Chapter 14

Fluids in Motion

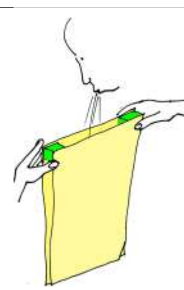
14.1 Fluids moving across surfaces—Qualitative analysis

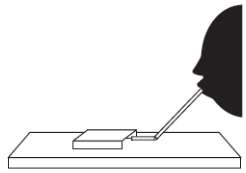
14.1.1 Observe and explain

PIVOTAL ***Lab or class:*** *Equipment per group:* sheets of paper, straws, empty soda cans, smooth desk surface.

In your group, conduct the experiments described below and observe what happens.

a. Then work with your group members to complete the table that follows.

Word description	**Sketch and identify a system.**	**Sketch a force diagram for the system. Include the force that the fluid exerts on the system on both sides.**
Hold two pieces of paper vertically, separated by two small blocks as shown in the sketch. Place your lips just above the sheets. Observe what happens if you blow hard between the sheets.	 The left paper is the system.	Immediately after you start blowing. Choose the left paper as the system and only consider horizontal forces.
Place two empty soda cans on a smooth table separated by about 1 cm (or you can place the cans on straws for a more dramatic effect). Blow hard between the cans.	 One of the cans is the system.	Immediately after you start blowing. Choose one can as the system.

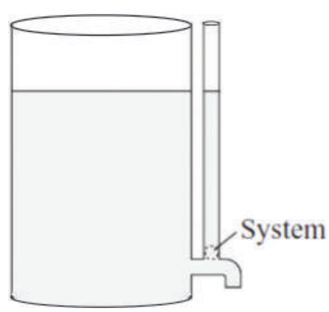
Fold a $5'' \times 8''$ index card into a U shape and place it on a level surface as shown in the sketch. Observe what happens to the card if you vigorously blow air through a straw under the card.	 The horizontal surface of card is the system.	Immediately after you start blowing hard. The top part of the card is the system and consider only vertical forces.

b. Develop an explanation for the observations in these three experiments. Think about how the pressure of a fluid against a surface changes as the speed of the fluid moving across the surface increases.

14.1.2 Test your idea

Lab or class:

You have an industrial-style coffeemaker. An open narrow tube in the front of the pot indicates the amount of coffee that remains.



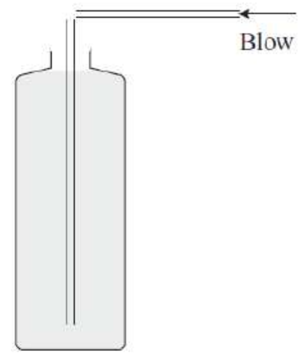
a. Apply the explanation devised in Activity 14.1.1b to compare the pressure of the coffee moving through the spigot (shown in the illustration) when the spigot is open and the pressure when the coffee is not flowing (the spigot is closed). Then, predict what happens to the level of the coffee in the tube when the coffee flows out of the spigot.

b. If you observe a similar coffeemaker, you will see that the level of coffee in the tube drops down when you open the spigot and stays down while the coffee is being poured. Then it goes up when the spigot is closed. Does this observation match your prediction? Explain.

14.1.3 Test your idea

***PIVOTAL* Lab:** *Equipment per group:* water bottles, straws.

Work with your group members to agree on a prediction about the experiment described below. Then perform the experiment and compare the outcome to your prediction.



Experiment: Insert a straight straw into a bottle filled near the top with water; the top of the straw should be near the top of the water.

a. Predict what happens when you blow hard through a second straw placed horizontally so that the airstream moves across the top of the vertical straw in the water. Explain how you made the prediction.

b. Perform the experiment and record your results. Reconcile any discrepancies between the results and your prediction.

14.1.4 Reading exercise

Read Section 14.1 in the textbook and answer Review Question 14.1.

14.2 Flow rate and fluid speed

14.2.1 Observe and explain

***PIVOTAL* Lab or class:** *Equipment per group:* syringe, water.

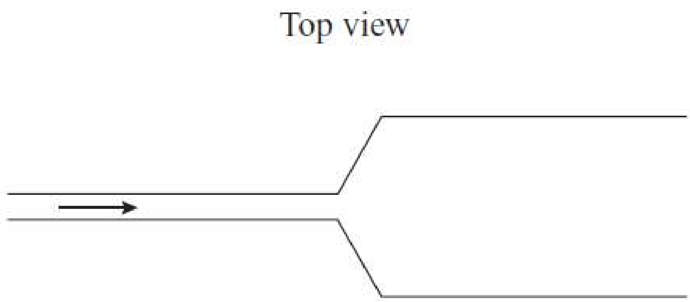
a. With your group members observe how a syringe works and record your observations. Focus your attention on the speed with which the piston is moving and the speed with which the water comes out of the syringe.

b. Explain the difference in the speeds.

14.2.2 Observe and explain

***PIVOTAL* Class:**

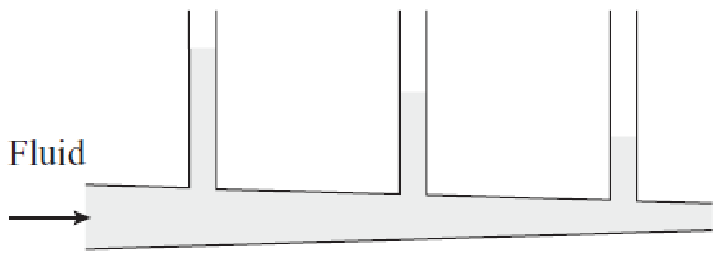
You kayak down a narrow and swift mountain river. As you approach a meadow, you notice that the river becomes much wider (as shown in the figure below) and that the speed of the water decreases. Explain why.



14.2.3 Represent and reason

PIVOTAL ***Lab or class:*** (lab if a Venturi tube is available, class if not)

Below you see a variation of an apparatus called a Venturi tube. Water flows through the horizontal tube and its levels in vertical tubes (where water is not moving) are as you see in the figure below. Work with your group members to discuss answers to the following questions:



a. Describe in detail what you observe.

b. Explain why it is happening.

c. What is the difference between the description and the explanation?

14.2.4 Reading exercise

Read Sections 14.1 and 14.2 and answer Review Questions 14.1 and 2.

14.3 Types of fluid flow

14.3.1 Derive

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

The goal of this activity is to derive the relation between the speed of the fluid through a tube and the cross-sectional area of the tube and the flow rate. The flow rate $Q = \Delta V / \Delta t$ of fluid through a tube is defined as the ratio of the volume ΔV of fluid passing a cross section in the tube and the time interval Δt needed for the fluid to pass.

a. Sketch a tube filled with a liquid as seen from the side and indicate a cross section in the tube.

b. Suppose that all of the fluid a distance Δx from that cross section passes the cross section in time interval Δt. How does the flow rate depend on the average speed of the fluid through the tube v and the tube's cross sectional area A?

c. Under what conditions is the flow rate the same in a subsequent part of the tube where the cross-sectional area is different?

d. How does the speed compare between a narrower part of the tube and a wider part? Explain.

14.3.2 Reading exercise

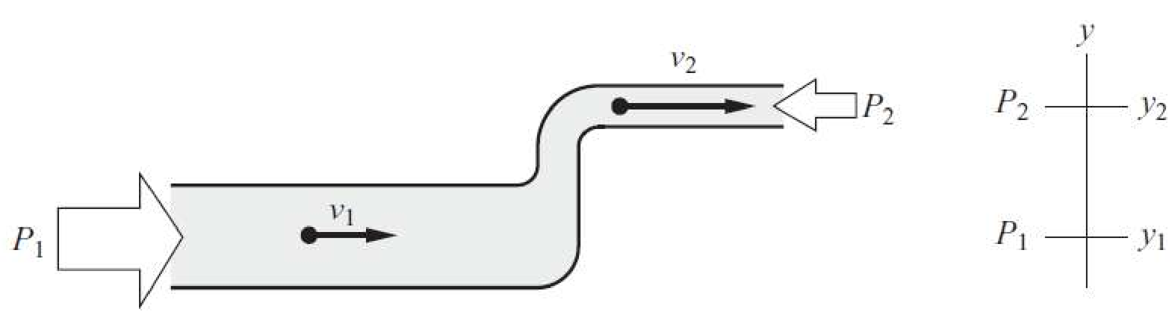
Read Section 14.3 and explain how a sphygmomanometer works.

14.4 Bernoulli's equation

14.4.1 Derive

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

Consider the tube carrying fluid shown below.



The shaded fluid and Earth are the system. Fluid at the left end of the tube (position 1) pushes toward the right with pressure P_1 and exerts a force $F_1 = P_1 A_1$. Fluid at the right end of the tube (position 2) pushes back toward the left with pressure P_2 and exerts a force $F_2 = P_2 A_2$. These two external forces do work on the system and cause its kinetic energy and the gravitational potential energy of the shaded fluid-Earth system to change.

a. Show that the fluid on the left pushing the shaded fluid forward a distance Δx_1 (the displacement on the left) does work $\Delta W_{\text{left}} = P_1 A_1 \Delta x_1 = P_1 \Delta V$, where A_1 is the cross-sectional area of the tube on the left and ΔV is the volume of fluid that has moved forward.

b. Show that the fluid on the right does work $\Delta W_{\text{right}} = -P_2\, A_2 \Delta x_2 = -P_2 \Delta V$. Note that Δx_2 is the distance the system fluid moves to the right.

c. Show that the fluid that has moved from the left side to the right side has mass $\rho \Delta V$ and has effectively changed elevation by $y_2 - y_1$. In other words, show that the change in gravitational potential energy is $\Delta U_{\text{g}} = \rho \Delta V g (y_2 - y_1)$.

d. Show that $\rho \Delta V$, the mass of fluid that has moved forward, has effectively changed kinetic energy by $\Delta K = (1/2) \rho \Delta V \left(v_2{}^2 - v_1{}^2\right)$.

e. Combine the results of parts **a.**–**d**. to show that:

$$P_1 - P_2 = (1/2)\rho\left(v_2{}^2 - v_1{}^2\right) + \rho g\left(y_2 - y_1\right)$$

Rearranging terms, we get:

$$(1/2)\rho v_1{}^2 + \rho g y_1 + P_1 = (1/2)\rho v_2{}^2 + \rho g y_2 + P_2$$

This is called *Bernoulli's equation*. Note that the sum of the kinetic energy density (kinetic energy of a unit volume of the fluid), the gravitational potential energy density (potential energy of a unit volume), and the pressure at position 1 equals the sum of these three terms at position 2.

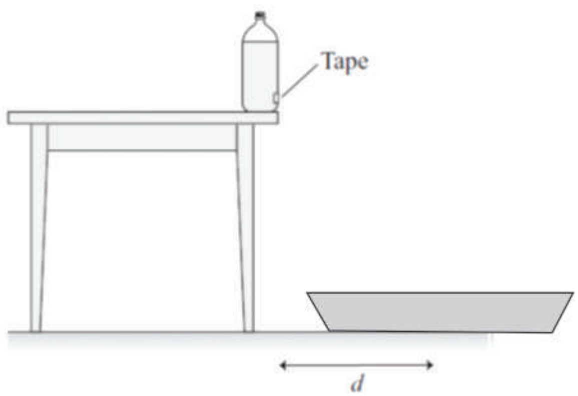
f. What assumptions about the structure and the flow of the fluid did you make while doing this derivation?

g. Explain how Bernoulli's equation relates to energy conservation and how you can use it to explain experiments in Activity 11.1.1.

14.4.2 Test your idea

***Lab:** Equipment:* a 2-L plastic bottle with a 4-mm-diameter hole on the side near the bottom (initially covered with tape), a wide container to collect water.

Fill the bottle with water and place it at the edge of a table, with the hole facing away from the table and toward the floor, as shown in the figure below. Use Bernoulli's equation to predict quantitatively the largest distance from the table's edge at which the water will reach the floor if you remove the tape and thus open the hole. (Make sure the top of the bottle is open.) Answer the questions below to make the prediction and to evaluate the result.



a. On the sketch, label quantities that you will measure and quantities that you will calculate. Measure the needed quantities and record them.

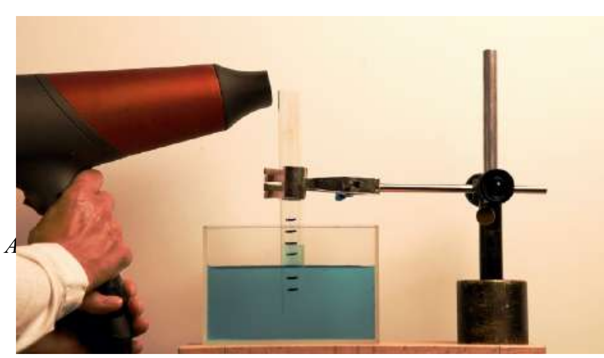
b. Outline a mathematical procedure to make the prediction. Then complete the procedure to predict where the water will reach the floor: Use Bernoulli's equation to find the speed of the water leaving the hole. Then use your knowledge of kinematics to calculate how far the water jet will travel horizontally.

c. List the assumptions you made and describe how they will affect the result.

d. Perform the experiment. Record the results and make a judgment about whether Bernoulli's equation applies to the water flowing out of the bottle.

14.4.3 Apply

***PIVOTAL* Lab or Class:** *Equipment per group:* whiteboard and markers.



The goal of this activity is to determine the same physical quantity using two different methods. The physical quantity is the speed of the air exiting a hairdryer. You can either repeat the experiments, described below, yourself and collect similar data or you can use the data provided below. After you determine the speed using two methods, compare the results. Are they the same or different? How certain are you in each of the values?

Experiment 1: Take a plastic tube and put it vertically into a container with water. The level of the water in the tube is the same as in the container. Then take a hairdryer, set it on cold, and blow cold air directly above the tube. The area of the cross section of the opening through which the air is blowing is $18\,\text{cm}^2$. You observe that the water in the tube rises 20 mm above the level of the water outside the tube (see the photo above).

Experiment 2: The same hairdryer fills a 200-L plastic garbage bag in 6 seconds (see the photo at right).

14.4.4 Reading exercise

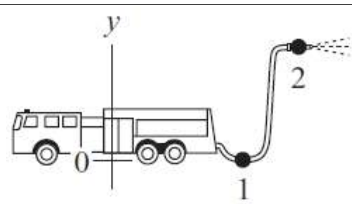
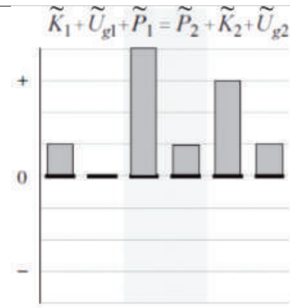
Read Section 14.4 and answer Review Question 14.4.

14.5 Skills for analyzing processes using Bernoulli's equation

14.5.1 Represent and reason

PIVOTAL ***Class:*** *Equipment per group:* whiteboard and markers.

In the table that follows, examine the consistency between the different representations for points 1 and 2 in the situation involving a moving fluid.

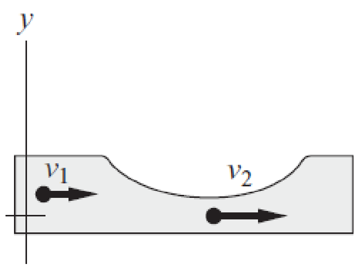
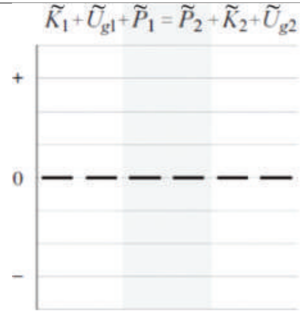
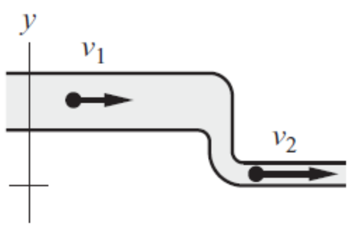
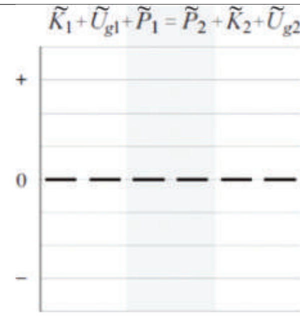
Words	**Sketch**	**Bernoulli bar chart**	**Bernoulli's equation applied**
A fire truck pumps water through a big hose up to a smaller hose on the ledge of a building. Water sprays out of the smaller hose onto a fire in the building.			$0.5\rho v_1^2 + P_1$ $= P_2 + 0.5\rho v_2^2 + \rho g y_2$

Are the different representations consistent with each other? Explain.

14.5.2 Represent and reason

PIVOTAL ***Class:*** *Equipment per group:* whiteboard and markers.

The sketches below represent two different processes. Fill in the table that follows to represent each process using a qualitative Bernoulli bar chart and the application of Bernoulli's equation (only include terms that are not zero). Compare the two points shown by dots in the fluid. Note that the velocity arrows in the sketches do not necessarily have the correct relative lengths.

Sketch	**Bernoulli bar chart**	**Apply Bernoulli's equation**
a. 		
b. 		

14.5.3 Bar-chart Jeopardy

Class: *Equipment per group:* whiteboard and markers.

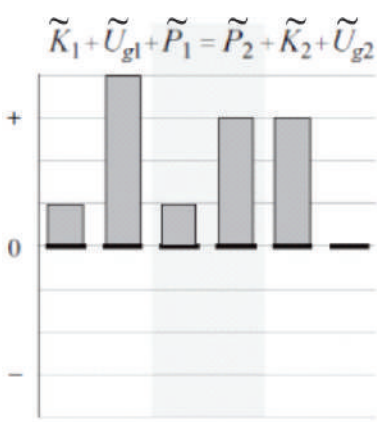
The qualitative Bernoulli bar charts below each represent a different fluid-flow process. For each:

a. Describe the situation in words.

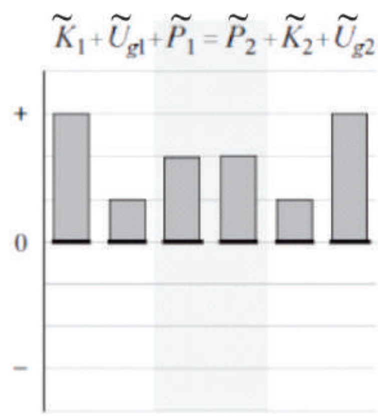
b. Sketch the situation.

c. Apply Bernoulli's equation.

1.



2.



14.5.4 Equation Jeopardy

PIVOTAL Class: *Equipment per group:* whiteboard and markers.

The application of Bernoulli's equation (in symbols) for two processes is shown below. For each:

a. Construct a consistent Bernoulli bar chart.

b. Draw a consistent sketch of a situation (there are many possibilities).

c. Describe the situation in words.

1. $0.5\rho v_1{}^2 + P_1 = P_2 + 0.5\rho v_2{}^2 + \rho g y_2$

2. $0.5\rho v_1{}^2 + P_1 = 0.5\rho v_2{}^2 + P_2$

14.5.5 Represent and reason

Class: *Equipment per group:* whiteboard and markers.

For the two situations described in words, represent the processes in other ways—sketches, qualitative Bernoulli bar charts, and the application of Bernoulli's equation to the processes. Be sure that the different representations are consistent with each other. Do not solve for anything.

Word description:

1. The average speed of blood in the aorta is 72 cm/s, and the average pressure is 1.3×10^4 N/m^2 above atmospheric pressure. The blood splits into about 10 large arteries, where blood flows at average speed of 20 cm/s. Ignore elevation changes.

2. The average speed of blood in the aorta is 1.0 m/s, and the average pressure is 1.3×10^4 N/m^2 above atmospheric pressure. The blood passes plaque with a reduced cross-sectional area in which it travels at an average speed of 10 m/s.

a. Sketch the process.

b. Construct a consistent Bernoulli bar chart for the process.

c. Apply Bernoulli's equation for the process.

14.5.6 Regular problem

***PIVOTAL* Class:** *Equipment per group:* whiteboard and markers.

Solve the problem below following the problem-solving strategy steps outlined in the table. Then compare your solution to the solution in the worked Example 14.2 in Section 14.5 of the textbook.

What is the speed with which water flows from a hole punched in the side of an open plastic bottle? The hole is 10 cm below the water surface.

Sketch and translate • Sketch the situation. Include an upward-pointing y-coordinate axis. Choose an origin and positive direction for the coordinate axis. • Choose points 1 and 2 at positions in the fluid where you know the pressure/speed/position or that involve the quantity you are trying to determine. • Choose a system.	
Simplify and diagram • Identify any assumptions you are making. For example, can we assume that there are no resistive forces exerted on the flowing fluid? • Construct a Bernoulli bar chart.	
Represent mathematically • Use the sketch and bar chart to help apply Bernoulli's equation. • You may need to combine Bernoulli's equation with other equations, such as the equation of continuity $Q = v_1 A_1 = v_2 A_2$ and the definition of pressure $P = F/A$.	
Solve and evaluate • Solve the equations for an unknown quantity. • Evaluate the results to see if they are reasonable (the magnitude of the answer, its unit, how the answer changes in limiting cases, and so forth).	

11.45.7 Regular problem

Class: *Equipment per group:* whiteboard and markers.

The large front yard $(30\ \text{m} \times 50\ \text{m})$ of a farmhouse is watered from an irrigation canal. An 8-in-diameter pipe runs from the canal to the yard. The horizontal pipe is 0.60 m below the water surface in the canal. What time interval is needed to fill the yard with 0.10 m of water? Describe all assumptions that you make.

11.45.8 Evaluate the solution

The problem: The surface of water in a community reservoir is 40 m above a 0.60-cm-radius hose connected to the faucet in your house. Assume that $g = 10\ \text{N/kg}$. What is the flow rate of water from the nozzle of the hose? What assumptions did you make?

Proposed solution: Choose point 1 at the top surface of the reservoir and point 2 at the nozzle of the hose. Use Bernoulli's equation to determine the speed v_2 of water leaving the nozzle:

$$\rho g y_1 + P_{\text{atm}} = P_{\text{atm}} + (1/2)\rho v_2^{\,2}$$

$$v_2 = 2\left(1000\ \text{kg/m}^3\right)\left(10\ \text{m/s}^2\right)(40\ \text{m})/\left(1000\ \text{kg/m}^3\right) = 800\ \text{m/s}$$

The flow rate from the hose will be:

$$Q = vA = (800\ \text{m/s})\left[\pi\,(0.06\ \text{m})^2\right] = 9.04047808\ \text{m}^3/\text{s}$$

a. Identify any errors in the solution.

b. Provide a corrected solution if there are errors.

11.45.9 Pose a problem

You are watering plants in your backyard. Pose a fluid dynamics problem that you can solve using a hose, a bucket, a watch with a second hand, and a mass-measuring scale.

14.6 Viscous fluid flow

14.6.1 Reading exercise

Read Section 14.6 in the book and compare and contrast Bernoulli's equation and Poiseuille's law.

14.6.2 Explain

Class:

Why is it important to know the Reynolds number when applying Poiseuille's law?

14.7 Drag force

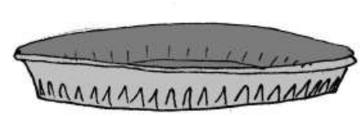
14.7.1 Reading exercise

Read Section 14.7 in the textbook and work through Example 14.7. Then answer Review Question 14.7.

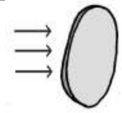
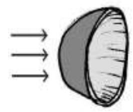
14.7.2 Apply

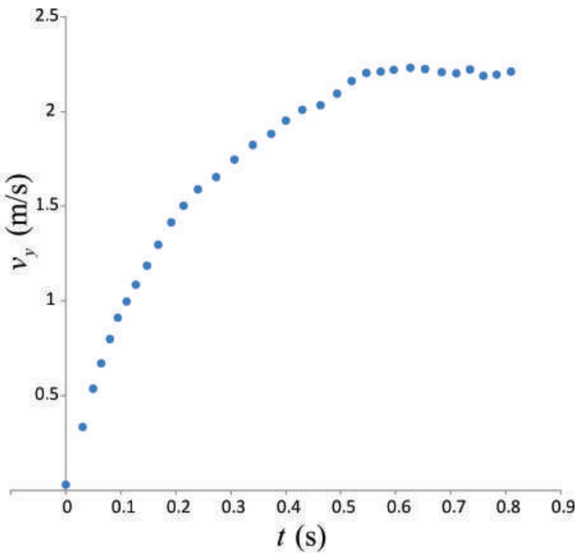
Class: *Equipment per group:* whiteboard and markers.

Work with your group members to apply your knowledge of the drag force.



Your friends from another group investigated how the speed of a 30-cm diameter aluminum pie pan, held horizontally, changes with time after it is released from about 2.0-m above ground. The sketch of the pie pan is on the right. Using a motion detector, they obtained the graph shown in the figure below. They Googled the values for the drag coefficient of different objects (see the table below). They measured the mass of the pie pan and found it to be 16 g. The task of your group is to decide whether it is reasonable to say that your friends' data are consistent with the following equation for a drag force $F_{\text{DF on P}} = \frac{1}{2} C_{\text{D}} v^2 \rho A$ (see the textbook, page 432). Explain how you made your judgment and to which part of the pie motion it refers. Indicate any assumptions that you made.

Thin circular plate, perpendicular to the flow		$C_D = 1.17$
Hollow hemisphere, facing flow		$C_D = 0.38$



a. Which feature of the graph allows you to determine the sum of the forces exerted on the pan at given time? Explain.

b. How does the drag force exerted by air on the pan change during the experiment?

c. How does the information about the sum of the forces and the speed help you find the force that Earth exerts on the pan?