Chapter 14

Fluids in Motion

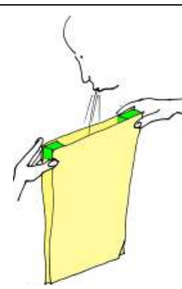
14.1 Fluids moving across surfaces—Qualitative analysis

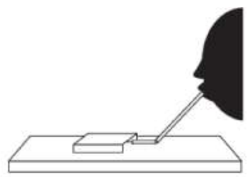
OALG 14.1.1 Observe and explain

Equipment: sheets of paper, straws, empty soda cans, smooth desk surface.

Conduct the experiments described below and observe what happens.

a. Complete the table that follows.

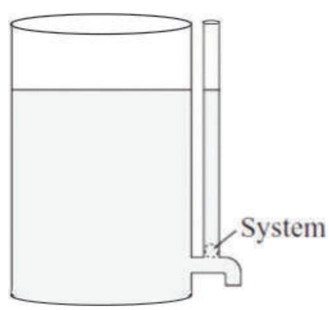
Describe in words	**Sketch and identify a system.**	**Sketch a force diagram for the system. Include the force that the fluid exerts on the system on both sides.**
Hold two pieces of paper vertically, separated by two small blocks as shown in the sketch. Place your lips just above the sheets. Observe what happens if you vigorously blow directly between the sheets.	 The left piece of 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). Observe what happens if you vigorously blow between the cans.		Immediately after you start blowing. Choose one can as the system.

	One of the cans is 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 and parallel to the card's top surface.	 The top horizontal surface of the card is the system.	Immediately after you start blowing vigorously. The top surface of the card is the system. Only consider 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 that surface increases.

OALG 14.1.2 Test your idea

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



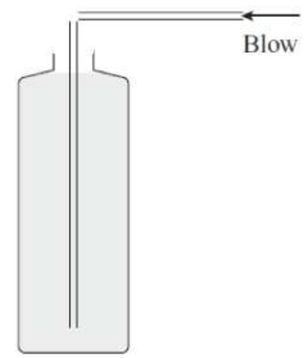
a. Apply the explanation that you devised in Activity 14.1.1b to compare the pressure of the coffee moving through the spigot (shown in the illustration) when the spigot is open and the pressure when the coffee is not flowing (the spigot is closed). Then, predict what happens to the level of the coffee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

OALG 14.1.3 Test your idea

Equipment: water bottles, straws.

Use the ideas that you devised in Activities 14.1.1 and 14.1.2 to make 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 nearly to the top with water; the top of the straw should be just above 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 your prediction.

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

OALG 14.1.4 Read and interrogate

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

OALG 14.1.5 Practice

Answer Questions 1-3 on page 435 in the textbook.

14.2 Flow rate and fluid speed

OALG 14.2.1 Observe and explain

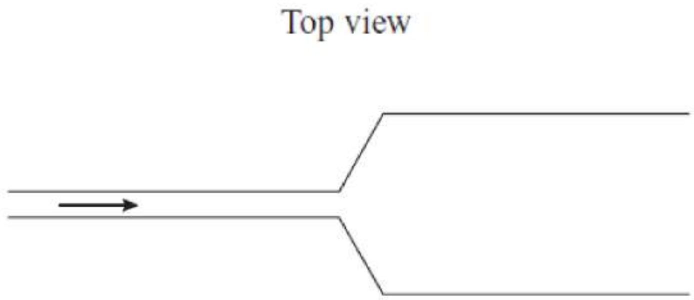
Equipment: syringe, water.

a. 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 is ejecting from the syringe.

b. Explain the difference in these speeds.

OALG 14.2.2 Observe and explain

You are kayaking 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.



OALG 14.2.3 Derive

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 a 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 that same cross section.

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?

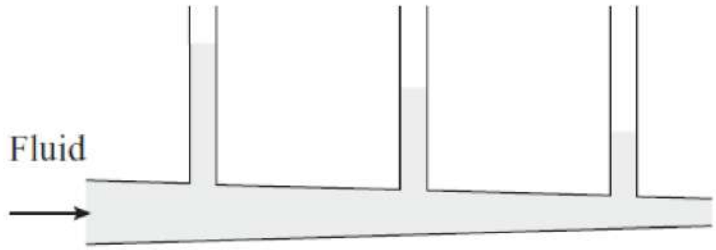
c. Under what conditions is the flow rate the same in a subsequent part of the tube where the cross-sectional area is different?

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

e. Read and interrogate Section 14.2. Explain how Figure 14.3 is relevant to this derivation.

OALG 14.2.4 Represent and reason

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. Answer the following questions:



a. Describe in detail what you observe.

b. Explain what you observe.

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

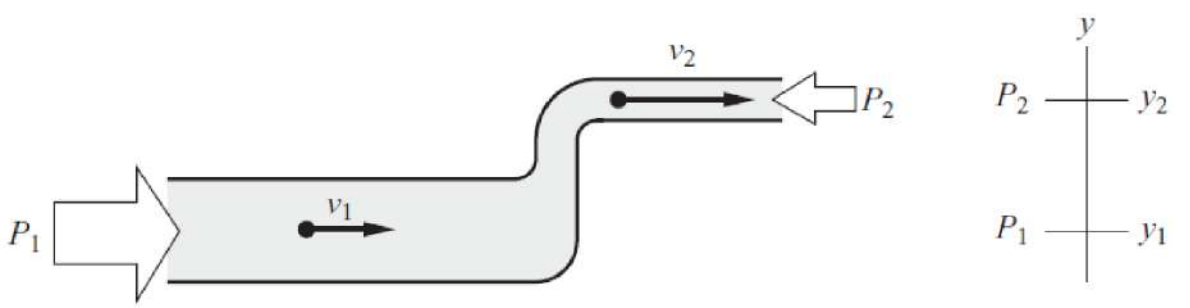
OALG 14.2.5 Practice

Solve Problems 1-3 on page 436 in the textbook.

14.4 Bernoulli's equation

OALG 14.4.1 Derive

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 $F_1 = P_1A_1$ on the shaded region. Fluid at the right end of the tube (position 2) pushes back toward the left with pressure P_2 and exerts a force $F_2 = P_2A_2$ on the shaded region. These two external forces do work on the system and cause its kinetic energy and the gravitational potential energy 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 that the fluid system 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?

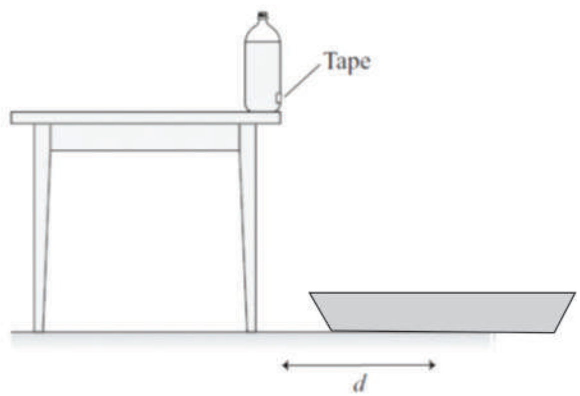
g. Explain how Bernoulli's equation relates to energy conservation and how you can use it to explain experiments in Activity 14.1.1.

h. Compare your work to the derivation in Section 14.4 in the textbook. Draw an energy density bar chart for the process of fluid flow used in the derivation

OALG 14.4.2 Test your idea

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, a ruler or another distance measuring instrument.

Fill a 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 your prediction and to evaluate your result.



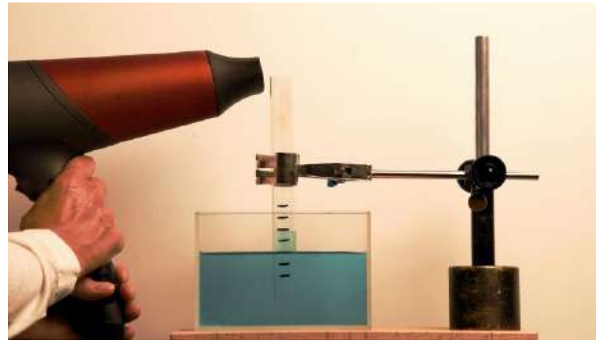
a. On the sketch, label physical quantities that you will measure and physical quantities that you will calculate. Measure the needed quantities and record them.

b. Outline a mathematical procedure to make your 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. If you are having difficulties, consult Example 14.2 on page 424 in the textbook.

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

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

OALG 14.4.3 Apply



Equipment: a hairdryer, a large plastic bag, a plastic tube (you can use a wide straw), a stopwatch, a ruler.

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 these two methods, compare your results. Are they the same or different? How certain are you in each of your 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).

OALG 14.4.4 Read and interrogate

Read and interrogate Section 14.4 and answer Review Question 14.4.

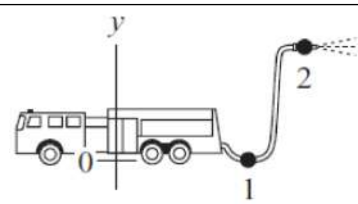
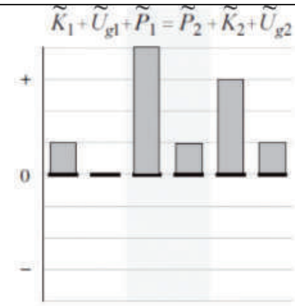
OALG 14.1.5 Practice

Answer Question 9 on page 435 in the textbook and solve Problems 7-12 on page 437 in the textbook.

14.5 Skills for analyzing processes using Bernoulli's equation

OALG 14.5.1 Represent and reason

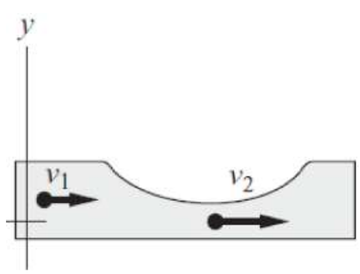
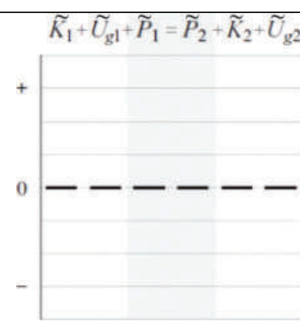
In the table that follows, examine the consistency between the different representations for points 1 and 2 in the situation involving a moving fluid.

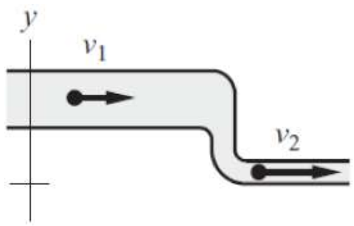
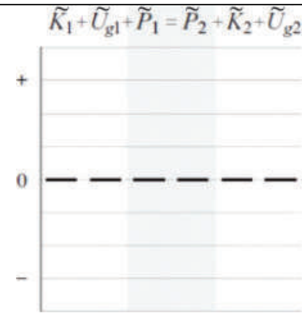
Verbal representation	**Sketch**	**Bernoulli bar chart**	**Application of Bernoulli's equation**
A fire truck pumps water through a big hose up to a smaller hose on the ledge of a building. Water sprays out of the smaller hose onto a fire in the building.			$0.5\rho v_1^{\,2}+P_1$ $=P_2+0.5\rho v_2^{\,2}+\rho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

Are the different representations consistent with each other? Explain.

OALG 14.5.2 Represent and reason

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 non 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. 		

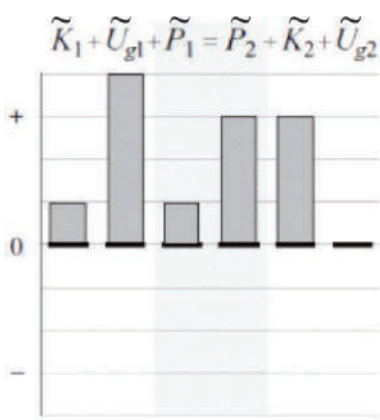
OALG 14.5.3 Bar-chart Jeopardy

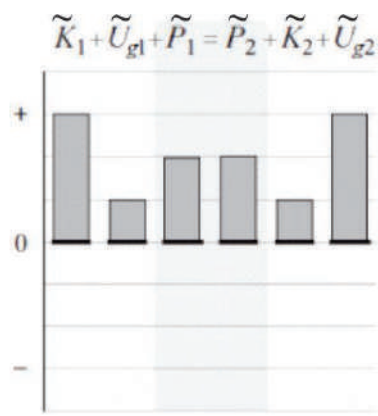
The qualitative Bernoulli bar charts below each represent a different fluid-flow process. For each:

a. Describe the situation in words.

b. Sketch the situation.

c. Apply Bernoulli's equation.

1. 

2. 

OALG 14.5.4 Equation Jeopardy

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

OALG 14.5.5 Represent and reason

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 $1.3\times 10^4\text{ N/m}^2$ above atmospheric pressure. The blood splits into about 10 large arteries, where blood flows at an 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 $1.3\times 10^4\text{ N/m}^2$ 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.

OALG 11.5.7 Regular problem

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.

OALG 11.5.8 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 the 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 the water leaving the nozzle:

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

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

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.

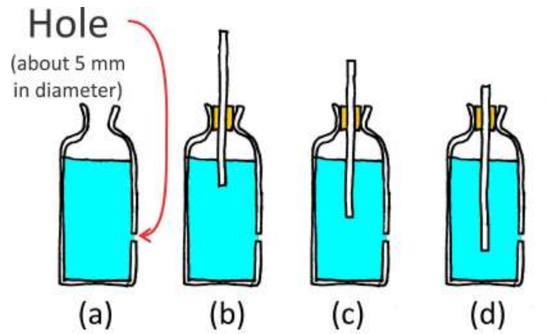
b. Provide a corrected solution if there are errors.

OALG 14.5.9 Apply

Equipment: A half-liter bottle, a large nail and a candle (to heat the nail), modeling clay, a straw, and a tray to collect water.

a. Heat up the nail and make a 5-mm hole in the bottle as shown in part (a) of the figure below. Prepare modeling clay to close the bottle opening and place the straw through it, but do not close the bottle yet.

b. In as much detail as possible, predict what will happen in the 4 experiments shown in the figure below. Note that the mouth of the bottle is open in part (a), in part (b), the bottle is sealed with clay and the bottom of the straw is significantly above the hole; in part (c), the straw is lowered, but its bottom is still above the hole (slightly); in part (d), the bottom of the straw is below the hole. For each of your predictions, use Pascal's and Bernoulli's laws, and your knowledge of atmospheric pressure and projectile motion. Consider additional assumptions that you might need to make.



c. Perform the experiments (do not forget to put the tray under the bottle to collect any water that will come out) and record the outcomes. Draw pictures if necessary.

If you did not have the necessary equipment to make the bottle, watch the experiments at https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-OALG-14-5-9.

d. Compare the outcomes to your predictions. Do you need to examine the assumptions? Or make any other revisions?

OALG 14.5.10 Practice

Solve Problems 21, 22, 27, 37, and 48 on pages 437-439 in the textbook.

14.6 Viscous fluid flow

OALG 14.6.1 Read and interrogate

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

OALG 14.6.2 Explain

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

14.7 Drag force

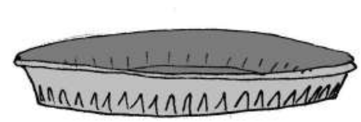
OALG 14.7.1 Read and interrogate

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

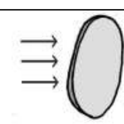
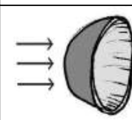
OALG 14.7.2 Practice

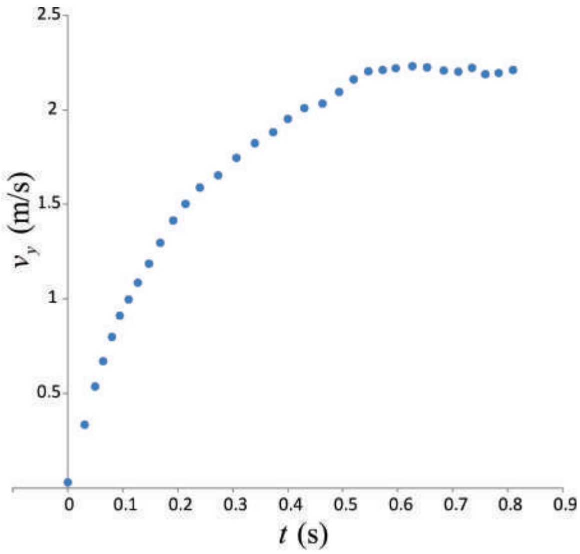
Work with Example 14.7 on page 433 in the textbook to learn how to approach multiple possibility problems. First, try to solve the problem yourself, and then compare your solution to the one in the textbook.

OALG 14.7.3 Apply



Your friends from another class 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. Your task is to decide whether it is reasonable to say that your friends' data are consistent with the following relation 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		$C_{\text{D}} = 1.17$
Hollow hemisphere, facing flow		$C_{\text{D}} = 0.38$



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