SCOPE, SEQUENCE, and COORDINATION

A National Curriculum Project for High School Science Education

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SCOPE, SEQUENCE, and COORDINATION

National Science Education Standard—Physical Science

Motions and Forces

a. Motions are described quantitatively in science using concepts given the names distance, displacement, speed, velocity, and acceleration. Relationships among these quantities are most easily interpreted and used to solve problems by means of graphical techniques involving slopes and areas under curves.

b. Between any two charged particles, electric force is vastly greater than the gravitational force. Most observable forces such as those exerted by a coiled spring or friction may be traced to electric forces acting between atoms and molecules.

Teacher Materials

Learning Sequence Item:

1021

Air Resistance and Friction

May 1996
Adapted by: Bill G. Aldridge

Translational Kinematics (a). Students should investigate qualitatively the resistance to motion that is presented by fluids—air in particular. Experiments with simple parachutes can be useful. They should be guided to recognize that the interaction with air of an object falling due to gravity may influence the results of their measurement of that acceleration, but they should see that neglecting this frictional effect and idealizing the results makes investigating acceleration due to gravity easier. They could then be challenged as to how this experiment would work differently on the moon. These skills would allow problem solving for motion in Earth's gravity *(Physics, A Framework for High School Science Education, p. 5*).

Elastic and Frictional Forces (b). Students must learn that when an object is at rest (or when the force is at right angles to the motion, as for the friction that provides centripetal force for a car going around a curve), friction is static. When the object is in motion, friction is usually kinetic. Students should solve problems involving friction on horizontal surfaces, using coefficients of friction and normal forces *(Physics, A Framework for High School Science Education, p. 24).*

Contents

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

1021

Learning Sequence

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Science as Inquiry	Science and Technology	Science in Personal and Social Perspectives	History and Nature of Science
Air Resistance and Area **Activity 1** Air Resistance and Wind Velocity **Activity 2** Friction **Activity 3** Air Resistance II **Assessment 3** Air Resistance III **Assessment 4**	Air Resistance I **Assessment 2**	Static vs. Kinetic **Assessment 1**	

Suggested Sequence of Events

Event #1

Lab Activity

1. Air Resistance and Area (40 minutes)

Event #2

Lab Activity

2. Air Resistance and Wind Velocity (60 minutes)

Event #3

Lab Activity

3. Friction (50 minutes)

Event #4

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

Suggested readings:

Chernoustan, Alexey, “A Gripping Story.” *Quantum*, Vol. 6, No. 4, March/April 1996, pp. 40–42.

Mitrofanov, Alexander, “Against the Current.” *Quantum*, Vol. 6, No. 5, May/June 1996, pp. 22–29.

Vogel, Steven, “When Leaves Save the Tree.” *Natural History*, Vol. 102, No. 9, Sept. 1993, pp. 58–63.

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.

Teacher Sheet

Science as Inquiry

Air Resistance and Area

Does the air resist?

Overview:

In this first activity we shall just consider air resistance. What does air resistance depend upon? Your student's intuitive ideas, stemming from their experience gives them a qualitative answer to this question. They know that a tissue (Kleenex) drifts slowly to the ground when dropped, but if one wads it up into a tight ball and drops it, the wad of tissue 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. A student's intuition also suggests that the air resistance should be proportional to that cross-sectional area. This intuitive suggestion can be made into a hypothesis that your students can test through an experiment.

Students also know from experience that the faster that the wind blows the harder it is to walk against the wind. Thus, they know from their experience that air resistance is also connected to wind speed.

In this first activity, their task is to determine, through an experiment, the relationship between cross-sectional area and air resistance. Students may also understand that shape, as it relates to streamlining, is a factor. To make this determination, they need to hold the air speed and shape constant.

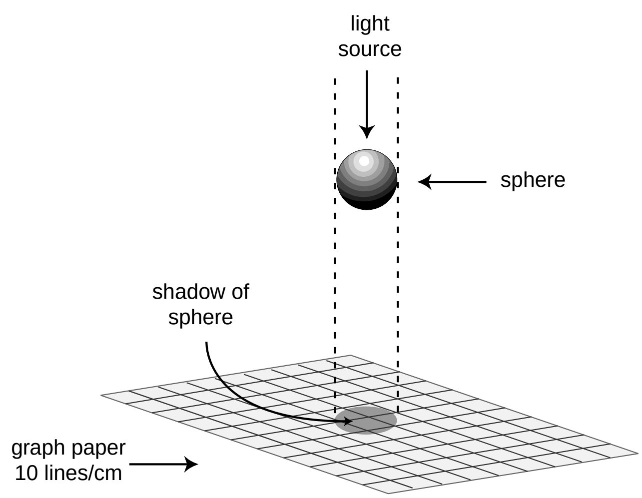
Materials:

Per lab group:

hair dryer with no-heat setting
(or fan with several settings)
graph paper with 10 mm x 10 mm squares, by mm, several sheets
thread or light string
spheres of various size and material
(iron, rubber, etc.), 4

Procedure:

For this experiment students will use a hair dryer, if it has a no-heat setting, or a fan, and objects that have a certain cross-sectional area. Temperature may be a variable, so keep the temperature constant, and preferably at room temperature. Keep the air speed constant by using the same setting on the fan or hair dryer, and make sure that the objects being studied are at the same distance from the source of air. Students need to center the air stream on each sphere. The simplest objects to use are small, smooth spheres, like a



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

Fig. 1

marble, a steel ball, a Ping-Pong ball, or various size rubber balls. They need four spheres of different cross-sectional area.

Students use a piece of graph paper to trace the boundaries of the shadow cast by the sphere when sunlight falls on it (see Fig. 1). The projection is the cross-section. Make sure that students use sunlight, or if sunlight is not available, that they use a source of light that has a well collimated beam. Otherwise, the rays are not parallel, and the image gives the wrong size for the cross-section. Students can then just count the squares to get the cross-section in square cm, which they can convert to square meters (divide square cm by 10,000 to get square meters). They will need to count the smallest squares, which are 1 mm x 1 mm, and when only part of one of these little squares is covered they need to estimate what fraction it is and add these various pieces. If they end up with square millimeters for their total, they will need to divide square millimeters by 1,000,000 to get square meters.

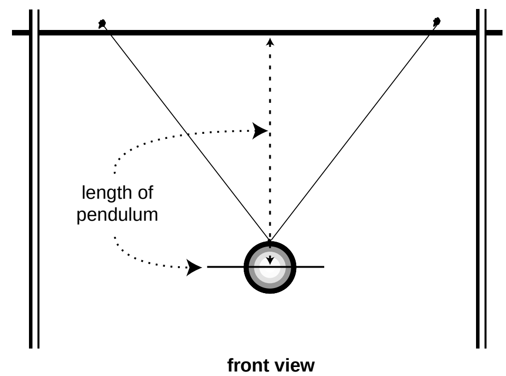


Fig. 2

Next students will connect the sphere to two threads. They should glue an end of each thread to the same point on the sphere. Then they hang the sphere as shown in the figure below, and turn on the air supply centered on the sphere. The reason they need two threads is that the air currents will cause a simple pendulum to oscillate all over the place, where a double thread suspension will allow the sphere to move only along one plane. This makes the length of the pendulum different from the lengths of the suspension threads, however. To get the length of this pendulum they must measure the distance from the center of the sphere to a point midway between the suspension points for the two threads.

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

So by measuring the cross-section and mass of several spheres, their displacement in the same air stream, and the length of the pendulum formed, students can find the air resistance.

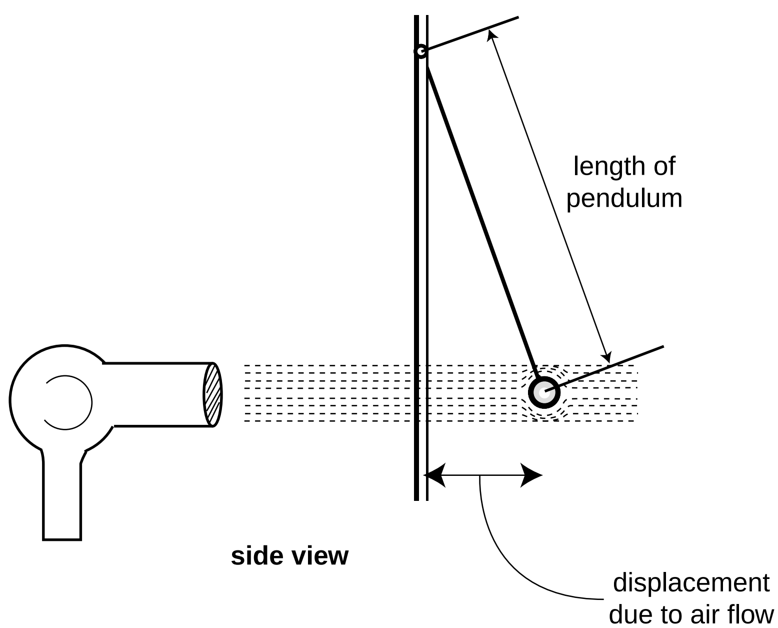


Fig. 3

Students should find air resistance for at least four spheres; then they will graph air resistance on the vertical axis and cross-section on the horizontal axis of a graph paper, giving them four points on the graph. They will get a straight line, with slope equal to a constant.

You should given each student an unknown sphere. Ask them to measure its mass and cross-section and predict its air resistance in the air stream they have produced. They should test their prediction by measuring that air resistance.

Background:

This activity is the first of two leading to an understanding of fluid resistance. The results are generalizable to any reasonably dense fluid with low viscosity. This would include water and air, for example.

There is an empirical law for fluid flow that gives the *Drag*:

$$Drag = C_D(\rho V^2/2)A$$

where the *Drag* is in newtons, C_D is a constant without a unit called the drag coefficient, ρ is the density of the fluid (for air, this is 1.190 kg/m^3 at 24°C at sea level), V is the wind velocity (or, for the fluid at rest, and the object moving, it's velocity relative to air), and A is the cross-section of the object moving. For a sphere, this cross-section is the same as that of a circle at any diameter, but other shapes can offer very complex cross-sections. A shadow of the sun's light formed by the object normally on graph paper is a fairly simple way to determine complex cross-sections.

The quantity, $\rho V^2/2$, has dimensions of pressure, and it is sometimes called, dynamic pressure. It is a term that appears in Bernoulli's Equation, and it represents the kinetic energy per unit volume of the moving fluid (if it is the fluid that is moving).

This relationship is very important in all of fluid dynamics, and it is especially important in the design of automobiles, airplanes, boats and ships.

Even though this equation can be deduced from fluid flow theory, it can also be arrived at empirically, and it was first found this way, historically. Students at Grade 10 are arriving at this relationship empirically, and in Grades 11 and 12 will look at it from the theoretical standpoint. For example, why is the fluid resistance proportional to the square of the velocity. This is not simple to explain, and requires the use of Newton's Laws of Motion and considerations of the surface characteristics of the moving object, not just its geometry. Thus we assume perfect streamlining and use smooth objects.

To determine this relationship empirically, students must hold variables constant. For example, to determine air resistance as a function of cross-section, both the air density and the air stream velocity must be held constant. The air density depends upon atmospheric pressure and it depends upon temperature, so both must be held constant. The air stream velocity is difficult to hold constant because it varies in different parts of an air stream, like that produced by a fan or a hair dryer. Thus the best you can do is keep the center of the sphere in the center of the air stream.

Answers to Student Questions.

1. Since the air resistance is proportional to the cross-section, three times more cross-section means three times more air resistance. Now since cross-section is always proportional to the square of a linear dimension, if you triple the diameter, the cross-section must increase by a factor of 3^2, or 9. So the air resistance is increased by a factor of 9.

2. This first answer is simple, *Drag* = constant x cross-section, or, *Drag* = *KA*, where *K* is a dimension less constant equal to the slope of the graph of air resistance versus cross-section, and depends upon other variables being held constant. If wind velocity, density, and temperature are all held constant, then the air resistance is proportional to the square of any linear measure. For example, a chord between two points of a sphere, if always in the same relative position regardless of the size of the sphere, is a linear measure. A radius is a linear measure, and so is the circumference. The perimeter of a solid is a linear measure, provided that all various sizes of that solid have the same ratio of side lengths. A linear measure allows us to use properties for objects of the same shape.

3. For objects of the same mass, the weights are always the same. The terminal velocity will be reached whenever the air resistance is equal to this weight. But for objects of smaller cross-section, they must travel at a higher speed to reach terminal velocity. Thus the velocity would not be held constant in such an experiment. Both the cross-section and the air speed would be changing, and you cannot do an experiment to find the relationship between a dependent variable and an independent variable when there are two independent variables.

Variations:

None.

Adapted from:
None.
Illustrations: M. S. Young

Science as Inquiry

Air Resistance and Wind Velocity

How does air resistance depend upon air speed?

Overview:

In Activity 1, students found that air resistance was proportional to the cross-section, when holding air speed and fluid density constant. They now need to hold cross-section and air density constant and vary the air speed. Then they can find the relationship between air resistance and air speed, with the cross-section and air density held constant. These kinds of experiments are the essence of experimental method, and of empirical science.

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 objects' velocity to be constant, and equivalently, 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. It is just the weight of the object moving at terminal velocity.

Now, what about the wind velocity. Velocity is relative. We don't care whether the wind is actually blowing past something, or we move something in still air. If the velocity of the object relative to still air can be determined, then the result would be the same as the object at rest and the air 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 it quickly achieves terminal velocity, and we measure how long it takes to fall to the ground, then we can find its terminal 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 create situations where the air resistance is different, and this situation also gives us different values for the wind speed.

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

Materials:

Per lab group:

lightweight cloth, circular sheet, at least 60 cm dia.
thread or string to hold weight-holder to parachute
thin aluminum cupcake cup used in baking cupcakes for weight holder
stop watch
meter stick or tape measure

Procedure:

For this experiment, students need to drop an object that quickly achieves its terminal velocity. The easiest device to use would be a small parachute. Or you can give them circular sheets of cloth. They should connect the parachute to at least four symmetric places on the weight holder. You could let students design their own parachute, which suspends a small container in which you can place masses. This way they can keep the cross-section constant (that of the parachute), while varying the weight (mg) of the falling object. Students should try different shapes of parachutes.

They should make a parachute that, with the weight-holder attached, it is large enough so that it falls rather slowly. For each of several different amounts of weight in the weight holder, they should drop the parachute from the same height each time, and measure how long it takes to hit the ground. This might best be done by climbing up on a ladder (while someone holds it steady) and drop the parachute. Or if there is room between stairs, they might be able to drop a parachute from one floor down to the lower floor of a building. They could also drop the parachute out a window of an upper floor of a house or apartment, or even a school building, provided someone is below to watch out for the parachute and to make sure that it does not fall on anyone. The cross-section of the parachute may not stay constant with different loads. Have students estimate how this shape might change.

Students should measure the mass of the parachute and its suspended container. Then they drop the parachute and measure its time of fall and distance of fall. They calculate the wind velocity (distance divided by time), and determine the air resistance in newtons (mass of parachute, weight holder and weights in kg times g as 9.8 m/s^2). Then they add a weight to the container, and repeat the observation. They use the new mass (parachute plus container plus weight added) to determine the new air resistance, and calculate the wind velocity from distance of fall divided by time of fall. They need to do this for at least four different weights. Next they make a table of air resistance and wind velocity. They will have at least four pairs of data. When they graph air resistance on the vertical axis and wind velocity on the horizontal axis, they will *not* get a straight line. It will be curved, and actually is a parabola.

Background:

Answers to Student Questions.

1. The graph is not a straight line. It is curved in the shape of a parabola. But the graph does very nearly pass through the origin (when velocity is zero, air resistance is zero). Because the parachute does not immediately achieve terminal velocity, its early speeds are slower than terminal velocity, thus the measured time of fall will be longer than it should be if the parachute were falling the entire distance at actual terminal velocity. For this reason the calculated value of terminal velocity will be too small. To predict the air resistance, students need only go to a value of wind velocity on the graph and read the graph to get air resistance.

2. This relationship is air resistance proportional to the square of the terminal velocity, so students will find a graph of air resistance versus the square of the velocity will give nearly a straight line. The line will probably intercept the horizontal axis to the right of the zero origin. That would give an estimate of the average squared amount by which the square of their measured terminal velocities are lower than their real values. The square root of this value would be an estimate of that average terminal velocity error.

3. This item requires that students understand that it is the relative velocity that is important and that the air resistance increases with the square of that relative velocity. An object can move while the air is still. But the “air speed” is the relative velocity. Doubling the relative velocity of air and car increases the air resistance by a factor of 2^2, or 4. The air resistance is 4 times greater.

4. This item has a head wind, so to get the wind velocity relative to the car, you must add these two speeds. So in the first case the wind velocity relative to the car is 25 mph plus 40 mph, or 65 mph. In the

second case, it is 25 mph plus 60 mph, or 85 mph. The ratio is 85/65 = 1.31. Thus the situations are that the wind velocity relative to the car increases by a factor of 1.31. The air resistance goes with the square of the wind velocity, so the air resistance must go up by a factor of $(1.31)^2$ or 1.71. The air resistance therefore increases by 171% when the car goes from 40 mph to 60 mph in a 25 mph head wind.

5. This is an experiment that holds cross-section constant and wind velocity constant while investigating the dependence of air resistance as a function of air density. The values of air density given take into account the fact that the average temperatures at these altitudes are different (higher altitudes give lower temperatures). Thus, these density figures are roughly correct as average observable values. The relationship is a straight line, so students will find that the air resistance is proportional to the air density. This result gives the three basic relationships for drag in fluid dynamics.

6. At sea level the air has a density of 1.192 kg/m^3. The cross-section of this ball is $(3.14159)(0.019\ m)^2$, or $(3.14159)(0.000361)m^2$, or 0.001134 m^2. We know that the air resistance is the ball's weight, (mg). So the air resistance is $(0.0025\ kg)(9.80\ m/s^2) = 0.0245$ newtons. The drag coefficient is 0.5. Using these quantities in the drag equation, we have,

$$0.0245\ kg \cdot m/s^2 = (0.5)(1.192\ kg/m^3)(0.001134\ m^2)v^2/2$$

Only one thing is unknown in this equation, the square of the terminal velocity. Solving for v^2, we have,

$$v^2 = 72.5\ m^2/s^2$$

Taking the square root of both sides, we have,

$$v = 8.5\ m/s$$

Variations:

None.

Adapted from:
None.

Science as Inquiry

Friction

What is another kind of resistance to motion?

Overview:

Your students 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, so that the terminal velocity is constant. Are there other, similar situations 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 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 your students will examine this force and try to determine how to express it in terms that we already know.

Materials:

Per lab group:

cardboard or wooden box, roughly 1 cubic foot in size
weights, 100 g to 1 kg
small rope or twine
bicycle wheel with tire inflated normally
spring scale that will read newtons (at least up to 20 newtons)
triple beam balance or other scale to measure large masses

Procedure:

Part A. Students place a weight(s) into the box, and attach a strong piece of twine or rope to the box, with a spring scale that reads force in newtons between their hand and the box. Fig. 1 shows this arrangement.

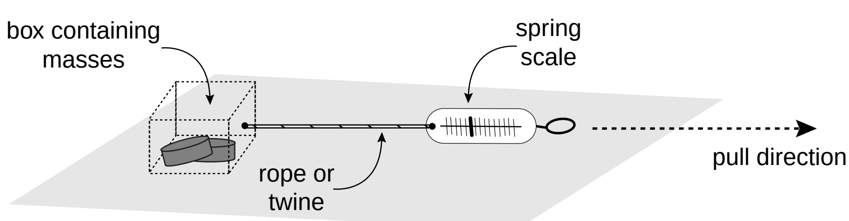


Fig. 1

Students measure the mass of the box and its contents, and use $w = mg$ to find the weight of the loaded box in newtons and diagram their results. When they are not pulling on the box, the forces acting on the box include the box's weight—directed downward, and the normal force of the table top or floor pushing up on the box. Their diagram should show two arrows representing these forces. One arrow should be pointed upward and the other downward, with the same length. The arrows should be labeled by the amounts of weight and equal normal force.

Students slowly and carefully pull on the box, while watching the spring scale. Just before the box starts to move, the force will reach a maximum. When the box starts moving, students should try to keep it moving at a constant velocity, this force will drop to a lower value. They do this several times, and take an average value of the force at the instant the box starts moving. For this situation, they diagram all of the forces acting on the box, with directions and labels of arrows with the amount of forces in newtons. They show the weight and normal forces as equal, but when they draw an arrow showing the force pulling on the box, they will not know to show another force on the box—the frictional force. You need to prompt them to conclude that such a force exists. Since students are pulling on the box, but it is not moving, there must be an equal an opposite force on the box in the opposite direction. Help students understand and include and label this force as well.

Students add additional weight to the box and repeat these measurements; again they draw the force diagram. They need at least four different values of weight in the box. When students finish, they will have four sets of data that include the weight of the box and contents in newtons, and how much force is required up to where the box starts moving along the table top. They graph this force on the vertical axis, and the weight of the box on the horizontal axis.

Part B. In this part of the experiment, students use the same sets of weights, in the same situation—but this time they observe how much force it takes to keep the box moving at a constant velocity across the table top or floor for each different weight of the box and its contents.

Part C. Students connect a spring scale to a bicycle wheel (the tire should be inflated to its normal value). They will place the wheel on a concrete surface similar to the street. With a colleague holding the wheel from falling over, a student will pull on the wheel until just before it starts to slide. They will then find the ratio of the weight in newtons of the bicycle wheel to this maximum static force. This is the coefficient of static friction between the bicycle tire and the pavement.

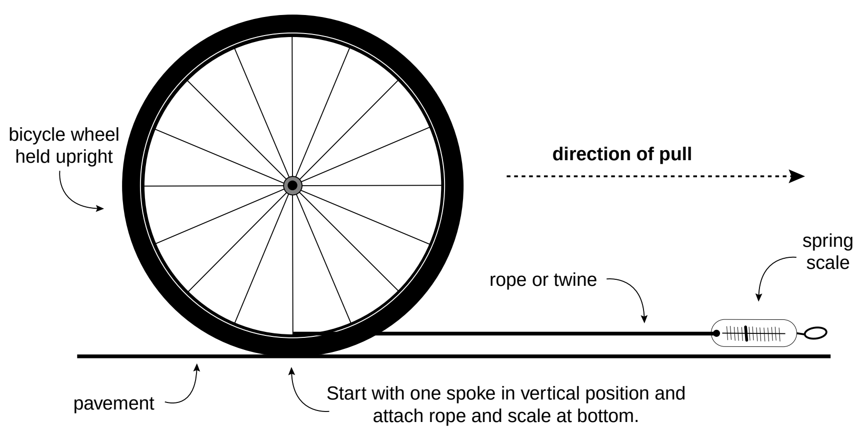


Fig. 2

Now, again with a colleague keeping the wheel from falling over, a student will pull on the wheel so that it slides without turning, and at a constant velocity across the pavement. They will find the ratio of this kinetic force to the weight in newtons of the bicycle wheel. This ratio is called the coefficient of kinetic friction. You should discuss with students the difference between these two coefficients and what they mean in terms of riding a bicycle, motorcycle, or driving a car.

Background:

In Part A, the students' graph will have a straight line passing through the origin, so this force will be proportional to the weight of the box and its contents. The slope of the graph will be the coefficient of static friction between the bottom of the box and the table. The force represented by this graph is equal but opposite to the force pulling back on the box just as 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.

In Part B, students observe that the force needed to keep the box moving at a constant velocity is less than that needed to just start the box to move. When they graph of this force versus the weight of the box, the slope will be less. This slope is the value of the coefficient of kinetic friction.

When the velocity is constant, there is no acceleration, and again the net force must be zero. The force students apply 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 in motion.

It will be difficult for students to understand the origin of frictional forces. You will need to raise questions with them about what happens at the boundary layers between two surfaces experiencing friction. Make clear to students that what they did was empirical. What you are now talking about is the theory—the explanations of empirical laws.

A very important application of static friction is when a tire is rolling but not skidding. Because the tire is turning and rolling along the pavement, students will have a tendency to think of this situation as kinetic. But the motion of a piece of the tire touching the pavement at any given instant is static, not kinetic. There is no sliding of the tire along that pavement. Indeed, if there were, the wheel would not be turning the same amount.

The other aspect of static friction with cars is the sideways static friction. This sideways force is important when a car goes around a curve. What prevents the car from skidding sideways—static friction. The force of static friction provides the centripetal force to the car to make it have the centripetal acceleration associated with that particular radius of curvature. If the curve is too sharp, and the radius of curvature is too low, then the force of static friction is insufficient to provide the necessary centripetal force, and the road must be banked to keep the car from skidding. These kinds of banked curves and friction problems are too complicated for grade 10, but will be considered in grade 11. But they can be discussed qualitatively in grade 10.

Answers to Student Questions.

1. For this question, the maximum force is the product of the coefficient of static friction and the normal force. The normal force is just equal to the weight of the copper-bottomed pan, or mg. This is then, (0.600)(9.80) newtons, or 5.88 newtons. Since the coefficient of static friction is 0.68, the maximum force needed is just (5.88)(0.68) newtons, or 3.94 newtons.

2. The correct static friction equation is written,

$$f \leq \mu_S N$$

Students should be able to describe how the frictional force keeps pace with the applied force, always being equal and opposite, until the maximum value is reached.

3. In Question 1, students found the maximum static frictional force between glass and copper. In

this question, they must find the kinetic frictional force. As you can see the coefficient of kinetic friction is smaller than the coefficient of static friction, and the force will be correspondingly less. The kinetic frictional force will be (0.98 N)(0.53), or 0.52 newtons.

4. This item is very important for safe driving of a car or of riding a bicycle or motorcycle safely. The maximum static friction between the tires and the pavement is higher than the kinetic friction. If the vehicle starts to skid, it must therefore travel further before it stops. So the stopping distance is less when the vehicle skids than when it comes to a stop without skidding. Interestingly, in the brakes of the car, and in the brakes of the bike or motorcycle, it is kinetic friction between brake pads and drum or disk that is used to stop the wheel from turning.

Variations:

None.

Adapted from:
None.
Illustrations: M. S. Young

Science in Personal and Social Perspectives

Static vs. Kinetic

Item:

How are the differences between static and kinetic friction important for safety in terms of stopping a car, truck, bicycle, or motorcycle?

Answer:

The fact that the maximum static friction is greater than kinetic friction means that a vehicle will move over a greater distance to stop if it skids (kinetic friction) than if it does not skid (static friction). Thus it is important for safety that the vehicle be brought to rest, without skidding. That is why modern brakes have anti-skidding features.

Science and Technology

Air Resistance, I

Item:

Design three different cars, one with the least air resistance, one with the most air resistance, and one with an air resistance that is average. Using the information in Fig. 1, draw a picture of what these three cars look like. In the illustration, each part of a car shape is associated with a quantity that can be used to estimate the drag coefficient for air resistance. To find the drag coefficient for a car, first find the sum, (sum = A + B + C + D + E + F + G + H), where these numbers appear in the parentheses in the descriptive reference for each part. After getting the sum, use the equation:

C_D = 0.16 + (0.0095) x sum

to find the drag coefficient for the car being designed. A greater drag coefficient means more air resistance at a given speed.

Answer:

The least air resistance would be for a car of design: A-1, B-1, C-1, D-1, E-1, F-1, G-1, and H-1. The sum factor would be sum = 8, and the drag coefficient would be:

C_D = 0.16 + (0.0095)(8), or C_D = 0.16 + 0.076, or C_D = 0.24.

The most air resistance would be for a car of design: A-6, B-4, C-3, D-3, E-8, F-3, G-6, H-6. The sum factor would be sum = 39, and the drag coefficient would be:

C_D = 0.16 + (0.0095)(39), or C_D = 0.16 + 0.37, or C_D = 0.53

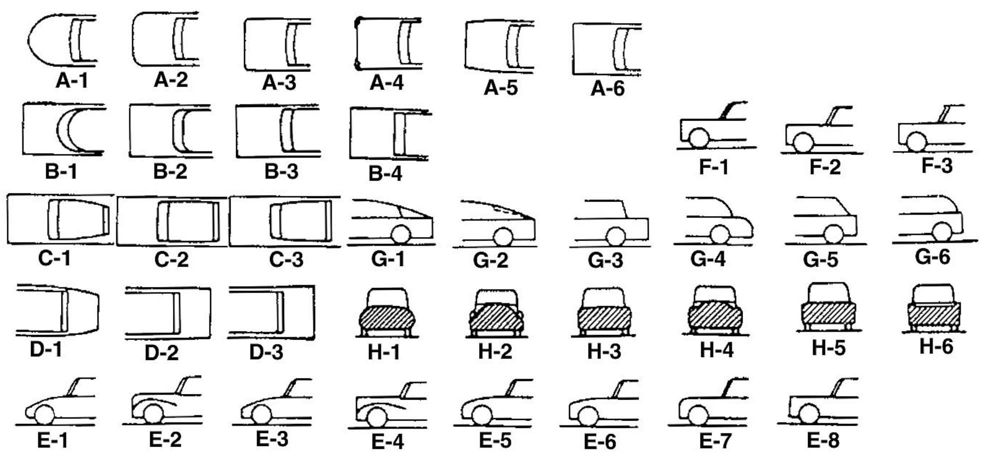
The air resistance of this car is going to be more than twice that of the other car. A car that would have some average air resistance would be A-3, B-3, C-2, D-2, E-4, F-2, G-4, H-3.

Students should use the word descriptions and pictorials to draw the design of these three types of cars. They should show various views of the car, and they should also try to draw a perspective picture of the car. This will give students with good artistic skills a chance to show some of the others, who may be good in physics, how to draw.

(continued)

Automobile Drag Coefficient Estimates

Drag rating values in parentheses are for use in the equation:
drag coefficient, $C_d = 0.16 + 0.0095\ \Sigma$ (summation) drag ratings. Σ drag ratings must include one rating from each of the nine categories listed (A through H).



A. Plan view, Front end

- A-1 Approximately semicircular **(1)**
- A-2 Well-rounded outer quarters **(2)**
- A-3 Round corners without protuberances **(3)**
- A-4 rounded corners with protuberances **(4)**
- A-5 Squared tapering-in corners **(5)**
- A-6 Squared constant-width front **(6)**

B. Plan view, Windshield

- B-1 Full wraparound [approx. semicircular] **(1)**
- B-2 Wrapped-round ends **(2)**
- B-3 Bowed **(3)**
- B-4 Flat **(4)**

C. Plan view, Roof

- C-1 Well- or medium-tapered to rear **(1)**
- C-2 Tapering to front and rear [max. width at BC post] or approx. constant width **(2)**
- C-3 Tapering to front [max. width at rear] **(3)**

D. Plan view, Lower Rear End

- D-1 Well- or medium-tapered to rear **(1)**
- D-2 Small taper to rear or constant width **(2)**
- D-3 Outward taper [or flared-out fins] **(3)**

E. Side Elevation, Front End

- E-1 Low, rounded front, sloping up **(1)**
- E-2 High, tapered, rounded hood **(1)**
- E-3 Low, squared front, sloping up **(2)**
- E-4 High, tapered, squared hood **(2)**
- E-5 Medium-height, rounded front, sloping up **(3)**
- E-6 Medium-height, squared front, sloping up **(4)**
- E-7 High, rounded front with horizontal hood **(4)**
- E-4 High, squared front with horizontal hood **(5)**

F. Side elevation, Windshield Peak

- F-1 Rounded **(1)**
- F-2 Squared [including flanges or gutters] **(2)**
- F-3 Forward-projecting peak **(3)**

G. Side elevation, Rear Roof/Trunk

- G-1 Fastback [roof line continuous to tail] **(1)**
- G-2 Semi-fastback [with discontinuity in line to tail] **(2)**
- G-3 Squared roof with trunk rear-edge squared **(3)**
- G-4 Rounded roof with rounded trunk **(4)**
- G-5 Squared roof with short or no trunk **(4)**
- G-6 Rounded roof with short or no trunk **(5)**

H. Front elevation, Cowl and Fender cross-section at Windshield

- H-1 Flush hood and fenders, well-rounded body sides **(1)**
- H-2 High cowl, low fenders **(2)**
- H-3 Hood flush with rounded-top fenders **(3)**
- H-4 High cowl with rounded-top fenders **(3)**
- H-5 Hood flush with square-edged fenders **(4)**
- H-6 Depressed hood with high, square-edged fenders **(5)**

Science as Inquiry

Air Resistance, II

Item:

Galileo dropped a cannon ball and a musket ball off the 60-meter-high leaning tower of Pisa at the same time. The cannon ball was 80 kg of lead. The musket ball was 200 g of lead. Since the volume, and therefore the mass of an object goes with the cube of its linear dimensions, and the fact that these are made of the same material, how much greater is the diameter of the cannon ball than the musket ball? How much more air resistance does the cannon ball experience than the musket ball? How does this greater force of air resistance compare with the greater weight of the cannon ball? If one hits the ground first (because of greater air resistance on the other) which one hits the ground first? Are these two objects likely to hit the ground at exactly the same time?

Answer:

The mass of the cannonball is 400 times greater than that of the musket ball. Since they are both made of lead, we can find the ratio of their radii (a linear dimension) by taking the cube root of this mass ratio. The radius of the cannonball must therefore be 7.37 times greater than the radius of the musket ball, (i.e., 7.37 x 7.37 x 7.37 = 400).

Since air resistance is proportional to the cross-section, and cross-section is proportional to the square of the radius, the air resistance on the cannonball must be (7.37)(7.37), or 54 times greater than that on the musket ball.

These two objects would not hit the ground at exactly the same time. But Galileo could not, at that time, have had precise enough time measuring devices to detect the difference, and the two objects were traveling too fast to see the difference.

The air resistance on the cannon ball is 54 times greater than that on the musket ball. But the weight of the cannon ball is 400 times that of the musket ball. Thus air has a much greater effect on the musket ball. It should hit a little later.

Science as Inquiry

Air Resistance, III

Item:

A person wants to find the acceleration of gravity by dropping a small, almost perfectly smooth, metal sphere from a height of 40.663 meters and timing its fall. The sphere falls through that distance in 2.900 seconds. Using the kinematics equation:

$$d = \tfrac{1}{2}gt^2$$

we find the value of g to be 9.67 m/s^2. The sphere has a mass of 800.0 grams and a radius of 3.000 cm. Given the density of air as 1.200 kg/m^3, and the drag coefficient for a certain metal sphere as 0.5000, calculate the maximum value of the air resistance as this sphere falls to the ground. Estimate the average frictional force due to the air resistance, and find a correction to the measured value of *g.* Since drag goes with the square of the velocity, and the velocity is increasing as the sphere falls, there is no particular value of air velocity that one can select to use. By a much more advanced analysis, it is possible to determine that the velocity value needed to compute the correction due to air resistance is 11.5 m/s.

Answer:

The student might first hypothesize that the sphere reaches its terminal velocity. If it did reach that velocity, then we can calculate its value from the drag equation. Let us try that first. We would have the drag equal to the weight of the sphere, which is just (0.800kg)(9.67 m/s^2), or 7.736 newtons. And the drag equation,

$$F_D = C_D\,(\rho v^2 A)/2$$

would appears as follows:

$$7.736\ \text{kg} \cdot \text{m/s}^2 = (0.5000)(1.200\ \text{kg/m}^3)(3.14159)(0.03000\ \text{m})(0.03000\ \text{m})v^2/2$$

When this equation is solved for v, we have v = 95.5 m/s. But if the acceleration due to gravity is g = 9.67 m/s^2, then the most that the speed can reach in 2.90 seconds is given by $v = gt$, or v = (9.67 m/s^2)(2.90 s) = 28.0 m/s. We are led to a contradiction of our hypothesis. The sphere never reaches its terminal velocity. It hits the ground before it can do so. The velocity that would produce the correction due to air resistance is given as 11.5 m/s. Thus,

Average air resistance = (0.50)(1.20 kg/m^3)(3.14159)(0.030 m)(0.030 m)(11.5 m/s)(11.5 m/s)/2

which gives a value of 0.112 newtons for the average air resistance. This force would produce an acceleration given by Newton's second law, $f = ma$. Thus, it would produce an acceleration of (0.112 N)/(0.800 kg) = 0.14 m/s^2 . This acceleration would be our best estimate of the air resistance correction to our measurement. Thus we would have a corrected acceleration of (9.67 + 0.14)m/s^2, for a result of 9.81 m/s^2.

Consumable Materials

Item	Quantity per lab group	Activity
aluminum cupcake cup for baking	1	2
cardboard or wooden box, 1 cu ft	1	3
cloth, lightweight, circular, 60-cm diameter	1	2
graph paper	several sheets	1
rope or twine	—	3
thread or light string	—	1, 2

Nonconsumable Materials

Item	Quantity per lab group	Activity
bicycle wheel with tire inflated normally	1	3
hair dryer with no heat setting or fan	1	1
meter stick or tape measure	1	2
spheres of various sizes and materials (iron, rubber, etc.)	4	1
spring scale (reading up to 20 newtons)	1	3
stopwatch	1	2
triple beam balance	1	3
weights, 100 g to 1 kg	—	3

Key to activities:
1. Air Resistance and Area
2. Air Resistance and Wind Velocity
3. Friction