SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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Student Materials

Learning Sequence Item:

1021

Air Resistance and Friction

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Adapted by: Bill G. Aldridge

Contents

This micro-unit was adapted by **Bill G. Aldridge** (SciEdSol, Henderson, Nev.)

Science as Inquiry

Air Resistance and Area

Does the air resist?

Overview:

Does the air resist? The question really refers to what is commonly referred to as air resistance. What is air resistance, and how does it resist motion?

This question is interesting in several ways. First, it is one thing to find out how air resists motion, but it is quite another thing to explain air resistance—that is to develop a theory to explain what happens. Second, is air resistance at all like resistance that fluids like water or oil have to the motion of objects immersed in them? Does air, itself behave like some kind of fluid? Is air resistance related to a fighter jet breaking the sound barrier?

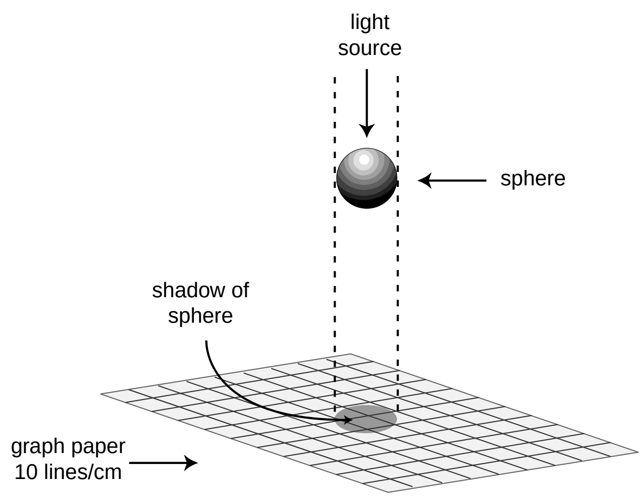
In this first activity we shall just consider air resistance. What does air resistance depend upon? Your own intuitive ideas, stemming from your experience gives you a qualitative answer to this question. You know that a tissue drifts slowly to the ground when dropped, but if you wad it up into a tight ball and drop it, it falls very quickly to the ground. What is different about these two situations?

It is the cross-sectional area of the object being dropped that the air can resist. Your own intuition suggests that the air resistance should be proportional to that cross-sectional area. This intuitive suggestion can be made into a hypothesis that you can test through an experiment. You also know that the faster the wind blows, the harder it is to walk against the wind. Thus, you know from your own personal experience that air resistance is also connected to wind speed.

Your first task is to determine, through an experiment, the relationship between cross-sectional area and air resistance. To do so, you need to hold the air speed constant.

Procedure:

Use a hair dryer (if it has a no-heat setting) or fan, and objects that have a certain cross-sectional area. The simplest objects to use are small smooth spheres, like a marble, a steel sphere, a Ping-Pong ball, or various size rubber balls. You will need four balls of different cross-sectional area. Temperature may be a variable, so keep the temperature constant, and preferably at room temperature, Also, keep the air speed constant by using the same setting on the fan or hair dryer, and make



Side view. Count squares to get cross-section. Paper must be at right angles to light rays (flat, directly under light source).

Fig. 1

sure that the object being studied is at the same distance from the hair dryer (or fan).

Use a piece of graph paper and trace the boundaries of the shadow cast by the sphere when sunlight falls on it (Fig. 1). This shadow projection is the cross-section. Count the squares covered by the shadow to get the cross-section in square cm. Convert the number of squares to square meters (divide square cm by 10,000).

Connect the sphere to two threads. Glue each thread to the same point on the sphere. Hang the sphere (Fig. 2), and turn the hair dryer on, centering the air current on the sphere (Fig. 3). Measure the distance from the center of the sphere to a point midway between the suspension points for the two threads. This gives you the length of this pendulum device.

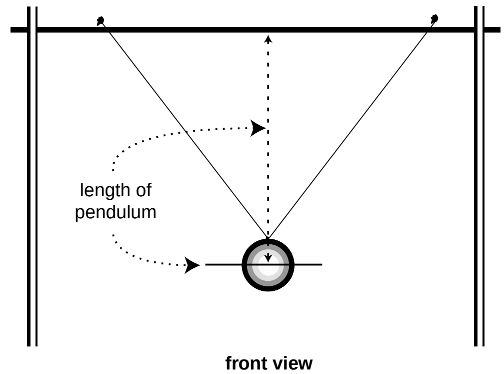


Fig. 2

For small displacements of the sphere in the air stream, the force (in newtons) of the air—*air resistance*—is equal to the weight of the sphere in newtons (mass in kg and g, which is 9.8 m/s^2) times the displacement in meters, and divided by the pendulum length (also in meters).

By measuring the cross-section and mass of each sphere, and its displacement in the same air stream, you can find the air resistance. Find the air resistance for at least four spheres; then graph air resistance on the vertical axis, and the cross-section on the horizontal axis, on a sheet of a graph paper. What is the relationship between air resistance and cross-section?

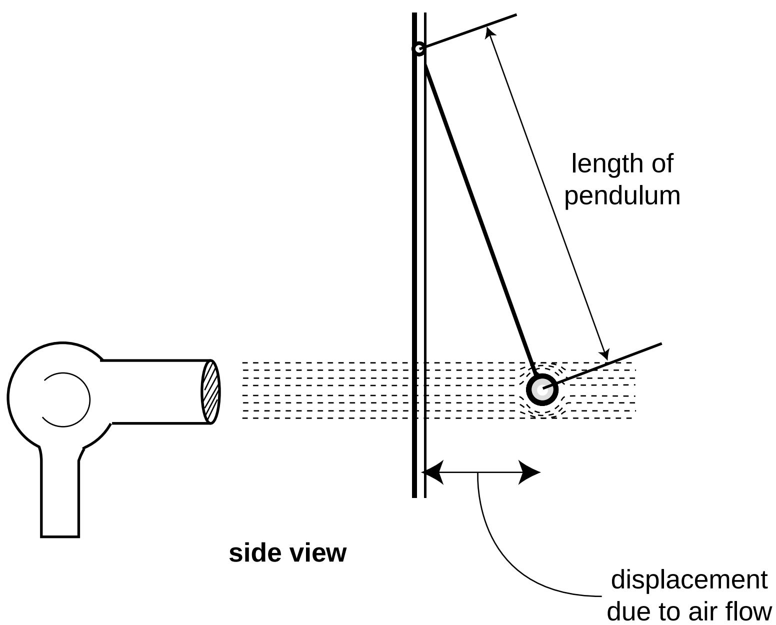


Fig. 3

Your teacher has given you a sphere. Measure its mass and cross-section and predict its air resistance in the air stream you have produced. Test your prediction by measuring that air resistance. How good was your prediction?

Questions:

1. The air resistance on a balloon is 10 newtons. If you blow the balloon up more, so that its cross-section is three times greater, how much air resistance does it have? If you triple the diameter of a sphere how much does it change the air resistance?

2. From your experiment you have learned a relationship between cross-section and air resistance. How would you write that relationship using an equation? What is the relationship between the air resistance and the diameter of a sphere? What is the relationship between the air resistance of some arbitrarily-shaped object and any linear measure identified on that object?

3. Why couldn't you have just measured the time of fall of objects of different cross-section, but of the same mass, to get the relationship between cross-section and air resistance? After all, when a falling object, like a Ping Pong ball or a parachute falls, it quickly reaches its terminal velocity. And at terminal velocity, the air resistance is equal to the objects weight in newtons. So, air resistance can be measured. You could keep mass the same, having a box attached to a parachute to hold weights, to adjust mass to be always the same. Then you could use different-sized parachutes to get different cross-sections. What is wrong with this experiment in terms of controlling variables?

Science as Inquiry

Air Resistance and Wind Velocity

How does air resistance depend upon air speed?

Overview:

You know from experience that the faster the wind blows, the harder it is to walk against the wind. Thus, you know that air resistance is depends upon wind speed. Now, how can we measure wind velocity and air resistance in an experiment where we hold cross-section constant? When you drop a light object with large cross-section like a feather, it almost immediately stops accelerating and falls at a constant velocity. If the velocity is constant, then the acceleration is zero. You could prove that such an object falls at a constant velocity by taking strobe photos of its motion. The images would be equally spaced, indicating that the object fell equal distances in equal times for each interval.

As you have previously learned, the constant velocity that something reaches when it falls is called its *terminal velocity.* Since there is a constant velocity, and zero acceleration, the net force must be zero. There are two forces acting on the falling object: gravity, in the form of the object's weight, and air resistance. For the velocity to be constant and the acceleration to be zero, these two forces must be equal and opposite in direction. Gravity is directed downward and air resistance upward. Thus, the weight, mg, of the object must be equal to the air resistance. This makes it easy to measure the air resistance.

How can we investigate the relationship between air speed and the air resistance holding other variables constant? If the velocity of the object relative to still air can be determined, then the result is the same as if the object is at rest and the air is moving against the object at the same speed. Thus, if we drop an object that has a certain cross-section—which does not change—and measure how long it takes for it to fall to the ground, then we can find its velocity by taking the distance divided by the time of fall. The air resistance is just its weight, mg. By using objects of different mass—but the same cross-section—we have situations where the air resistance is different, and this gives us different values for the wind speed.

In this way you can investigate the relationship between wind speed and air resistance, while holding cross-section constant.

Procedure:

Design a parachute which is connected to a small container in which you place masses. (This way you can keep the cross-section constant—that of the parachute—while varying the mass of the falling object.) You may need to try different designs to keep the cross-section constant. Make the parachute large enough so that it falls rather slowly. Drop the parachute from the same height each time, and measure how long it takes for the parachute to hit the ground. This might best be done by climbing up on a ladder (while someone holds it steady) and then dropping the parachute. Or, if there is room between stairs, you might be able to drop a parachute from one floor down to the lower floor of a building. You might be able to drop the parachute out a window of an upper floor of your house or apartment, provided someone is below to watch out for the parachute and to make sure that it does not fall on someone.

Find the mass of the parachute and its suspended container. Then drop the parachute and measure its time of fall and distance of fall. Calculate the wind velocity (distance divided by time), and determine the air resistance in newtons (mass in kg and g as 9.8 m/s^2). Add a mass to the container, and repeat the observation. Use the new mass (parachute + container + weight) to determine the new air resistance, and calculate the wind velocity from distance of fall divided by time of fall. Do this for at least four different masses. Make a table of air resistance and wind velocity. You will have at least four pairs of data. Make a graph of air resistance on the vertical axis and wind velocity on the horizontal axis.

Questions:

1. What does the graph of air resistance vs. air speed (relative wind velocity) look like? Is it a straight line? Describe how you would use this graph to predict the air resistance of this parachute for a given wind velocity.

2. When scientists analyze data that do not graph as a straight line, they begin to look for relationships that called nonlinear. Only equations with variables to the first power graph as straight lines. So such an equation is called linear. Equations to the second or higher order graph as curves. Actually, a simple equation like $y = x^2$ makes a graph of a parabola. So scientists know when they see a curve, and not a straight line graph, that they must consider some relationship other than one that is linear. If the relationship is simple, then it might be a square root relationship, or it might be a squared relationship. To find out, one just needs to take the square root of all of the values of one of the variables and make a new graph. If the graph is a straight line, then the guess was right. If not, then try something else. For your data, take the square root of air speed and graph air resistance versus square root of air speed. If that does not give a straight line, then square each air speed and make a graph of air resistance vs. the square of air speed. Does this give a straight line? If you get a straight line from one of these techniques, what does the slope represent? Write an equation representing this relationship.

3. When you are driving a car at 30 mph, there is a certain air resistance. If you increase your speed to 60 mph, how much greater is the air resistance? (Assume that there is no wind.)

4. Suppose that you are driving into a 25 mph wind at 40 mph. You increase your speed to 60 mph. How much greater is the air resistance?

5. Suppose that you are in contact by the Internet with three friends who have done this same experiment using identical parachutes but vary the weights so that the parachutes pull the same amount in the same time. But one friend is in Denver, Colo., where the altitude is about 5,000 ft (and air has a density of about 1.025 kg/m^3), another is in a mountain village in Mexico where the altitude is 10,000 ft (where air has a density of 0.881 kg/m^3), and a third lives in a sea coast town in Maryland where the altitude is 0—sea level (and air has a density of 1.192 kg/m^3). The friend in Denver observed an air resistance of 1.03 newtons with his parachute in the city. When he climbs to the top of a nearby mountain, where the altitude is 14,000 ft (and air has a density of 0.779 kg/m^3), he observes an air resistance of only 0.78 newtons. The friend in Mexico observed an air resistance of 0.89 newtons, and the friend in Maryland observed an air resistance of 1.20 newtons. Graph the air resistance on the vertical axis and the air density on the horizontal axis. What kind of relationship between air resistance and air density, if any, do you deduce from this graph? Write an equation for this relationship.

6. In Activities 1 and 2, and through the answer to Question 5, you identified and examined the three variables that determine air resistance—a quantity better known among aerospace, hydrodynamic and automotive engineers as *drag*. These three relationships can be combined into one equation, as follows:

$F = C_D \rho v^2 A/2$

where F is the drag (air resistance in Newtons) C_D is a constant called the drag coefficient, ρ is the air density, A is the cross section of the object, and v is the wind velocity. These quantities must be expressed in the proper SI units (meters, kilograms, newtons). For a smooth sphere, the drag coefficient has a value of about 0.5 ± 0.1. Using this value of the drag coefficient for a sphere, find the terminal velocity of a Ping Pong ball (mass = 0.0025 kg; radius = 1.9 cm.) when dropped from rest at sea level.

Science as Inquiry

Friction

What is another kind of resistance to motion?

Overview:

You have examined air resistance as a form of resistance to motion. When an object falls under the force of gravity, and if it falls far enough for long enough, it will reach a terminal velocity. At this time, the force of gravity is balanced by air resistance, so the net force is zero. When net force is zero, and there is no acceleration, terminal velocity is constant. Are there other, situations where frictional force equals applied force that do not involve air resistance?

If you attach a rope to a box of sand that is placed on the floor, and you pull on the rope, you can make the box of sand move. If you pull hard enough, the box will accelerate. But what if you pull just enough so that the box moves at a constant speed? You are exerting a force on the box, but the box is not accelerating. According to Newton's Second Law, if there is zero acceleration, then there is no net force. But you *are* exerting a force on the box. So how does the net force get to be zero? There must be some other force between the floor and the box, and that force must be pushing back on the box as you pull it forward.

In this activity we will examine this force and try to determine how to express it in terms that we already know.

Procedure:

Part A. Place a weight into a box, attach a strong piece of twine or rope to the box and a spring scale (that reads force in newtons) between your hand and the box. Figure 1 shows this arrangement.

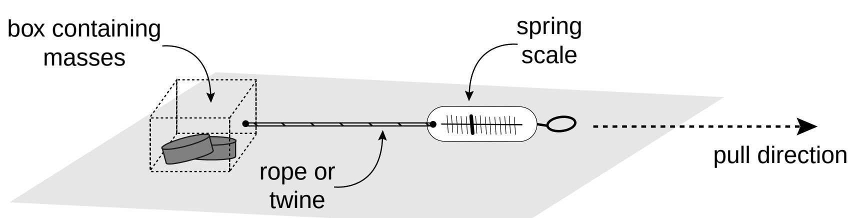


Fig. 1

Measure the mass of the box and its contents. Find the weight of the loaded box in newtons. When you are not pulling on the box, what are all of the forces acting on the box? Draw a diagram showing arrows representing these forces. Let the arrows point in the direction of these forces, and let the length of the arrows be a measure of the strength of the forces. Label the arrows by the amounts of force involved.

Very slowly and carefully pull on the box while watching the spring scale. What is the value of the force at the instant the box just starts to move? Do this several times, and take an average value of the force at the instant the box starts moving. For this situation, show all of the forces acting on the box, with their direction and label the arrows with the amount of forces in newtons.

Since you are pulling on the box, but it is not moving, there must be an equal an opposite force pulling on the box in the opposite direction. Be sure to include and label this force as well. Add weights to the box and repeat these measurements; also draw the force diagram. Do this for at least four different values of weight in the box.

When you have finished, you will have four sets of data that include the weight of the box and contents in newtons and the maximum force required to start it moving along the floor or table top. Make a graph of this force on the vertical axis, and the weight of the box on the horizontal axis. What kind of relationship do you observe? Find the value of the slope of this graph.

The force represented by this graph is equal but opposite to the force pulling back on the box just before it starts to move. This resistive force is given a name. It is called *static friction* because it is measured while the box is static—not moving.

Part B. Using the same sets of weights, in the same situation, observe how much force it takes to keep the box moving at a constant velocity across the table top or floor. Do this for each different set of weights in the box. How does the force required to keep the box moving at a constant speed compare with the force needed just to get the box to start to move? Make a graph of this force versus the weight of the box. Find the value of the slope of this graph.

When the velocity is constant, there is no acceleration, and again the net force must be zero. The force you are applying to pull the box at a constant velocity must be equal to some force pulling back on the box. That force has to be between the box and the table top. We call that force *kinetic friction* because the box is kinetic—in motion.

Part C. Connect a spring scale to a bicycle wheel (the tire should be inflated to its normal value). Place the wheel on a concrete surface similar to the street. With a partner holding the wheel upright, pull the rope until just before the wheel starts to slide (Fig. 3). Find the ratio of the weight in newtons of the bicycle wheel to the this maximum static force.

Now, pull on the rope so that the wheel slides without turning at a constant velocity across the pavement. Find the ratio of this kinetic force to the weight in newtons of the bicycle wheel.

The first ratio is called the *coefficient of static friction,* and the second ratio is called the *coefficient of kinetic friction.* How do they compare? What do they mean?

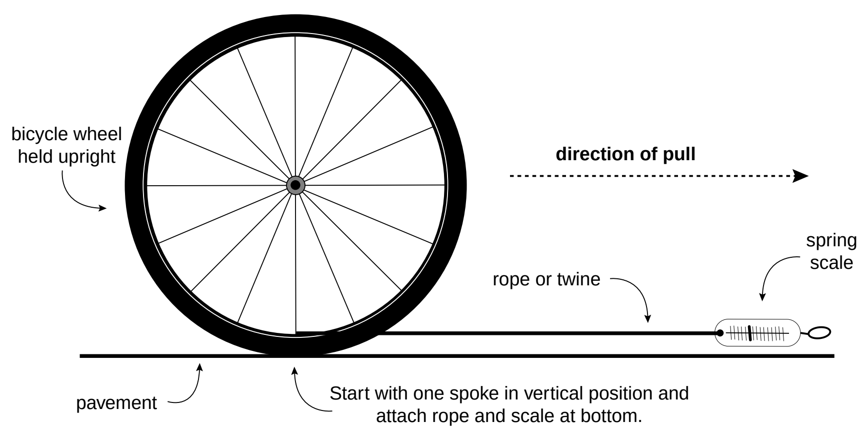


Fig. 2

Questions:

1. When you found the relationship between static friction and maximum force for a static situation, the slope of the graph of static friction and this maximum static force is given a name. It is called the coefficient of static friction. It is represented by the symbol, μ_S. Thus, you can write the equation $f_{max} = \mu_S W$, where W is the weight of the box and f_{max} is the maximum static force of friction. For reasons that you will learn later, the more important force to use on the right hand of this equation is the force with which the table pushes up on the box. This is called the normal force, and represented by N. As long as the table is level the normal force and weight

have the same magnitude. But if the table is inclined, so that you are pulling the box uphill or downhill, the normal force between the box and the table is less than the weight. And it is this force between these surfaces that determines friction. Thus, the equation is usually written as follows:

$$f_{max} = \mu_S N$$

The coefficient of static friction between glass and copper is 0.68. What is the maximum force you would need to exert on a copper-bottomed pan having a mass of 600 g to get it to just start to move across a glass cutting board?

2. The equation for maximum static friction does not give any information on the frictional force that exists during the time that you begin to pull on an object, but have not reached the point where it starts to move. Describe in your own words how this force changes, and write an inequality to represent it.

3. When an object is moving while in contact with another surface, the force of friction, called kinetic friction, is related to the normal force by the equation,

$$f_k = \mu_k N$$

where μ_k is called the *coefficient of kinetic friction.* The coefficient of kinetic friction between copper and glass has a value of 0.53. What is the force you would need to exert on a copper-bottomed pan having a mass of 100 g to move it at a constant velocity across a glass cutting board? How does this result compare with that of Question 2? How do these results compare with those you observed in your experiments?

4. When driving a car and you must stop suddenly, why is it important to try to come to a stop without skidding?