SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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National Science Education Standard—Physical Science
Motions and Forces

SS&C Inferred Generalization. During the interaction of two systems, A and B, the force exerted by A on B is equal and opposite to the force exerted by B on A. Since the duration of the interaction provides the time interval, and the forces are equal in magnitude, the changes in momentum of the two systems must also be identical, but oppositely directed. The total momentum must therefore remain the same. This is the *law of conservation of momentum*.

Teacher Materials

Learning Sequence Item:

917

Law of Conservation of Momentum

August 1996
Adapted by: Stephen Druger

Conservation of Momentum. At this level students learn to distinguish between forces acting on an object and forces exerted by the object. They need to examine pairs of real objects, identifying the forces on each object and their points of application and direction. They should consider qualitative questions or problems, like the horse-cart "paradox." A qualitative understanding of single-mass emission rockets should be developed. These are best illustrated with "exploding carts" of different masses. (*Physics, A Framework for High School Science Education, p. 14*).

Contents

This micro-unit was adapted by **Stephen Druger** (Northwestern University, Evanston, Ill.)

917
Learning Sequence

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Science as Inquiry	Science and Technology	Science in Personal and Social Perspectives	History and Nature of Science
Who's Pushing? **Activity 1** Pushing and Pulling **Activity 2** Point of Application **Activity 3** Exploding Carts **Activity 4** Push 'em Back! **Activity 5** Donkey and Cart **Assessment 1** Tug-of-War **Assessment 2** Sliding on Ice **Assessment 3** Two Forces, One Object **Assessment 4**			

Suggested Sequence of Events

Event #1

Lab Activity

1. Who's Pushing? (25 minutes)

Optional Activity

2. Pushing and Pulling (25 minutes)

Event #2

Lab Activity

3. Point of Application (40 minutes)

Event #3

Lab Activity

4. Exploding Carts (40 minutes)

Alternative or Additional Activity

5. Push 'em Back! (50 minutes)

Event #4

Readings from Science as Inquiry, Science and Technology, Science in Personal and Social Perspectives, and History and Nature of Science

To be added

Assessment items are at the back of this volume.

Assessment Recommendations

This teacher materials packet contains a few items suggested for classroom assessment. Often, three types of items are included. Some have been tested and reviewed, but not all.

1. Multiple choice questions accompanied by short essays, called justification, that allow teachers to find out if students really understand their selections on the multiple choice.

2. Open-ended questions asking for essay responses.

3. Suggestions for performance tasks, usually including laboratory work, questions to be answered, data to be graphed and processed, and inferences to be made. Some tasks include proposals for student design of such tasks. These may sometimes closely resemble a good laboratory task, since the best types of laboratories are assessing student skills and performance at all times. Special assessment tasks will not be needed if measures such as questions, tabulations, graphs, calculations, etc., are incorporated into regular lab activities.

Teachers are encouraged to make changes in these items to suit their own classroom situations and to develop further items of their own, hopefully finding inspiration in the models we have provided. We hope you may consider adding your best items to our pool. We also will be very pleased to hear of proposed revisions to our items when you think they are needed.

Science as Inquiry

Who's Pushing?

What is the effect on an object when you apply a force?

Overview:

Using two identical mail scales, and then two identical spring balances, students observe that when one object exerts a force on the second, the second exerts a force on the first that is equal in magnitude but opposite in direction.

Materials:

Per lab group:
mail scales, 2
spring balances, 2
string
rubber band (long)

Procedure:

Part 1. Each mail scale should be carefully adjusted to read zero when on its side. Holding the mail scales horizontally, students should press the tops of the scales together by applying various forces on one while holding the other in a fixed position (Figure 1). They then compare the readings on the two scales.

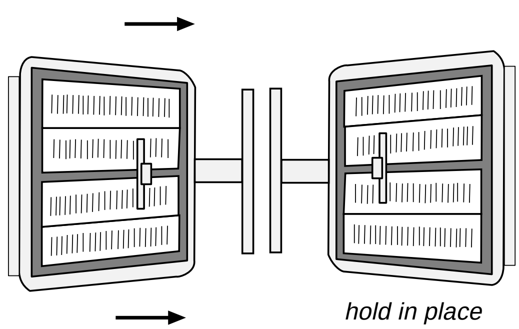
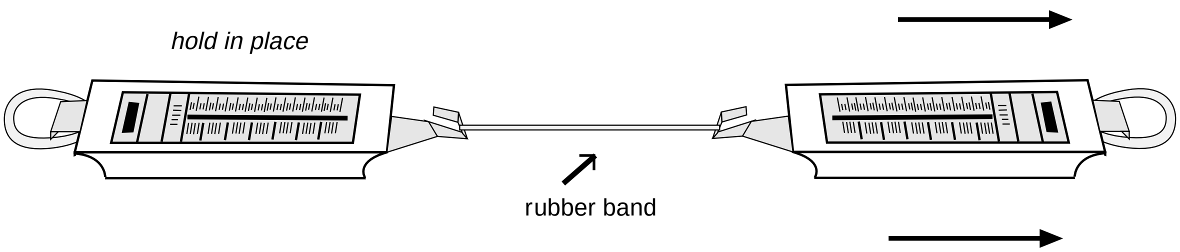


Figure 1

Part 2. Two identical spring balances should be adjusted to read zero when held horizontally, keeping in mind that the weight of the hooks will change their readings when they are held horizontally instead of vertically. The bottom hooks of the balances (i.e., the bottom hook if it were vertical) are then tied to opposite ends of a long string. Students pull on one scale while holding the other in place for various applied forces and record the results. They should observe that the measured force on one balance is equal to the measured force on the other. They then repeat the exercise by connecting the two hooks with a long rubber band instead of a string, observing the same equality of forces (Figure 2).

Figure 2



Ask students to try to make the force readings unequal. They should find that the two forces are always equal.

Background:

According to Newton's third law, when one object exerts a force on another, the second exerts a force of equal strength, but opposite in direction, on the first. This applies no matter which object is moving in what way. *It is crucial to recognize that this applies to the forces acting on two different objects.* It is not correct to add the two equal and opposite forces referred to in Newton's third law as if they both were acting on the same object and then, for example, to use it to calculate the acceleration of the object.

Confusion on that point occurs often, especially because forces acting together on the same object that happen for other reasons to be equal in magnitude but opposite in direction often occur in calculating the acceleration of an object using Newton's second law, F = ma.

Students should see from this activity that the forces that each spring balance exerts on the other through the string are of equal strength but act in opposite directions. As also emphasized throughout this micro-unit, what are being compared are two forces acting on different objects, or equivalently, the force an object exerts and the force exerted back on it in response.

Conceptually, the elastic nature of the rubber band, and the fact that it changes shape markedly in response to the force, might suggest that it is an exception to the equal but opposite forces referred to in Newton's third law. The actual experiment should dispel that idea, although some students might find the result surprising.

Adapted from: none

Optional activity for Event 1

Teacher Sheet

Science as Inquiry

Pushing and Pulling

Does the direction of an applied force matter?

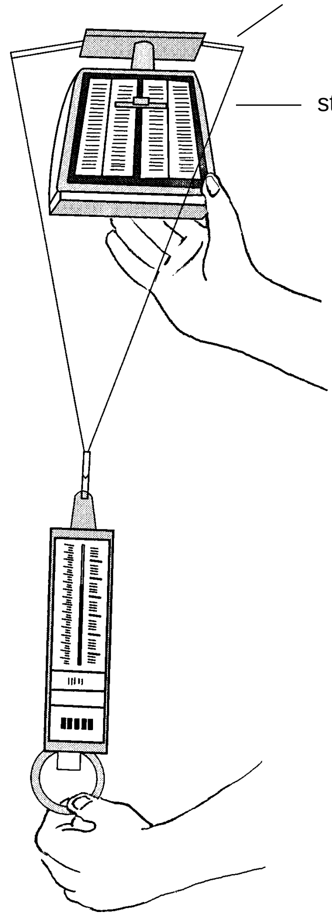
Overview:

In this activity, students observe that even when the force between two objects (with a string acting as an intermediary) can be regarded as pushing one object and pulling the other, the forces between the two are still equal in magnitude and opposite in direction. Students also identify the directions of different forces and the different objects on which each force and its equal but opposite counterpart act.

Materials:

Per lab group:

mail scale
spring balance (preferably calibrated in ounces to measure force in the same units as the mail scale)
string or fishing line
tape
straw (or other rigid plastic tube)



Procedure:

Have students tape a drinking straw or plastic tube with the string (or fishing line) running through it to the top of the mail scale and carefully adjust the mail scale to read zero with the extra weight on it. Similarly, have them adjust the spring balance so it reads zero when held upside down.

Students next couple the two scales as shown so that the straw is pushing down on the mail scale when the string pulls up on the spring scale. They then exert different forces on the spring scale while holding the mail scale in position. For each applied force, they compare the readings of the two scales.

Background:

The distinction between "pushing" and "pulling" to produce a force at a given point depends on the direction of the applied force, and in the present case is probably a matter of interpretation. The real goal of the activity is not that of analyzing such a distinction. Instead, because students are likely to think of these as two distinct ways to apply a force, the intention is to provide a further demonstration of the generality of Newton's third law by showing it applies even when the force on one object could be considered to be pushing it and on the other object to be pulling it.

Students are expected in answering questions about their observations to note that forces of equal strength but in opposite directions are acting *on different objects* at each point where one object exerts a force on the other (in this case through the string as an intermediary).

Adapted from: none

Science as Inquiry

Point of Application

Does it matter where it's pushed?

Overview:

In this activity, students examine qualitatively the effect when equal forces with opposite directions act together, each at a different location on an object.

Materials:

Per lab group:

paper, one large sheet
ruler
string
tape
tabletop, or other flat working surface

Procedure:

Have students tape a large piece of paper to the tabletop, and using a ruler or meter stick, draw a line parallel to the paper's edge. They then tie lengths of string to a ruler 2.5 cm (one inch) in from each end and two strings right at the middle of the ruler (see Figure 1). The knots at the midpoint should rest on opposite sides of the ruler as shown, as should the knots at each end. The strings should be taped securely in position on the ruler, especially near the knots.

Students arrange the ruler perpendicular to the line on the paper. They then pull with equal forces to the right on one string and to the left on the other, noting that this causes the ruler to rotate. Little rotation is produced by pulling simultaneously with equal force to the right and to the left at the midpoint of the ruler.

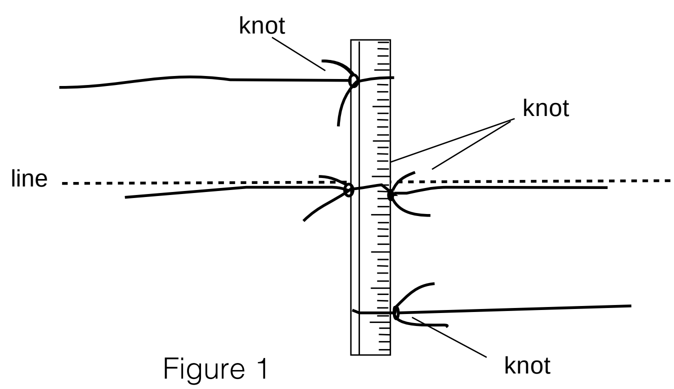
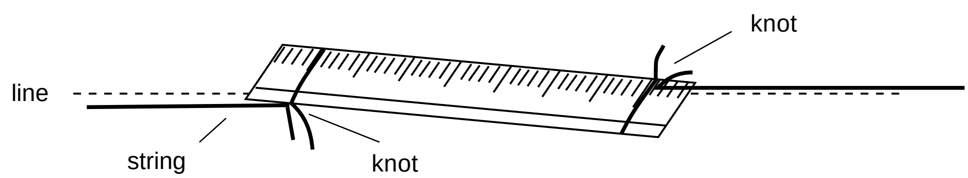


Figure 1

Students next pull the string at one end slightly to the right while simultaneously pulling the string on the other end to the left, so that the ruler readjusts into position with the strings lined up with and pulling along the line on the paper (Figure 2). The ruler lines up not parallel to the line but rather with the line from one point of application of the force to the other point of application coinciding with the direction of the forces. Students are asked to specify conditions under which an object will not be rotated when two equal forces in opposite directions are applied to different points.

Figure 2



Background:

When two forces are applied simultaneously to different points of an object, merely having the forces equal in magnitude but opposite in direction is not sufficient to prevent them from causing the object to rotate. Mechanical equilibrium, in which the forces cause no net acceleration of the object, also requires zero net torque for rotation around any point.

This extra condition applies only when the two forces are applied at different points. In the diagram, with the ruler perpendicular to the forces applied, the torque produced by the force of the uppermost string for rotation about the center of the ruler as a rotation axis would be the distance to the axis of rotation multiplied by the force component perpendicular to the ruler. More generally, for a ruler not necessarily perpendicular to the applied force, the distance to be used in calculating the torque is the perpendicular distance from the rotation axis to a line coinciding with the force vector at its point of application.

The distance just described is zero if the force is applied directly at the point about which possible rotation is considered. It is also zero if the force direction lies right along the line from the point of application of the force to the point about which rotation is considered. This situation applied, for example, when the ruler was pulled in opposite directions at its center by two strings perpendicular to the ruler. It also applied when the ruler was pulled by strings at both ends and it readjusted its position, at which point the line from one knot where the force is applied to the other had the same direction as the two forces of equal magnitude but opposite direction applied at the locations of the knots.

Students are not expected to deal with torque at this level. They are expected instead to recognize that the force applied to different points of an object can produce different responses, so that in the most general case the place where the force is applied has to be considered. In trying to formulate a rule that determines when they would expect the forces not to make the block rotate, it is intended merely that they describe in their own words such possibilities as having the forces directed oppositely in a way that lies along the line connecting the two points where the forces act, or having the two oppositely directed forces of equal strength applied at the same point.

Adapted from: none

Science as Inquiry

Exploding Carts

How are rockets propelled?

Overview:

Students observe the consequences of Newton's third law in the case where two carts exerting forces on each other are free to move.

Materials:

Per lab group:

laboratory carts (or equivalent), 2 identical
spring
mass, 1 kg
string
scissors (sharp)

Procedure:

Have students weigh the carts to check that they have the same mass. They should then compress the spring between the two carts and tie the two carts together with string. Snipping the string with a sharp pair of scissors then results in both carts responding by moving. Some carts are constructed with a built-in spring mechanism that accomplishes the same effect without the need to tie the carts together or to use a separate spring. When carts are identical, they are seen to be set into motion equally.

This exercise is then tried with an extra 1 kg of mass as cargo on one cart, with the result that the less massive cart moves the most when the string is cut.

Background:

Newton's third law implies that each cart, acting through the spring, exerts an equal but opposite force on the other. When carts of identical mass are released by cutting the string, they are experiencing equal forces in opposite directions, they have equal mass, and, as implied by Newton's second law (*force* = *mass* × *acceleration*), they are therefore accelerated the same way but in opposite directions. This assumes that such effects as frictional forces within the wheel bearings are either negligible or else the same for both carts.

For carts of unequal mass, doubling the mass for the same average force means half the average acceleration over the time the force acts, so the less massive cart experiences the greater acceleration.

In general then, pushing a mass back from the cart whether the mass is free to move or not implies that the cart is pushed forward by the reaction force. This is the principle of a rocket, which ejects burned fuel at high speed from the back, propelling the rocket forward. The equivalent explanation for rocket propulsion in terms of momentum conservation, which is a consequence of Newton's third law, may be found in the teacher's sheet for the water rocket activity in micro-unit 1012.

The popular misconception that a rocket is propelled by expelled gas pushing against the air behind it can be readily dispelled by considering that rocket propulsion also works in the near vacuum of space, where there is nothing behind the rocket for the expelled exhaust gases to push against.

Adapted from: none

alternative/additional activity for Event 3

Teacher Sheet

Science as Inquiry

Push 'em Back!

How is a rocket propelled?

Overview:

A rubber ball is allowed to roll off an inclined plane constructed from cardboard and supported so that the ball is free to roll. Students observe that not only does the cardboard exert a force on the ball that produces a horizontal component of motion for the ball in one direction, but the ball in return exerts a force that accelerates the cardboard in the opposite direction. The mass dependence of the acceleration produced is examined qualitatively.

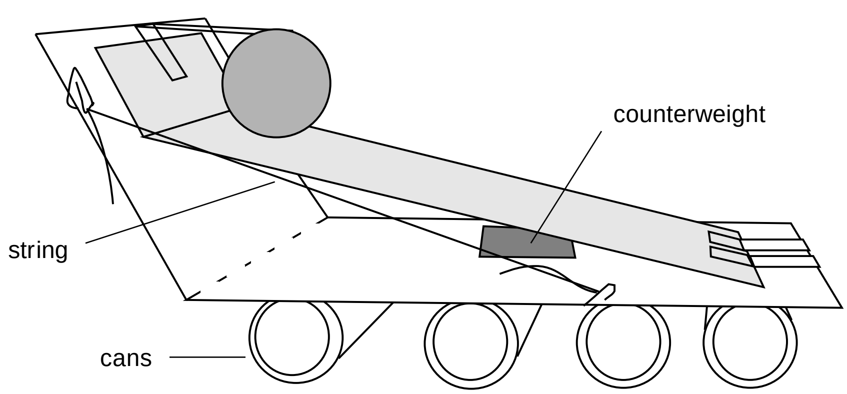
Materials:

Per lab group:

corrugated cardboard
aluminum beverage cans (empty, dry, and undented), 3–4
rubber ball
cutting tool for cardboard
string
tape
paper clips or stapler
masses for counterweights

Procedure:

Using cardboard, students construct the apparatus shown below. Alternatively, the apparatus can be constructed in advance of the class for student use. Have students cut the cardboard as shown. They should use a cutting edge and ruler to etch a line partly into the cardboard so that a flap can be folded up and use large paper clips or staples together with string to secure the flap at about a 45^{o} angle with the horizontal.



Tape holds the rubber ball in position at the top edge of the flap. Empty aluminum soft drink cans should be placed under the cardboard, so that the cardboard can roll on them. A counterweight near the center of the horizontal section of the cardboard keeps it from tipping over.

Students then carefully cut the tape with a pair of sharp scissors to allow the ball to roll down the incline. They observe that as the ball rolls, the cardboard is pushed in the opposite direction. They should repeat this exercise with about 0.5 kg more mass as the counterweight. Slower motion of the cardboard is seen to result with the greater mass placed on it.

Background:

This activity serves as an alternative to Activity 4, since it demonstrates essentially the same idea. The student questions are therefore similar to those in Activity 4.

When the ball, initially held in position by the tape, becomes free to roll, it can acquire a downward component of force only by also being subjected to a horizontal component of force by the cardboard. According to Newton's third law, the horizontal component of the force that the cardboard exerts on the ball to produce the corresponding horizontal acceleration implies a horizontal component of reaction force on the cardboard apparatus. Thus the cardboard and the counterweight on it are accelerated in the opposite direction to the horizontal part of the motion of the ball. If the mass of the counterweight is increased, the greater inertia of the cardboard platform and the counterweight means that they experience less acceleration even though the ball has the same mass and rolls down from the same height as before.

In general then, ejecting a mass backward tends to propel the platform forward, as a result of the reaction force that the platform experiences by pushing the expelled object backwards. This illustrates the origin of a rocket's thrust. A rocket ejects exhaust gas at high speed in a backward direction, and the forces within the rocket that give the exhaust gas its high velocity imply a reaction force in the opposite direction on the rocket, propelling the rocket forward. The equivalent explanation for rocket propulsion directly in terms of momentum conservation, which is a consequence of Newton's third law, may be found in the teacher's sheet for the water rocket activity in micro-unit 1012.

The popular misconception that a rocket is propelled by expelled gas pushing against the air behind it can be readily dispelled by considering that rocket propulsion also works in the near vacuum of space, where there is nothing behind the rocket for the exhaust gases to push against.

Adapted from: none

Donkey and Cart

Item:

Here is a famous puzzle to explain. A donkey pulls a cart and exerts a force to the right. The cart therefore exerts the same amount of force on the donkey to the left. Shouldn't that mean that it is impossible for the donkey to move the cart? Explain why the argument is correct or not correct.

Answer:

The argument is incorrect. The two forces involved are just as strong and in opposite directions, but they act on different objects. One acts on the donkey, the other on the cart. So we should not add them together to decide how the donkey moves, or how the cart moves.

Tug-of-War

Item:

A physics class is planning a picnic that will include a tug-of-war in which all participants are on laboratory carts. Each team will pull the rope in opposite directions on level paved ground. The team that pulls the other team one meter past a line midway between them while staying on their own side of the line wins.

Team one has a secret plan: all will suddenly pull on the rope together as hard as possible before the other team can do anything other than hold the rope.

Suppose each team member has his or her identical twin on the other team. (This is a very unusual physics class.) What would be the outcome after team one uses its secret plan, and why?

Answer:

The outcome would probably be a tie. When the first team exerts a force on the second team, the second team, merely by holding the rope, exerts an equal but opposite force on the first. By pulling suddenly on the rope, team one would set both teams equally in motion toward the line, so both teams would either crash into each other at the line or, if they manage to miss, would roll over the line.

Sliding on Ice

Item:

Suppose a 100-lb student is trapped on a frictionless layer of ice on a pond and he pushes a 40-lb rock so that it slides away on the ice. The result would be:

A. The student would stay in position on the ice, and the rock would go sliding over to the shore.
B. Both would be set into motion, but the rock would move faster.
C. The student and the rock would move equally in opposite directions.
D. Both would be set into motion, but the student would move faster.

Answer:

B.

Justification:

We have seen that when one object pushes another, each exerts an equally strong force on the other in opposite directions, and the heavier, more massive object responds less to the force than the lighter, less massive object.

Two Forces, One Object

Item:

Two forces act at the same time on the same object. Which of the following is true?

A. If the forces are equal in strength but opposite in direction, they will not cause the object to start moving.
B. If the forces are applied to different points on the object, the object will rotate.
C. The two forces are equal in size but opposite in direction.
D. None of the previous statements is entirely correct without additional information.

Answer:

D.

Justification:

In the activities it was seen that equal forces in opposite directions applied at different points could make the object rotate, but we saw that under some conditions they did not produce rotation. So "A" and "B" are both incorrect. "C" is incorrect because it is the forces exerted by the objects *on each other* that are equal in size but opposite in direction; two forces acting *on the same* object need not be equal nor in opposite directions.

Consumables

Item	Quantity per lab group	Activity
aluminum beverage cans (empty, dry, and undented)	3–4	5*
corrugated cardboard	—	5*
paper	1 large sheet	3
string	—	1, 3, 4, 5*
string or fishing line	—	2*
rubber band (long)	1	1
straw (or other rigid plastic tube)	1	2*
tape	—	*2, 3, 5*

Nonconsumables

Item	Quantity per lab group	Activity
cutting tool (for cardboard)	1	5*
laboratory carts	2	4
mail scale	1	2*
mail scales	2	1
masses (for counterweights)	—	5*
paper clips or stapler	—	5*
rubber ball	1	5*
ruler	1	3
scissors (sharp)	1	4
spring	1	4
spring balance	1	2*
spring balances	2	1
tabletop or other flat working surface	—	3

*Indicates alternative/additional activity

Key to activities:
1. Who's Pushing?
2. Pushing and Pulling
3. Point of Application
4. Exploding Carts
5. Push 'em Back

Activity Sources

none