23. Work and Mechanical Advantage

Simply Forceful - The Sequel

Objectives

In this activity, students further investigate the way simple machines make work easier by combining two simple machines to make a compound machine.

Students will investigate force and simple machines while they:

- Recognize that a force is a push or a pull
- Recall that simple machines change the amount of input force, the direction in which the force is applied, or both
- Recognize that a compound machine is made of two or more simple machines
- Reinforce their understanding of the different arrangements of pulleys
- Recognize that force is measured in newtons (N), mass is measured in kilograms (kg), and length is measured in meters (m)
- Recognize that moving a force through a distance is known as *work*
- Compute mechanical advantage
- Design and conduct a scientific investigation

Procedural Overview

Students gain experience conducting the following procedures:

- Setting up equipment and work area to measure the force required to lift a mass with varying configurations of fixed and moveable pulleys, in combination with an inclined plane (a ramp)
- Designing and building structures to test how pulley systems change the direction of applied force, the amount of applied force, or both
- Assembling fixed and moveable pulley systems and trying these combinations as they apply a force to pull a cart up an inclined plane

Time Requirement

- Introductory discussion and lab activity, Part 1 – Making predictions — 25 minutes
- Lab activity, Part 2 – Using a ramp — 25 minutes
- Lab activity, Part 3 – Using pulleys and a ramp — 30 minutes
- Analysis — 25 minutes

Materials and Equipment

For teacher demonstration:

- ☐ Tinker Toys™ or other building materials
- ☐ PAScar or other cart or toy car
- ☐ Pulleys
- ☐ String

For each student or group:

- ☐ Data collection system
- ☐ Force sensor with hook
- ☐ Meter stick or ruler
- ☐ Balance
- ☐ Tinker Toys™ or other building materials
- ☐ PAScar or other cart or toy car
- ☐ Pulleys
- ☐ String

Concepts Students Should Already Know

Students should be familiar with the following concepts:

- The six simple machines, including the differences between fixed and movable pulley systems.
- How to measure mass in SI units of kilograms and grams, and length in meters.
- How to compute the ratio of two lengths (the length of an inclined plane and the height to which the plane rises).
- How to read and interpret a coordinate graph.
- The basics of using the data collection system.

Related Labs in This Guide

Prerequisites:

- Simply Forceful

Labs conceptually related to this one include:

- May the Force Be With You

Using Your Data Collection System

Students use the following technical procedures in this activity. The instructions for them are in the appendix that corresponds to your PASCO data collection system (identified by the number following the symbol: "�"). Please make copies of these instructions available for your students.

- Starting a new experiment on the data collection system �(1.2)
- Connecting a sensor to the data collection system �(2.1)
- Recording a run of data �(6.2)
- Displaying data in a graph �(7.1.1)
- Adjusting the scale of a graph �(7.1.2)
- Displaying multiple data runs on a graph�(7.1.3)
- Saving your experiment �(11.1)

Background

The six simple machines, which are the inclined plane, the wedge, the lever, the wheel and axle, the pulley, and the screw, can be used in combinations to produce compound machines. As with simple machines, compound machines are designed to make work easier. Work is done any time a force, such as a push or a pull, is exerted over a distance.

Work = Force x Distance
or
W = F x D

A key idea of work is the fact that the object to which a force is being applied must move *in the direction of the force*. When moving an object up an inclined plane, or "ramp," for example, the force must be applied in a direction *parallel to the ramp* in order for work to be done.

It is important to remember that no machines can change the amount of work that is done; they can change only the amount of force, the direction of the force, or the distance over which the force is applied. The m*echanical advantage* of the machine is the number of times the input force is multiplied. In a perfect world, the amount of input force would be exactly equal to the amount of output force for any machine, but even the most efficiently designed machines waste some of the input force, generally in the form of friction, which exists in all machines.

Friction is a force that opposes motion, which you may be familiar with from trying to move heavy items. Most people would rather use a hand-truck to move their filing cabinet rather than push it across the carpeted floor. Calculated values for mechanical advantage therefore never perfectly agree with experimental results.

Using a fixed pulley changes the direction of the input force, but does not multiply it; a fixed pulley has a mechanical advantage of one (it multiplies the input force by 1) Using a movable pulley gives a mechanical advantage of 2 (it doubles the input force). The mechanical advantage of an inclined plane or ramp is given by the ratio of the ramp's length to its height. The longer the ramp, the greater the mechanical advantage it has.

Using a combination of two simple machines whose mechanical advantages are both greater than 1 results in a summing effect of the applied input force. In other words, using both a ramp *and* a movable pulley multiplies the input force more than using either one of these machines by itself.

Pre-Lab Discussion and Activity

Engage students in the following discussion or activity:

Ask students to review with their lab group members the six simple machines as discussed in the Simply Forceful activity, as well as the different arrangements of pulleys. Have students list the types of pulley arrangements and classify them by type, by direction of input force, and by change in amount of force necessary. Introduce the term "mechanical advantage" and refer to the mechanical advantage as the number that tells us by how much the input force is multiplied.

Ask students, "If a pulley has a mechanical advantage of 2, what does it do to the input force?" They should recognize that the input force is doubled, or multiplied by 2.

Show students an example of the type of inclined plane, or ramp, they will be using for this activity. Ask them how they think the ramp might affect the amount of force necessary to move an object. List their suggestions on the board. Call students' attention to the height of the ramp, and help them to see that the ramp can raise an object to that height.

Once students have considered the suggestions they listed on the board, direct their attention toward Thinking About the Question. Remind students that in this activity they are building on prior knowledge and experiences and that reviewing what they already know is a good way to prepare for extending their learning.

Preparation and Tips

These are the materials and equipment to set up prior to the lab:

- Students will need time to design and construct their pulley support "towers" and devise a means of connecting them to their ramps. Tinker Toys™ are ideal for these structures, as they have all the necessary parts, including the pulley wheels and string. However, if Tinker Toys™ are not available, wire coat hangers can be straightened and reshaped to support a small commercially available pulley.

- Small pulleys that are relatively inexpensive are available at all hardware stores.

- Carts and tracks are the ideal equipment for this activity. Tracks may be inclined by placing books under one end. However, if carts and tracks are not available, other materials will readily suffice. Ramps may be constructed of almost anything available including shelving from the bookcase, meter sticks taped together, portable whiteboards or chalkboards, or items students have brought from home.

- Build a prototype pulley and ramp structure ahead of time for students to see. Tell them that they are free to design their own "style" or to use your design. Be sure to check each group's structure for effectiveness.

- If you do not have access to carts, supply toy vehicles or have students bring toy vehicles from home. The activity is easier if the vehicles are more massive. A larger toy car will give better results than a smaller toy car. If students bring in toys, provide tape or other means of labeling the toys with students' names so they can be returned. If toy cars need modifications so that the force sensor hooks can be attached, provide tape, string, wire, et cetera for students to make these modifications.

- Remind students that not all the ramps need to be the same height or length. It is the *ratio* of the length to the height that determines the mechanical advantage. Make sure students are confident about their length and height measurements; suggest that lab group members check one another's measurements for accuracy and precision. If you know that students will need help computing the mechanical advantage of their ramps, lead them through one or more examples before they begin the activity.
- Install the hooks in each force sensor, if necessary.
- The clean-up time for this activity needs to be taken into consideration as you plan; you can streamline the clean-up process if you have clearly communicated the procedures to students ahead of time.

Safety

Add this important safety precaution to your normal laboratory procedures:

- Do not apply a pushing or pulling force greater than 50 newtons to the force sensors (doing so will damage the sensor).

Driving Question

What happens to the amount of force needed to move an object when simple machines are used in combination?

Thinking about the Question

In the previous activity, Simply Forceful, you saw that using a simple machine such as a pulley can change the amount of input force necessary to move an object. You also discovered that a pulley can change the direction in which the input force is applied without changing the amount of input force.

As you know, there are only six simple machines, but they serve as the building blocks for almost all other machines. People invented these simple machines to help make work easier by changing either the direction or amount of input force necessary, or both. In physical science, work means using an input force to move an object.

In this activity, you will be working with two different simple machines connected together to determine how they change the direction or the amount of force necessary to move an object. You will also investigate what happens to the amount of necessary force when you change the distance through which the force is applied.

Discuss with your lab group members the way that different arrangements of pulleys change the direction or the amount of force, or both, required to lift an object off the table. Discuss in your group how ramps work, what type of simple machine they are, and how you might construct one using the materials provided in your class.

Sequencing Challenge

Note: This is an optional ancillary activity.

The steps below are part of the Procedure for this lab activity. They are not in the right order. Determine the proper order and write numbers in the circles that put the steps in the correct sequence.

2/3	1	5	4	2/3
Predict how much force will be necessary to lift a cart off the table.	Make sure each lab group member is aware of safety rules and procedures for this lab.	Compare the data for fixed and moveable pulleys.	Record force data as you pull the cart up the ramp.	Construct a ramp out of available materials.

Investigating the Question

Note: When students see the symbol "�" with a superscripted number following a step, they should refer to the numbered Tech Tips listed in the Tech Tips appendix that corresponds to your PASCO data collection system. There they will find detailed technical instructions for performing that step. Please make copies of these instructions available for your students.

Part 1 – Making predictions

1. ☐ Write your predictions for the following:

   a. What amount of force will be necessary to lift a cart off the table?

   b. How will the amount of necessary force change if the cart is pulled up a ramp to the same height?

   c. What effect will there be on the amount of force necessary to pull the cart up the ramp if one or more fixed or movable pulleys are used?

   Answers will vary. One student group answered as follows: We predict it will take at least 5 N of force to lift our truck off the table. When we pull the truck up the ramp, it will probably take less force. If we use a fixed pulley, we predict only the direction of the force will change. If we use a movable pulley, it will probably take even less force.

2. ☐ In the space below, sketch a force versus time graph that reflects your predictions

Part 2a – Lifting straight up against gravity

3. ☐ Start a new experiment on the data collection system. �[1.2]

4. ☐ Connect a force sensor to the data collection system. �(2.1)

5. ☐ Display Force on the y-axis of a graph with Time on the x-axis. �(7.1.1)

6. ☐ Hold the force sensor with its hook down, and press the "zero" button.

7. ☐ Gently attach the force sensor's hook to your cart, using a piece of string.

8. ☐ Begin data recording. �(6.2)

9. ☐ Holding the force sensor steady, lift the cart until it is off the table and hold it in place until the force data stabilizes.

10. ☐ Stop data recording. �(6.2)

11. ☐ Observe your graph of force versus time. What do you notice about your data?

Once the force data stabilized, our cart pulled with a constant force of 7.2 N. While it was being suspended, the force on it was constant.

Part 2b – Using a ramp

12. ☐ Using materials provided, construct a ramp for your cart to travel on. Test the cart on the ramp to be sure it rolls well. How might a poorly-rolling cart affect your force data?

If it does not roll well, then it would take more force to pull it than it actually would need due to the friction which opposes the cart's motion. Our data and results would reflect this friction.

13. ☐ Measure the length and height of the ramp. Record these measurements below:

Ramp Length: 0.86 M

Ramp Height: 0.15 M

14. ☐ Place a force sensor flat on the ramp and press the "zero" button. This tells the sensor that it is measuring force parallel to the ramp. When is it important to zero the force sensor in experiments?

You have to zero the sensor anytime you change the orientation of the sensor, before recording new data.

15. ☐ Place the cart at the lower end of the ramp, ready to roll.

16. ☐ Gently attach the cart to the force sensor's hook, using a piece of string.

17. ☐ Begin data recording. �(6.2)

18. ☐ Pull on the force sensor slowly and steadily to roll the cart up the ramp, continuing as far up the ramp as you can pull it.

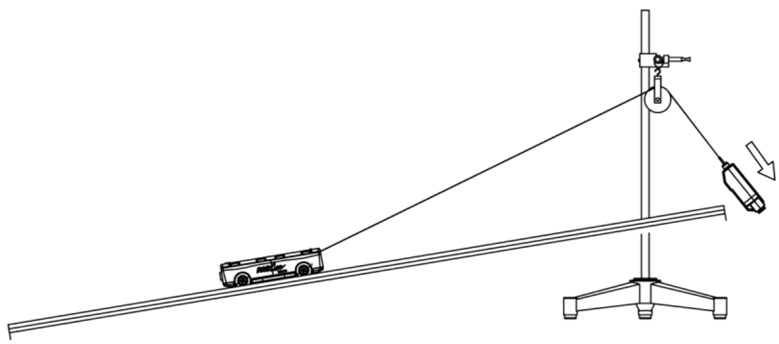
19. ☐ Stop data recording. �(6.2)

20. ☐ Observe your graph of force data. You may need to rescale your graph to see all of your data. �(7.1.2) Note below any patterns or observations you see.

Student answers will vary. One student group answered as follows: We observed that it took less force to pull the truck up the ramp than it did just to lift it straight up off the table.

Part 3 – Using pulleys and a ramp

21. ☐ Using materials as you did in the Simple Machines and Force activity, devise a fixed pulley system. You will pull the cart up the ramp by pulling down on the force sensor.



22. ☐ Test your design to make sure it works as designed. Make adjustments if necessary.

23. ☐ Press the “zero” button while the force sensor’s hook is pointing down.

24. ☐ Begin data recording. �(6.2)

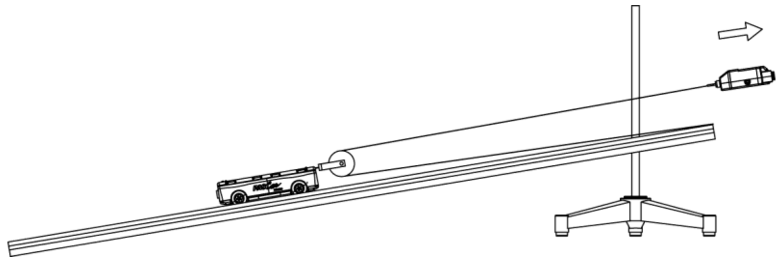
25. ☐ Pull down on the force sensor slowly and steadily, to make the cart travel up the ramp.

26. ☐ Stop data recording. �(6.2)

27. ☐ Observe your graph of force data. �(7.1.3) You may need to rescale your graph to see all of your data. �(7.1.2) Note below any patterns or observations you see:

The force for the fixed pulley was almost the same as for just lifting up the truck,even though we pulled it up the ramp with the pulley.

28. ☐ Again, using materials as you did in the Simple Machines and Force activity, devise a movable pulley system so that the pulley travels along with the cart. You will again pull the cart up the ramp by pulling on the force sensor in a direction parallel to the ramp.



29. ☐ Test your design to make sure it works as designed. Make adjustments if necessary.

30. ☐ Place the force sensor flat on the ramp and press the “zero” button.

31. ☐ Gently attach the string to the force sensor’s hook.

32. ☐ Begin data recording. �(6.2)

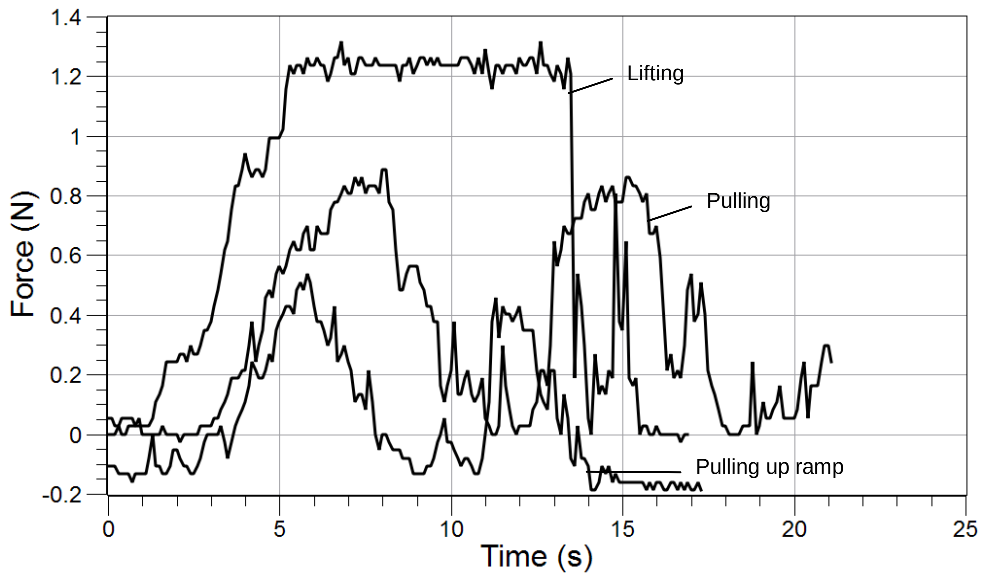
33. ☐ Pull on the force sensor slowly and steadily to roll the cart up the ramp.

34. ☐ Stop data recording. �(6.2)

35. ☐ Observe your graph of force data �(7.1.3) You may need to rescale your graph to see all of your data. �(7.1.2) Note below any patterns or observations you see:

Student answers may vary. One student group answered as follows: The force for the fixed pulley was 7.2 N, and for the movable pulley was 0.9 N.

Sample Data



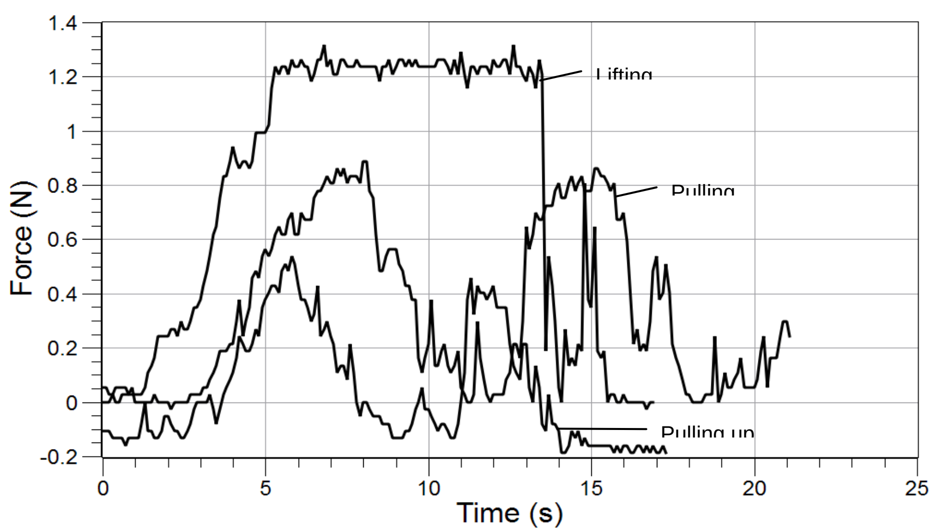
Answering the Question

Analysis

1. How did your predictions from Part 1 compare to the results in Part 2?

   Our prediction agreed with our results since it did take less force when we used the ramp and moveable pulley than when we used the fixed pulley or when we just lifted the truck straight up.

2. Sketch the graphs of force versus time from your experimental trials.



3. The ramp you constructed is an example of an inclined plane which changes the amount of input force you need to apply to lift the cart. The ramp's *mechanical advantage* tells the number of times it increases the force applied to it. The mechanical advantage of a ramp can be calculated from the following equation:

Mechanical Advantage = Length of Incline / Height of Incline

4. Using your measurements from Part 2, calculate the mechanical advantage of your ramp:

Answers will vary. One student group answered as follows:

$$\text{Mechanical advantage} = \frac{\text{length of incline}}{\text{height of incline}} = \frac{0.86\text{m}}{0.15\text{m}} = 5.73 \text{ times}$$

5. About how many times does your ramp multiply your input force on the cart compared to lifting the cart straight up to the same height?

Answers will vary. One student group answered as follows: Our ramp multiplied our force by 5.73 times (almost 6 times).

6. When a force moves an object over a distance, we say that work is done on the object. When you pulled your cart up the ramp, how was work being done on the cart?

Answers will vary. One student group answered as follows: The object we moved was our truck, which we moved by pulling it. The force was the pull. The distance was the ramp it went up.

7. How did the fixed pulley change the amount or direction of input force that was applied to the cart?

The fixed pulley did not take less force, but it did change the direction so we could pull down to move the truck up the ramp.

8. How did the movable pulley change the amount or direction of input force that was applied to the cart?

Answers will vary. One student group answered as follows: With the moveable pulley attached to our truck, it took the least amount of force to lift it up the ramp. It actually took less than 1N of force to pull the truck, compared to 7.5 N to lift it straight off the table.

9. The ramp and pulley system you constructed is an example of a *compound machine* – two or more simple machines working together. Although each simple or compound machine makes work easier, there is always a trade-off of some sort between how much force must be applied and the distance over which that force is applied. Look at your force data for the different combinations of machines as well as for lifting the cart straight up. What combination of simple machines resulted in the least amount of force necessary to move the cart off the table? Do your experimental results tend to agree or disagree with your calculations from questions 3 and 4? Explain your reasoning.

Answers will vary. One student group answered as follows: Our best combination of machines for moving our truck up with the least force was a ramp and a moving pulley attached to our truck. We calculated the mechanical advantage to be 5.73 for our ramp, meaning it multiplied our input pulling force by that amount. But in order to multiply our force by that amount, we had to pull the truck for a much longer distance (the length of the ramp) than we would have had to pull it when lifting it straight up. So, we traded distance for force.

Key Term Challenge

Fill in the blanks from the randomly ordered words below:

newtons	compound machine	work	force
pulley	mechanical advantage	input force	inclined
ramp			

1. The force applied to a machine is called the __input force_.

2. A/an _____compound machine______ is one made from two or more simple machines.

3. A force acting over a distance to move an object is known in physical science as _______work.

4. The SI unit used to measure the force is _____newtons______ .

5. The _____mechanical advantage______ tells us how many times a machine multiplies the applied force. It is a ratio of the input force to the output force.

6. Any push or pull exerted on an object, whether or not it causes the object to move, is known as a/an _____force______ .

7. A simple machine known as a/an _____pulley______ is made from a rope, a string, or a belt wrapped around a wheel.

8. A simple machine with a flat, sloped surface that makes it easier to lift a heavy load by using less force over a greater distance is known as a/an _____inclined plane______ .

9. A pulley that has a mechanical advantage of 3 multiplies the _____input force______ by three times that amount.

Further Investigations

Design an investigation to see how one of the three classes of levers changes the input force.

Design an investigation to test each of the three classes of levers to find out how they change input force.

Design and test a ramp to demonstrate how the calculated (ideal) mechanical advantage differs from the experimental (actual) mechanical advantage. How close can you get the experimental mechanical advantage to match the calculated mechanical advantage?

Rubric

For scoring students' accomplishments and performance in the different sections of this laboratory activity, refer to the Activity Rubric in the Introduction.