, impulse, and conservation of momentum so they can more effectively design investigations related to those concepts. This might include just a single day or a single lesson, with students assigned a set of related problems from the textbook prior to the lab. You may decide to use one or more of the recommended resources listed as portions of assigned work to help develop concepts. However, the lab itself should be the vehicle for clarification of these concepts, so that students are truly "investigating" the meaning of concepts.

The Investigation

Students begin the lab with a qualitative investigation of the basics of momentum in Part I, where they examine the movements of carts and learn to apply the vocabulary to a description of momentum, force, and impulse. In Parts II and III, students design investigations to qualitatively gather data to examine force and impulse when carts interact — followed by measurements they then use to examine conservation of linear momentum. You should keep the pulse of how the student groups progress, depending on student proficiency. It may be necessary to convene for small-group reporting between each part in order to ensure that students understand the concepts before proceeding to the next part. This may be particularly important after Part II, which is longer and requires the application of several different concepts.

Part I: Qualitative Introduction (~10 minutes)

The first part of this activity is a qualitative introduction to the concept of momentum and how objects interact when they collide.

Have students in each group use their hands to stop as quickly as possible two identical carts rolling towards them (both carts should be stopped at roughly the same time). One cart should be moving about twice as fast as the other. Then they should repeat this procedure with both carts moving at the same speed but with one having additional masses on it. To achieve these nearly identical speeds, students can push both carts simultaneously by placing each cart against a bent ruler that then acts like a spring launcher. (Commercial devices will have a rubber band or spring launcher at each end of a track.) This part can be done on one track or on parallel tracks. The students should then discuss which cart was more difficult to stop and why they think it was more difficult to stop. Ask the students to come up with a way that would enable them to demonstrate that the force needed to be exerted on the cart in order to stop it can differ depending on the means used to stop it (e.g., by using a spring and then a ball of clay to stop each cart, and then comparing the compression of the spring to the indentation made in the clay as a means of distinguishing the force necessary to stop the cart). The point is for students to get a qualitative understanding of the stopping force as a function of cart speed and cart mass.

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The property of the carts students are describing and observing is called *momentum*. Students should also discuss the forces and impulses exerted by their hands (and by the springs or the clay) on the carts in the process of stopping them. In which case(s) does time play a role?

Part II: Colliding Carts (~30 minutes)

In this activity students design an experiment in which two carts gently collide with each other in different ways.

Task the students to calculate the velocities of the carts before and after different types of collisions. They should report their methods and their uncertainty, and then calculate the momentum of the system before and after each type of collision. Students should design at least four different variations, with the collisions ranging, for example, from one with a moving cart colliding with a parked cart, to one with two carts moving towards each other, to one with two carts moving in the same direction where the faster cart collides with the slower cart. Students should record masses and velocities before and after each collision.

Acting as a facilitator, help students to understand and realize the importance of running trials numerous times. Students should ultimately run the trials multiple times to look for patterns in the data which indicate the role mass plays in each collision. Then they should look at the data and see if they can come up with a rule for each collision. For example, they could collide equal mass carts and unequal mass carts, and see if they notice a pattern. After that they can play around and see if the rule still holds when both carts are moving. The student groups should then make presentations to the larger group that include discussions of the forces the carts exert on each other as well as the impulses delivered.

Part III: Explosions (~20 minutes)

In this activity, students build up to the idea of conservation of momentum via “explosions” of two objects moving away from one another. This can be done with two identical carts with a spring compressed between them. Releasing the spring will cause the carts to move apart, and students then calculate the momentum of both carts. [**NOTE:** Students may need to be prompted with the idea that since the center of mass of the spring does not accelerate, the force exerted by the spring on one cart is equal and opposite to the force exerted by the spring on the other cart.] Prior to releasing the carts, have the students predict what they expect to happen when the carts are released. They should come up with the expectation that if the carts start at rest, the final total momentum of the two carts should be zero. Then have students extend the activity to carts of unequal mass to again show that total momentum is constant.

Guide students to consider another way of looking at their data (i.e., using the conservation of momentum of the cart, to calculate the ratio of the two velocities during the trials where carts of unequal mass were used). For example, for one velocity to be twice the size of the other, they would need to double the mass of the other cart. Have the students write up their procedures and their experiments.

[**NOTE:** If students calculate velocities using direct distance–time measurements, their results may not show conservation as clearly as if the velocities are determined using motion sensors or video analysis methods.]

Extension

Students could follow up with an experiment where they stop a moving cart with a rubber band attached to a force sensor. That would show the force/time/impulse relationship. The cart is attached by a string/rubber band combination to a force sensor: it moves away from the sensor, extends the rubber band, stops, and then moves backward toward the force sensor. If used in conjunction with a motion detector, a full force/time/impulse/momentum analysis can be done. Several commercial types of equipment include motion sensors and force sensors that can be used for this extension. Students could produce from this data a "Force vs. Time" graph and use the area under the graph to calculate impulse.

Common Student Challenges

One of the large challenges students face with momentum is that they think momentum and inertia are the same thing. They think that larger objects will always have a larger momentum, which is not necessarily the case. In terms of conservation of momentum, students tend to place a higher value on the velocity aspect. If a small object moving quickly hits a larger object, they might expect that the larger object would move fast, because they don't realize that objects can be moving at different speeds and still have the same momentum. Students also tend to believe that conservation of momentum is only true in elastic collisions or (better but still wrong) in isolated systems. The difference between constant and conserved is often lost.

Another challenge with this topic is that students tend to think that force and impulse are synonymous. They do not realize that impulse also involves how long the force is acting on an object. Students should be required to create and/or analyze a plot of force vs. time to determine impulse (and change in momentum), either as a part of this lab or as a follow-up assignment, to reinforce this concept. If a force sensor is available, comparing the area under the curve (either by counting squares or using the computer to calculate it) of the force acting on a cart vs. time to the change in momentum of the cart is a powerful way to show that impulse on an object is the change in momentum of that object.

Particularly important is the demonstration (along with calculations) of the vector nature of change in momentum (e.g., a ball hitting a wall and bouncing back) to emphasize that the change in direction generates a much larger change in momentum (and thus larger force) than a ball that hits the wall and stops. It is important here for the teacher to emphasize the vector property of momentum by pointing out that if the ball hits the wall horizontally moving at a velocity $\vec{v}$, after an elastic collision with the wall the ball bounces back with a velocity $-\vec{v}$. The change in momentum of the ball is proportional to its final velocity minus initial velocity:

$$\Delta\vec{p} = m\Delta\vec{v} = m(\vec{v}_f - \vec{v}_o) = m(-\vec{v} - \vec{v}) = -2m\vec{v}$$

On the other hand, if the ball hits the wall and stops, the change in momentum of the ball is less:

$$\Delta\vec{p} = m\Delta\vec{v} = m(\vec{v}_f - \vec{v}_o) = m(0 - \vec{v}) = -m\vec{v}$$

Analyzing Results

Part I:
In the first part of this lab, students qualitatively explore and report (either verbally to their partners and/or in a journal) how hard they had to push on the cart — or how much force was exerted by another object, as designed by the students earlier — to make it stop. Once the two procedures in this part are done, you might want to confirm their understanding by asking if it was possible for the larger mass cart to require the same force to stop as the smaller mass cart (which was moving faster). Students should use the terms *momentum*, *force*, and *impulse* correctly in their reporting from this part in readiness for Parts II and III. If time allows, small student groups can prepare 2–3 minute presentations to the class, with you acting as facilitator, to gain feedback on improvement in procedure and correct use of terminology before proceeding to the quantitative measurements.

Questions to ask students might include:

- What quantities affect momentum?
- How is force related to change in momentum?
- When two carts collide, how do the forces they exert on each other compare?
- How is impulse related to force and to change in momentum?
- When two carts collide, how do the impulses they deliver to each other compare?

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Part II:
In the second part, students develop a method to calculate velocity. Ask them about uncertainty in the experiment. The largest will be a reaction-time error, such as a delay in starting and stopping the stopwatch. Have the students create a data table where they calculate the momentum of a system before and after each collision. Students should calculate the theoretical value for total momentum of both carts after each collision, based on the total momentum of the carts before the collision, and compare that calculated value to the experimental value for total momentum after collision, based on measurements after each collision.

Students should discuss possible sources of difference in the two values. If motion sensors or video analysis are used, students should also be able to determine the time of collision and from that calculate the impulses and forces the carts exert on each other.

Part III:
In this part the goal is to see if the previous pattern (initial momentum equals final momentum) still holds true in a situation where there is an explosion (i.e., two carts are held stationary with a compressed spring between them). The same procedures as in Part II can be used to measure and determine total momentum after the explosion to compare to the theoretical value of zero, since that was the total momentum prior to the collision. Students will have some difficulty here, as they may lose a sense of the magnitude of the uncertainty. Additionally, poor measurement techniques for both carts may, in fact, yield an answer near to the "correct" sum of zero.

You might want to provide prompts, such as: "What conclusions can be drawn about the change in momentum of cart 1 compared to that of cart 2?" Be sure to discuss how force, time, mass, and velocity play a role in your observations.

If students have been required to create at least one meaningful graph that can be used in analysis, the graph produced might be a "Velocity vs. Time" graph for one or both of the moving carts produced to show change in sign with change in direction before and after collision. If motion sensors or data analysis equipment are used, these graphs can be selected from those produced on the computer. Students should realize and comment that the amount of uncertainty in their measurements will depend upon the measurement methods employed (e.g., students using motion sensors may have a smaller amount of uncertainty than students making direct measurements with marked distances and stopwatches).

Assessing Student Understanding

After completing this investigation, students should be able to use the terms *momentum*, *force*, and *impulse* correctly to describe the motions of a system of objects before and after interactions. They should also be able to explain the meaning of conservation of linear momentum and the conditions under which momentum is constant.

Students should be able to:

- Design an experiment to show that in either an explosion (where a single object becomes multiple objects) or a collision (where multiple objects come into contact and exert forces on each other) the total momentum before the collision or explosion has to equal the total momentum afterward (providing there are no net external forces acting on the system);
- Demonstrate situations in which different forces are required to stop objects with different momenta;
- Calculate momentum and impulse (and also force if data analysis or sensors are used);
- Use calculations to show that linear momentum is conserved; and
- Produce a graph that can be used to show meaningful relationships related to momentum, such as force vs. time or velocity vs. time.

Assessing the Science Practices

Science Practice 4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

Proficient	Uses the velocity–time data accurately to calculate forces and impulses and also to calculate conservation of momentum in Parts II and III of the investigation.
Nearly Proficient	Uses the data to calculate cart velocities, forces, and impulses but has some errors in calculations.
On the Path to Proficiency	Connects the concepts of spring potential energy, the kinetic energy, and the gravitational potential energy to the big idea of conservation of energy with minor errors. States where each energy is a maximum. Describes the sources of energy losses.
An Attempt	Gathers data for cart collisions but data interpretation is not present.

Science Practice 4.2 The student can *design a plan* for collecting data to answer a particular scientific question.

Proficient	Designs an experimental plan that is well communicated and leads to values for cart velocities that can be used to accurately calculate forces, impulses, and momentum conservation values.
Nearly Proficient	Designs an experimental plan to collect data for cart velocities before and after interactions that might prove effective; however, the plan is not clearly communicated or has a flaw that will produce errors.
On the Path to Proficiency	Designs an experimental plan to determine cart velocities but makes multiple errors in the plan that will lead to erroneous values.
An Attempt	Designs an experimental plan to determine cart velocities, but the design will not prove effective in answering the experimental questions.

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Science Practice 4.3 The student can *collect data* to answer a particular scientific question.

Proficient	Collects data in such a way to as to minimize uncertainty; the data collected is adequate to make all calculations for cart velocities, forces, and momentum before and after interactions.
Nearly Proficient	Collects data that can be used to determine cart velocities, but does not follow through with additional data necessary to complete all calculations for force, impulse, and momentum.
On the Path to Proficiency	Collects data but collection methods are such that uncertainty is so large that calculated values will not be meaningful.
An Attempt	Collects data but the data collected will not answer any portion of the questions posed.

Science Practice 4.4 The student can *evaluate sources of data* to answer a particular scientific question.

Proficient	Addresses assumptions in the experimental design effectively, and discusses uncertainties in data gathering appropriately. If electronic methods are used to gather data, selects appropriate ranges from graphs produced by the computer, for example.
Nearly Proficient	Discusses uncertainties in the measurements in gathering data, but the discussion is incomplete or has flaws; for example, a systematic error such as a nonlevel track is evident but not realized or addressed.
On the Path to Proficiency	Collects data that can be used to calculate cart velocities, but attempts at explanations of uncertainty in the measurements are flawed.
An Attempt	Collects data but does not address uncertainty in their measurements.

Science Practice 5.1 The student can *analyze data* to identify patterns or relationships.

Proficient	Determines values for velocity, force, impulse and momentum in each scenario correctly. Constructs a correct graph from the data, such as the use of force vs. time to verify impulse calculations from velocities.
Nearly Proficient	Makes accurate calculations and graphical representation. Calculates cart velocities, forces, impulses, and momenta, but there may be errors in calculations or the graphical representation is attempted but has an error.
On the Path to Proficiency	Attempts the calculations and the graphical representation, and then makes attempts to calculate forces and impulses, but there is confusion in how the terms are used or there are errors in the calculations and the graphical representation is incorrect.
An Attempt	Unable to calculate forces, impulses, and momenta correctly from the data collected. Does not attempt a graphical representation.

Science Practice 5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Proficient	Reports correct relationships among force, momentum, and impulse in all three parts of the experiment, and demonstrates insight into these concepts during postlab discussions.
Nearly Proficient	Makes correct conclusions about force and momentum that need only minimal correction during postlab discussion. Makes correct conclusions about relationships between force and momentum, or about conservation of momentum during collisions, needing only minimal refinement.
On the Path to Proficiency	Makes some correct conclusions about force and momentum that need correction during postlab discussion. Makes incorrect conclusions about relationships between force and momentum or about conservation of momentum during collisions.
An Attempt	Unable to make correct conclusions about force and momentum. Unable to make correct conclusions about relationships between force and momentum or about conservation of momentum during collisions.

Science Practice 6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.

Proficient	Makes meaningful predictions about momentum concepts that are effectively applied to the quantitative portions of the lab.
Nearly Proficient	Makes meaningful predictions after the qualitative portion of the lab, and needs only minimal guidance on how to proceed during the quantitative portions.
On the Path to Proficiency	Makes only a few meaningful predictions after the qualitative portion of the lab, and needs guidance on how to proceed during the quantitative portions.
An Attempt	Unable to make meaningful predictions during the qualitative portion of the lab that will apply to quantitative measurements.

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Science Practice 7.2 The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Proficient	Describes a practical application in the analysis section of the lab report that is complete and accurate.
Nearly Proficient	Describes a practical application in the analysis section of the lab report that is generally correct but is not complete or contains an incorrect step.
On the Path to Proficiency	Makes an attempt to describe a practical application in the analysis section of the lab report that is partially correct, but the connection contains some incorrect physics.
An Attempt	Makes an attempt to describe a practical application in the analysis section of the lab report but the connection is flawed.

Supplemental Resources

"Collision Lab." PhET. University of Colorado Boulder. Accessed September 1, 2014. https://phet.colorado.edu/en/simulation/collision-lab. [*This simulation could be assigned work to follow up the investigation.*]

ComPADRE. Accessed September 1, 2014. www.compadre.org. [*This website has a free collection of resources and publications for physics educators. Click on "Classical Mechanics" under the "By Topic" section in the lower left of the landing page; then click on linear momentum which provides a list of physics education research documents relating to momentums.*]

"Elastic and Inelastic Collision." Walter Fendt. Accessed September 1, 2014. http://www.walter-fendt.de/ph14e/collision.htm. [*This is an applet to help simulate the results of collisions and can help differentiate between elastic and inelastic collisions.*]

"Learning Cycle on Newton's Third Law using the Momentum Approach." Rutgers Physics and Astronomy Education Research Group. Accessed September 1, 2014. http://paer.rutgers.edu/pt3/experimentindex.php?topicid=3&cycleid=4. [*A series of videos highlighting Newton's Third Law from a momentum approach. Though these videos are set up for Newton's Third Law, they revolve around momentum. You will find the "Happy and Sad Ball" experiment here.*]

O'Brien Pride, Tanya, Stamatis Vokos, and Lillian C. McDermott. "The Challenge of Matching Learning Assessments to Teaching Goals: An Example from the Work–Energy and Impulse–Momentum Theorems." *American Journal of Physics* 66, no. 2 (1998): 147–157.

Rosengrant, David, and Mzoughi, Taha. "Preliminary Study of Impulse Momentum Diagrams." Paper presented at the Physics Education Research Conference, Part of the PER Conference series, Edmonton, Canada: July 23–24, 2008.

Singh, Chandralekha, and David Rosengrant. "Students' Conceptual Knowledge of Energy and Momentum." Paper presented at the Physics Education Research Conference, Part of the PER Conference series, Rochester, New York: July 25–26, 2001.