Chapter 3

Newtonian Mechanics

3.1 Describing and representing interactions

3.1.1 Observe and represent

***PIVOTAL* Lab or class:** *Equipment per group:* whiteboard and markers, 1 medicine ball (alternative: bowling ball), 1 basket ball (alternative: volley ball, or a kid's inflatable rubber ball with similar size to a bowling/medicine ball).

Each member of the group while standing: hold medicine ball in one hand and a basketball ball in the other hand (make sure you hold the medicine ball first and then follow up with the basketball). Focus on what you need to do to hold each ball still. The goal of this activity is to learn to draw a new representation called a "force diagram." Do this on a piece of paper or on a small whiteboard with your group. Share your ideas with each other.

a. Centered at the top of your page/whiteboard, draw a sketch of a person standing on the ground, holding the balls, one in each hand. To draw a force diagram, you first need to identify systems/objects of interest. In this case, each ball is a system or an object of interest. Draw a circle around each ball to signify this. Divide the rest of your page/whiteboard into a left column for one ball and a right column for the other.

b. The next question you need to ask yourselves is what other objects are interacting with each system/object of interest? So in this case, what other objects are interacting with each ball? If you are stuck, discuss the following: What do you think would happen to the ball if your hand were the only object interacting with it? List the objects interacting with each ball at the top of that ball's column.

c. Drawing the force diagram: Below your lists of interacting objects, leaving enough space, draw a dot that represents each ball as a point-like object. On each dot draw an arrow to show how your hand pushes on the ball. Let the tail of the arrow start at the dot. This arrow represents the force that your hand exerts on the ball. How could you label this force arrow to show that it is the force your hand exerts on the ball? Add this label to your representation for each ball.

d. Repeat this for the other interactions you identified. Represent these interactions on the force diagrams. Try to make the lengths of the force arrows in the two diagrams representative of the relative magnitudes of the forces. The arrows on the force diagram represent force vectors, physical quantities that have both magnitude and direction.

e. Discuss with your group: The word "force" is used in physics for a physical quantity that characterizes the interaction between two objects. A single object does not have a force because a force is defined as the interaction of two objects. Using the definition of a force in physics, give three examples from everyday life when the use of the term force does not match the meaning of this word in physics.

(a) "May the force be with you." (b) Your mother exerts a positive force on your life. (c) They crashed into each other with a lot of force.

3.1.2 Test your idea

Class or lab: *Single demo setup:* Bell jar and vacuum pump large enough to accommodate a 2L soda bottle, empty 2L soda bottle. Light spring (k = 3N/m or 6N/m), ruler taped to outside of bell jar. [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-1-2]

a. In the previous activity, did your group decide that air interacts with the ball?

b. If yes, do you think that the total force that the air exerts on the ball points up or down?

c. Discuss with your group members what experiment(s) can you perform to test your idea about whether the air pushes up or down on the ball. Describe the experiment(s) and state the predictions of what should happen if the air pushes up/down on the ball.

d. If the equipment that you need for the experiment is available, conduct the experiment and record the outcome. Did it match the prediction? If not, revise your thinking about how air interacts with stationary objects. If the equipment is not available, read the description of the outcome of a possible experiment on page 53 in the textbook.

Use the text on page 53 in the textbook to guide the discussion here.

3.1.3 Read and analyze

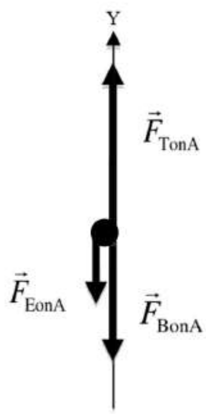
Work through Conceptual Exercise 3.1 on page 54 in the textbook, do the *Try it yourself* example, and compare your solution to the solutions of your group members. Revise your work if necessary.

Work through Conceptual Exercise 3.1 on page 54 in the textbook, do the *Try it yourself* example,

a. *The system/object of interest is book A.*

b. *Book B pushes down on A, Earth pulls down on A, and the table surface pushes up on A. Notice that book C does not interact with A (is not touching it).*

c. *A dot represents A. Two arrows with their tails at the dot point down and one arrow with its tail at the dot points up. The force diagram for A is shown below.*

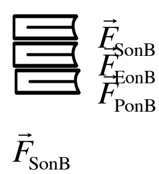


3.1.4 Reason

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

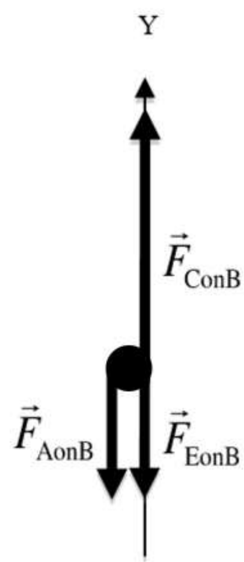
You stack three identical books on a table. Book A is on the top, book B in the middle, and book C on the bottom.

a. Sketch the situation.



b. Choose book B as the system/object of interest for a force diagram. Carefully draw a closed dashed line around book B to indicate that it is the system—your whole focus of attention. The top of the line should go between the top of book B and the bottom of book A. The bottom of the line should go between the bottom of book B and the top of book C. This is very important as it allows you to visualize what external forces to include in a force diagram for the system (book B in this case).

c. Below the sketch, construct a force diagram for book B. Remember in the force diagram to model the system as a point-like object, to include force vectors representing how each object outside the system (external objects) interacts with the system, and to label each vector on the force diagram with a force symbol that includes two subscripts (the first for the object that exerts the force on the system and the second for the object/system on which that force is exerted). For example, the force that book A exerts on book B can be written as $\vec{F}_{\text{A on B}}$. Try to make the lengths of the force arrows representative of the relative magnitudes of the forces.



d. Discuss: If you added all the vectors on your force diagram together, what should be the combined result? Adjust the lengths of the different vectors on your force diagram if needed.

3.1.5 Reading exercise

Read Section 3.1 in the textbook and answer the Review Question 3.1.

3.2 Adding and measuring forces

3.2.1 Observe and find a pattern

***PIVOTAL* Lab version:** *Equipment per group:* A spring scale, a platform scale (calibrated in newtons) and an object that you can hang on the spring scale.

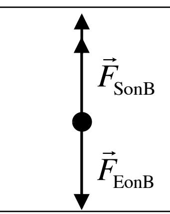
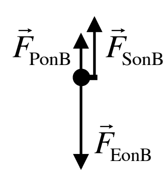
Design an experiment to investigate the relationship between the forces that the platform scale and the spring scale exert on the object when they are both supporting the object and the object is at rest. Describe the pattern in words and mathematically using your knowledge of vectors.

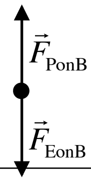
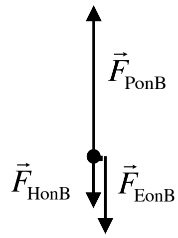
***PIVOTAL* Class version:** *Equipment per group:* whiteboard and markers

Your goal is to investigate the relationship between the forces that the platform scale and the spring scale exert on the object when they are both supporting the object and the object is at rest. Describe the pattern in words and mathematically using your knowledge of vectors. With your group, conduct the experiments described in the first column of the table and fill in the empty cells.

3.2.1 Observe and find a pattern

Hang the object from the spring scale and lower it so supported in part by the platform scale and the spring scale. The sum of the two scale readings should equal Earth's force on the object.

Experiment	**List the objects interacting with the 1-kg block of interest.**	**Draw a force diagram for the 1-kg block.**	**Discuss the relationship between the direction(s) and magnitudes(s) of the vectors on your force diagram.**
(a) You hang a 1-kg block from a string attached to a spring scale; the scale reads 9.8 N.	*Spring scale and Earth*		*They add to zero.*
(b) You lower the block onto a platform scale. The spring scale reads 6.0 N, the platform scale reads 3.8 N.	*Spring scale, platform scale, and Earth*		*They add to zero.*

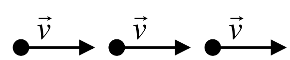
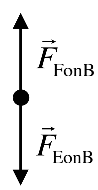
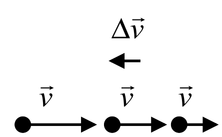
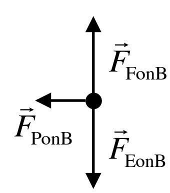
(c) You remove the spring scale and leave the block on the platform scale; it reads 9.8 N.	*Platform scale and Earth*		*They add to zero*
(d) You press down on the block on the scale with your hand. The platform scale reads 16.8 N.	***Platform scale, Earth and hand***		*Your hand must be exerting a 7.0 N force so all the forces add to zero.*

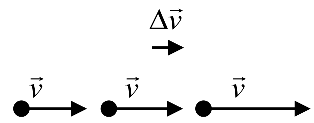
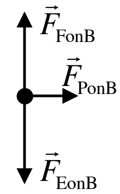
3.2.2 Reading exercise

Read Section 3.2 in the textbook and explain the title of the section, in other words why is the method of measuring forces based on their addition?

3.3 Conceptual relationship between force and motion

3.3.1 Observe and find a pattern

Observational experiment	**Analysis**	
	Motion diagram	**Force diagram**
Experiment 1. A bowling ball rolls on smooth floor in a straight line.	$\Delta\vec{v} = 0$ 	
Experiment 2. Push the moving bowling ball very lightly in the direction opposite to the direction of the ball's motion trying to exert a constant push.		

<table>
<tr><td>Experiment 3. Continuously push the bowling ball exerting a constant light push in the direction the ball is moving.</td><td>
</td><td>
</td></tr>
<tr><td colspan="3">Patterns
The $\Delta\vec{v}$ arrow on the motion diagram and the vector sum of the forces exerted on the ball are in the same direction.</td></tr>
</table>

3.3.2 Observe and find a pattern

Class or lab: *Equipment per group:* 1 small ball.
[https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-3-2]

You need a golf ball or any small ball for this activity. With your group members perform each experiment described below. Then construct a motion diagram and a force diagram for the ball's motion during each experiment. Based on our investigation in Activity 3.1.2, you can ignore any force or forces that the air might exert on the ball.

a. Throw a golf ball upward. Observe its motion *after* it leaves your hand until it reaches the top of its flight. For details, see the video (use the above link).

b. Hold a golf ball using your straight arm raised up and drop it. Observe its motion *after* it leaves your hand until just before it hits the floor.

c. Examine the results of both experiments. Is there the same pattern in the directions of the sum of the forces that other objects exert on the ball and in the directions of the $\Delta\vec{v}$ arrows on the motion diagram as in the previous activity? If so, describe the patterns.

When the ball is going up, the $\Delta\vec{v}$ *arrow points down, when the ball is moving down, the* $\Delta\vec{v}$ *arrow points down too.*

d. Use the patterns that you found in Activity 3.3.1 and in this activity to formulate a statement relating the direction of the sum of the forces exerted on an object by other objects and on one or more of the kinematics quantities that describe its motion.

As when the ball is going up the down there is only one object interacting with it (if we neglect air), Earth, and the force exerted by Earth on the ball always points down, so does the $\Delta\vec{v}$ *arrow on the motion diagram.*

3.3.3 Test an idea

***PIVOTAL* Lab:** *Equipment per group:* 1 bowling ball, multiple sugar packets, stopwatch (alternative: cellphone app.), 1 meter stick, 1 mallet

Shawn says that an object always moves in the direction of the sum of the forces exerted on it by other objects. Jade says that an object's $\Delta\vec{v}$ arrow on the motion diagram is always in the direction of the sum of the forces exerted on it by other objects. How can you decide who is right? You need to test both ideas. To test them:

a. Work with your group members to design an experiment whose outcome you can predict using both ideas. The predictions about the outcome of the same experiment based on two ideas need to be different in order to help you make the decision. Think of what additional assumptions you used in the predictions (an assumption is something that you accept as true.)

Possible experiments: (i) throw an object as a projectile; (ii) use an air track and a cart that is already in motion, (iii) lift an object hanging on a spring scale and observe the reading when the object slows down to a stop.

b. Draw sketches of the experiments and show clearly how the predictions are based on the ideas under test.

Experiment	*Jade's prediction*	*Shawn's prediction*
i	*The sum of the forces points down, thus the object will accelerate down, but as it is already moving when we released it, it will change its motion so that the* $\Delta\vec{v}$ *arrow on the motion diagram points down but it should not move down right away.*	*The ball should start moving down the moment we released it.*
ii	*The sum of the forces exerted on the cart is zero, thus, once in motion, it should move at constant velocity*	*As the sum of the forces is zero, the cart should stop if nobody pushes it.*
ii	*When the object slows down to a stop while going up, the* $\Delta\vec{v}$ *arrow points down, thus the sum of the forces points down, therefore the scale should read less when the object is slowing down while going up than when it is going up at constant speed or speeding up.*	*The object is going up, thus the sum of the forces exerted on it should be up and there fore the scale should read more.*

c. Perform the experiment and record the outcome. What can you say about the ideas? What can you say about your assumptions?

The outcomes matched predictions based on Jade's hypothesis not Shawn's. We can reject it.

3.3.4 Reading exercise

Now that you have done the activities, read Section 3.3 in the textbook and answer the following question: Alan says that a prediction is an educated guess, Eugenia says that a prediction is the same as a hypothesis, it explains some observed phenomenon, and David says that a prediction is a description of an outcome of a specific experiment. Use Testing Experiment Table 3.2 to resolve the argument and give examples of the predictions from this table that refute Alan's and Eugenia's ideas.

Based on the reasoning shown in table 3.2 a prediction is the description of the outcome of a specific testing experiment. The prediction should be based on the hypothesis that one is testing. A hypothesis is some general statement inferred from the patterns in the data collected during an observational experiment. In the table the predictions describe the blinking pattern on a photo taken during a specific experiment.

3.3.4 Test an idea

PIVOTAL ***Class or lab:*** *Equipment per group:* whiteboard and markers,10 N spring scale, 500 g object.

An elevator starts at rest at the first floor of a building and stops at the top floor. The elevator then returns to the first floor. You decide to test the following idea: an object's $\Delta\vec{v}$ arrow on its motion diagram is always in the direction of the sum of the forces exerted on it by other objects. You do this by hanging a 500 g object from a spring scale while riding the elevator up and back down again. Complete the table that follows to determine the relative magnitude of the force that the spring scale exerts on the object, $F_{\text{S on O}}$, compared to the force that Earth exerts on the object, $F_{\text{E on O}}$. The motion diagram and the force diagram should be consistent with each other and with the rule you're testing relating motion and forces. Predict, for each of the following seven phases of the motion, whether the spring scale will read more than $F_{\text{E on O}}$, the same as $F_{\text{E on O}}$, or less than $F_{\text{E on O}}$.

a. The elevator and object hang at rest at the first floor.

b. The elevator and object start moving upward, going faster and faster.

c. The elevator and object move upward with a constant speed.

d. The elevator and object slow down as they approach the top floor.

e. The elevator and object start moving downward, going faster and faster.

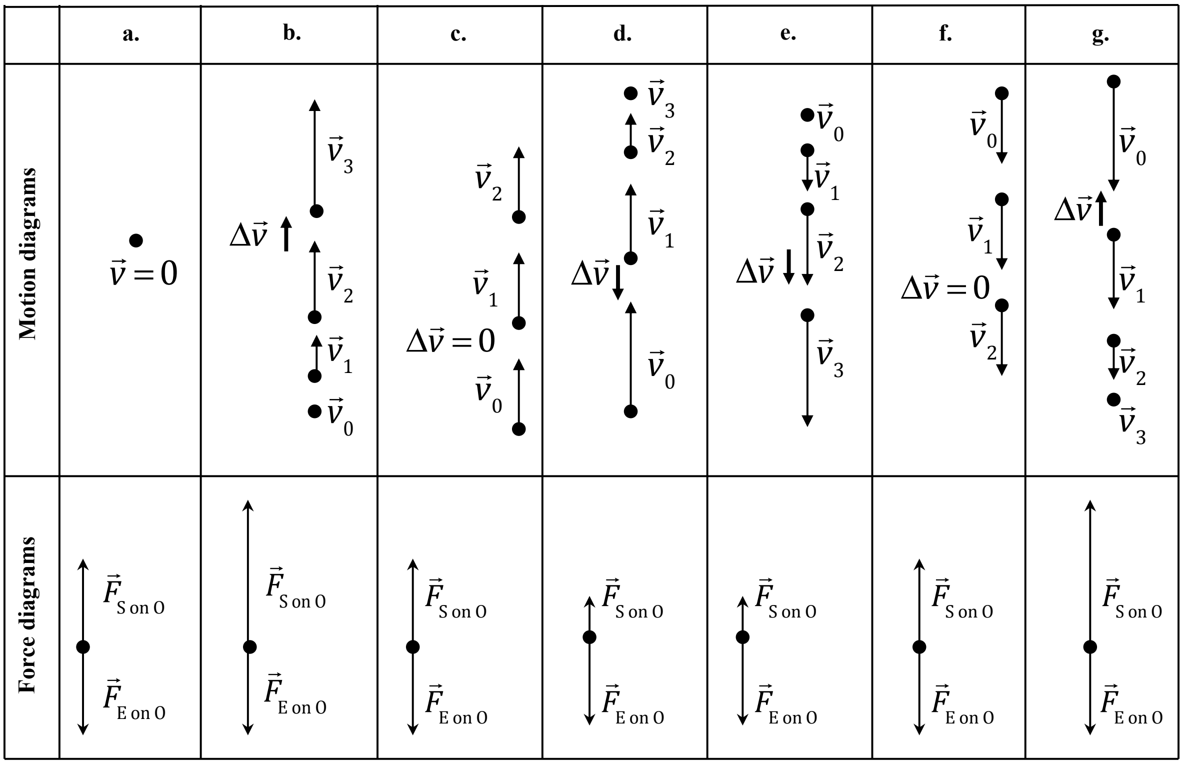
f. The elevator and object move downward with a constant speed.

g. The elevator and object slow down as they approach the first floor and come to a stop.

	a.	**b.**	**c.**	**d.**	**e.**	**f.**	**g.**
Motion diagram							
Force diagram							

Now, with your group members, take a 500 g object and a spring scale and perform the experiment. If it helps, use your phone to video the spring scale reading as the elevator is moving.

Solution:



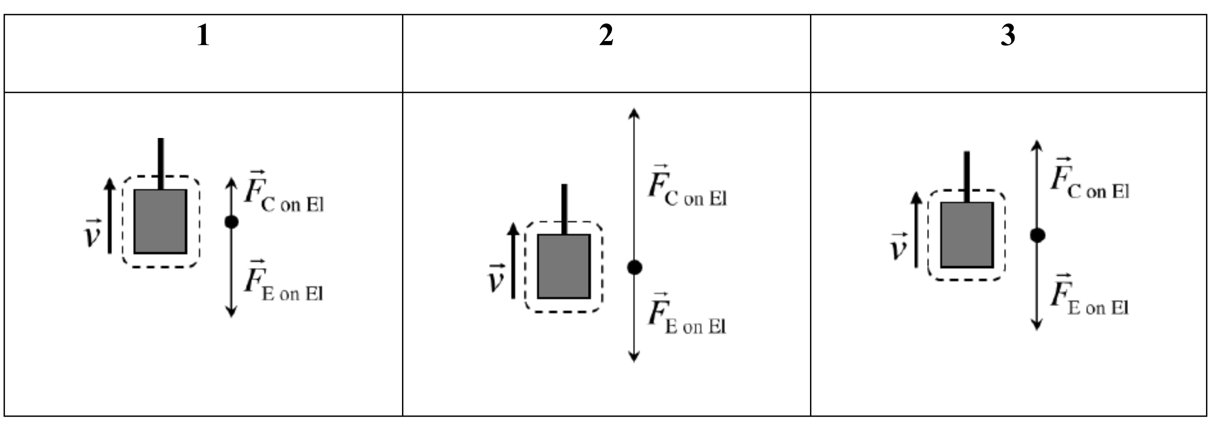
3.3.5 Represent and reason

Class: *Equipment per group:* whiteboard and markers

Below you see three different situations and the corresponding force diagrams for a circled system (an elevator) in each situation.

a. For each situation, describe the motion of the elevator in words and draw a motion diagram.

b. Consider: How can you make sure the motion of the elevator is consistent with the given force diagram? (Hint: what is the direction of the sum of the forces in each force diagram?)



***a. (1)** The upward moving elevator is slowing down (the delta v arrow is down).*

(2) The upward moving elevator is speeding up (the delta v arrow is up).

(3) The elevator is moving up at constant speed (the delta v arrow is zero).

***b**. Note that the velocity change vectors in each motion diagram are consistent with the directions of the net force in the force diagrams.*

3.3.6 Observe and analyze

***PIVOTAL** **Class or lab:** Equipment per group:* whiteboard and markers, medicine ball. [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-3-6]

A friend drops a medicine ball so that it falls straight down. You catch it. Consider the motion of the ball from the instant it touches your hands (when the ball's downward speed starts to decrease) until the instant it stops (your hands have moved down with the ball while stopping it).

a. Sketch the process for an instant during time interval from the instant the ball touches your hands until the instant it stops. Choose the ball as the object of interest.

b. Construct a motion diagram for the stopping process.

See Figure 3.6 in the textbook

c. Construct three force diagrams for the ball for three different instants during the slowing down motion. Be sure each force diagram is consistent with the motion diagram.

Use the force diagram in Figure 3.6 in the textbook, for three instances when the ball is slowing down the force the your hands exert on the ball is always larger than the force exerted on the ball by Earth but the difference in lengths can be different at different instants.

d. Which object exerts a greater force on the ball as you are stopping it – you or Earth?

You, as the sum of the force should point up at all three instances.

3.3.7 Evaluate

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

Ulani is solving a physics problem involving a paratrooper, whose parachute did not open, landing in a deep snow bank. He sinks about one meter into the snow while stopping. Ulani draws the (unlabeled) force diagram shown on the right and says, "this force diagram could represent a paratrooper moving downward into the snow bank." José disagrees. Looking at the force diagram he says "the way you've drawn the force diagram, the paratrooper *cannot* be moving downward. He *must* be moving upward because the force pointing up is bigger than the force pointing down."

a. Correctly label the force diagram.

We can label the downward force as $F_{\text{E on P}}$ and the upward force as $F_{\text{S on P}}$.

b. Who do you agree with and why? For the person you disagree with, how would you convince them that they are incorrect?

I agree with Ulani. In a motion diagram for the paratrooper while sinking into the snow, the velocity change arrow is up. Hence the upward force exerted by the snow must be greater in magnitude than the downward force exerted by Earth.

3.4 Inertial reference frames and Newton's first law

3.4.1 Represent and reason

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

Imagine you're sitting on a stationary train and your friend is standing on the platform looking through the window. On the table in front of you is a tennis ball. The train starts to pull away from the station, speeding up as it does so. Draw motion and force diagrams for the ball as observed **a.** by you and **b.** by your friend as the train starts to accelerate. Remember the rule for force diagrams: A force describes an interaction between two objects. If you can't identify the object that is exerting a force on the object of interest, you can't put it in the force diagram!

	Motion diagram	**Force diagram**
a. For the ball, as observed by you on the train, i.e., draw the diagrams as seen in your reference frame.		
b. For the ball, as observed by your friend on the platform. i.e., draw the diagrams as seen in your friend's reference frame.		

For motion and force diagrams see similar sketches in Observational Experiment Table 3.3 in the textbook.

Discuss with your group: Is there a reference frame in which the force and motion diagrams are inconsistent with the rule you've just developed relating force and motion diagrams? What do you think is the characteristic of this reference frame that makes the force and motion diagrams inconsistent with each other? Think of other examples of reference frames in everyday life where the motion and force diagrams for an object in that reference frame are inconsistent with the rule you've developed. Should you discard the rule you've developed? Or (more preferably) come up with a statement (called an "assumption") about when the rule will and won't work.

In the accelerating reference frames the rule connecting force motions and motion diagrams does not work. When we want to use the rule to describe and explain the motion of an object we must validate the assumption that the observer is not accelerating.

3.4.2 Reading exercise

Read Section 3.4 in the textbook and answer Review Question 3.4.

3.5 Newton's second law

TIP In all experiments and problems, you should focus your attention on the forces exerted by other objects on the object of interest (the system), not on forces that the system exerts on other objects. Only forces exerted on the system are drawn on force diagrams.

3.5.1 Observe and find a pattern

PIVOTAL ***Class or lab:*** *Equipment per group:* whiteboard and markers, laptop computer.

Analysis of video experiment 1	
Acceleration (m/s^2)	Net force (N)
0.38	0.2
0.74	0.3
1.67	0.5

Watch (video experiment 1, [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-5-1a]) and (video experiment 2, [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-3-5-1b])

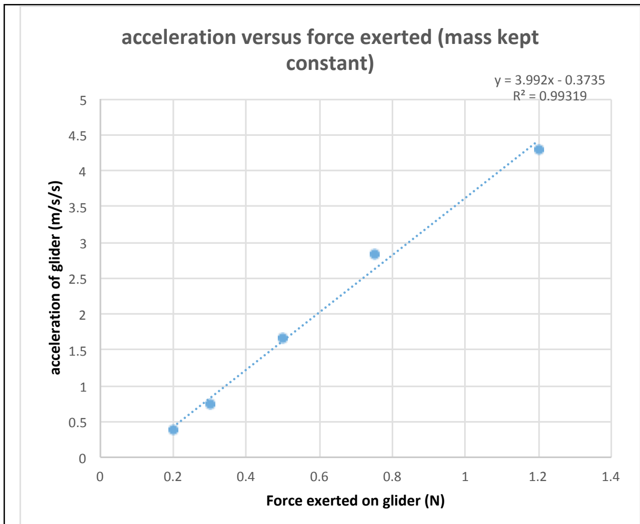
2.8	0.75
4.3	12
Analysis of video experiment 2	
Acceleration (m/s^2)	Mass (kg)
0.27	0.56
0.20	0.76
0.15	0.96
0.13	1.16
0.10	1.36

a. On a whiteboard, draw a force diagram for the cart in Experiment 1 and another for the cart in Experiment 2.

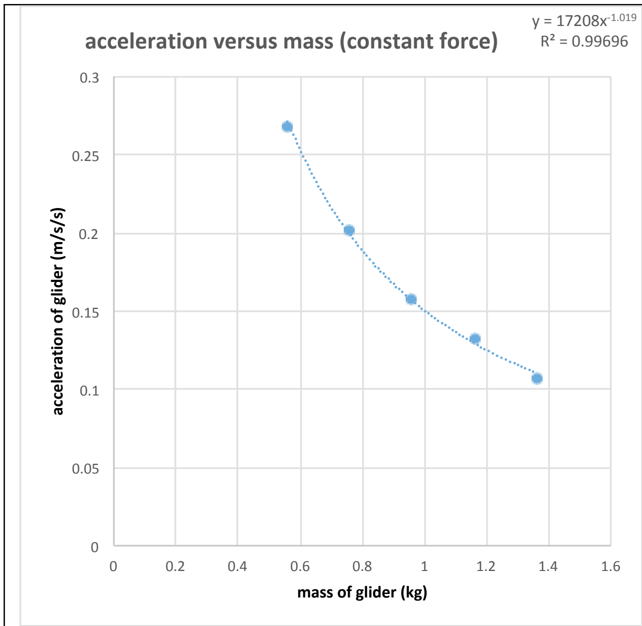
b. Then use the data in the table at right to devise a relationship that shows how each cart's acceleration depends on the cart's mass and on the net force exerted on the cart by the string or fan, Earth, and the track. Note: When doing such an analysis, devise a relationship for each independent variable one at a time and for the dependent variable (for example, use some of the data to see how the acceleration depends on the net force exerted and then use other parts of the data to see how the acceleration depends on the mass of the cart). Then combine these relationships to get a final relationship.

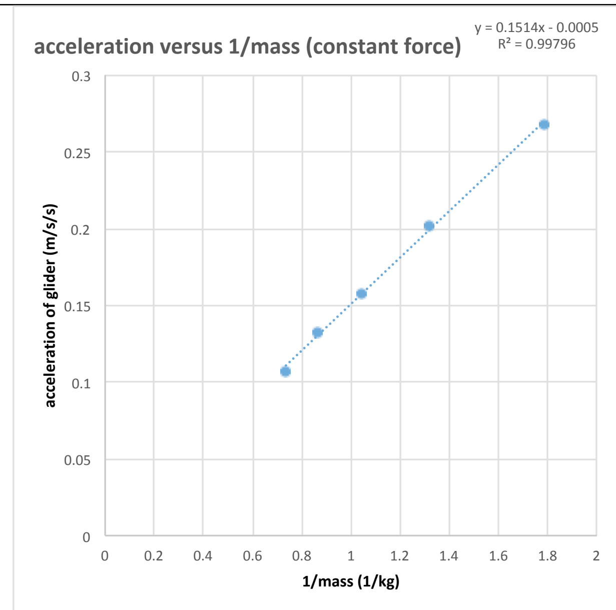
Solution:

Here is some of the graphical analysis using excel:



The graph to the left shows the linear relationship between the acceleration of the glider and the amount of force exerted on the glider by the string. The two graphs below show the analysis of experiment 2. There appears to be an inverse relationship between the acceleration of the glider and the mass of the glider



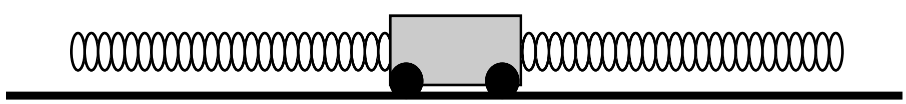


We can conclude from this graphical analysis that a α F and a α 1/m. The only way combine this two proportionalities into one equation is to multiply them: a = F/m

3.5.2 Find a pattern

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

Imagine there are springs attached to both ends of a cart. The springs can pull the cart left and right. Each spring pulls with the same strength, but the number of springs on each side of the cart can vary.



Examine the data in the following table and draw a force diagram for the cart in each experiment (show only the horizontal forces—the upward force that the surface exerts on the cart's wheels and the downward force that Earth exerts on the cart cancel).

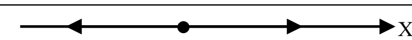
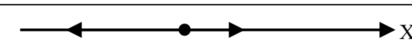
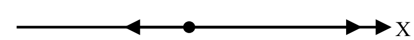
Number of springs pulling to the right	Number of springs pulling to the left	Acceleration of the cart	Draw a force diagram; show horizontal forces only

3	3	0	
1	2	–1.03 m/s^2	
3	1	1.98 m/s^2	
4	1	3.03 m/s^2	
2	6	–3.95 m/s^2	

a. Explain why we use negative signs in the acceleration column of the table.

b. Use the data in the table to devise a relationship between the cart's acceleration and the forces exerted by the springs, Earth, and the track on the cart.

c. Is this relationship consistent with the relationship you devised in Activity 3.5.1? Explain.

Number of springs pulling to the right	Number of springs pulling to the left	Acceleration of the cart	Draw a force diagram; show horizontal forces only
3	3	0	
1	2	–1.03 m/s^2	
3	1	1.98 m/s^2	
4	1	3.03 m/s^2	
2	6	–3.95 m/s^2	

a. *Forces are vector quantities—to the right are positive and to the left are negative.*

b. *The acceleration is proportional to the sum of forces that other objects exert on the system.*

c. *Yes—it is consistent.*

3.5.3 Explain

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

In Activities 3.5.1 and 3.5.2 you analyzed experiments in which the motion of an object was affected by other objects. Represent mathematically the relationship between the object's acceleration, the net force exerted on it by other objects, and its mass.

$$\vec{a} \sim \frac{\Sigma \vec{F}}{m}$$

3.5.4 Represent and reason

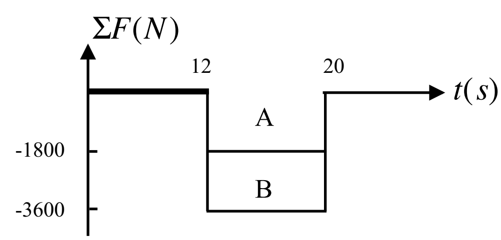
Class: *Equipment needed per group:* whiteboard and markers.

Two cars are moving along a horizontal road as described in the table below:

Time interval	**Car A**	**Car B**
$0 \le t < 12s$	Is moving at constant speed 12m/s	Is moving at constant speed 24 m/s
$12s \le t < 20s$	Is slowing down at constant rate	Is slowing down at constant rate
$t > 20$s	Is not moving	Is not moving

In both cases the combined mass of the car and the driver was equal to 1200 kg. Draw a single graph that shows the time dependence of the magnitude of the sum of the forces exerted on each car during the first 25 s of motion. Make sure your graph is quantitative.

Assuming that the car is moving in the positive direction:



3.5.5 Reading exercise

Read Section 3.5 in the textbook and answer Review Question 3.5

Disagree. Force is an interaction between two objects. Acceleration is a consequence of the forces.

3.6 Gravitational force law

3.6.1 Reason

Class: *Equipment per group:* whiteboard and markers

From Chapter 2 you know that all objects fall with the same acceleration of 9.8 m/s^2 independently of their mass. How is this possible if the acceleration of an object is inversely proportional to its mass? Construct a mathematical relationship for the magnitude of the force that Earth exerts on an object of mass *m*. Discuss different possibilities with your group members.

$$\vec{a} = \frac{\Sigma\vec{F}}{m} = \frac{m\vec{g}}{m} = \vec{g}$$

3.6.2 Test your idea

Lab: *Equipment per group:* Spring scale or platform scale calibrated in newtons, set of objects with calibrated masses.

Your goal is to test the hypothesis that Earth exerts a force on every object which is directly proportional to its mass. Work with your group members to design an experiment, make a prediction using this hypothesis, carry out the experiment, and record the outcome. Did you disprove the hypothesis?

Place two objects of significantly different mass on a shelf significantly high above Earth's surface. Push them off the shelf simultaneously and listen to the sounds when they hit the floor. If Earth exerts a force proportional to the mass of the object, then the objects' acceleration should be the same- g (see the equation in the last example). If Earth's force is in fact mg, then the objects should hit the floor at the same time. Assumption: air has no effect on the motion.

3.6.3 Reading exercise

Read Section 3.6 in the textbook and consider the following question: Is the following statement true? "Because *g* is the same for all objects, Earth must exert the same force on all objects". How would you convince a person studying physics of your opinion?

Put a heavy object on one end of a seesaw and a light object on the other end. If Earth exerts the same force on each object, the seesaw should balance. It does not.

3.7 Skills for applying Newton's second law for one dimensional processes

3.7.1 Practice problem solving strategy

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

To practice applying the 4-step problem solving strategy for solving complex problems, solve the problem below following the steps in the table, then consult the textbook solution in Example 3.4. After that, work through the *Try it yourself* problem on page 68.

Michael Holmes (70 kg) was moving downward at 36 m/s (180 mi/h) and was stopped by 2.0-m-high shrubbery and the ground. Estimate the average force exerted by the shrubbery and ground on his body while stopping his fall.

Sketch and translate ● Sketch the process. ● Choose the system. ● Choose a coordinate system. ● Label the sketch with everything you know about the situation. ● Identify the unknown that you need to find. Label it with a question mark on the sketch.	
Simplify and diagram ● Make appropriate simplifying assumptions about the process. For example, can you neglect the size of the system? Can you assume that forces or acceleration is constant? ● Then represent the process with a motion diagram and/or force diagram(s). Make sure the diagrams are consistent with each other.	
Represent mathematically ● Convert these qualitative representations into quantitative mathematical descriptions of the situation using kinematics equations and Newton's second law for motion along the axis. Determine the signs for the force components in the equations. Add the force components (with either positive or negative signs) to find the sum of the forces.	
Solve and evaluate	

● Substitute the known values into the mathematical expressions and solve for the unknowns. ● Finally, evaluate your work to see if it is reasonable (check units, limiting cases, and whether the answer has a reasonable magnitude). Check whether all representations—mathematical, pictorial, and graphical—are consistent with each other.	

3.7.2 Regular problem

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

An official World Record speed for ice-board windsurfing in 2012 was about 98.7 km/h and it was achieved on Lake Winnipesaukee, New Hampshire. From the YouTube video you can find out that the surfer's speed at time 114 min 35.0 sec was 50.1 mi/h and at 114 min 59.3 sec, 61.2 mi/h. Estimate the average sum of the forces exerted on the system during this time interval if the mass of the surfer is 80 kg and the mass of the sail, mast, and board is 20 kg. Indicate any assumptions you made.

We assume that the board is moving along a straight line during the time interval given in the problem. First, we determine the average acceleration of the board using the definition of acceleration and convert the result into $\mathrm{m/s^2}$*:*

$$a = \frac{\Delta v}{\Delta t} = \frac{11.1\ \mathrm{mi/h}}{24.3\ \mathrm{s}} = \frac{4.96\ \mathrm{m/s}}{24.3\ \mathrm{s}} = 0.20\ \mathrm{m/s^2}$$

Than we use Newton's second law to determine the sum of the forces exerted on the board and the surfer:

$$\Sigma F = a \cdot m_{\mathrm{sys}} = 0.20\ \mathrm{m/s^2} \times (80\ \mathrm{kg} + 20\ \mathrm{kg}) = 20\ \mathrm{N}$$

3.7.3 Reading exercise

Make sure you work through the worked examples in Section 3.7 in the textbook, after that answer Review Question 3.7.

3.8 Forces come in pairs: Newton's third law

3.8.1 Observe and explain

PIVOTAL Lab: *Equipment per group:* 2 dynamics carts, 2 force probes, 1 dynamics track, computer with data-logging software, hoop-spring bumpers, slotted weight set, string.

The goal of these experiments is to find a relationship between the force that an object A exerts on an object B and the force that object B exerts on object A when they are interacting with each other. Design and perform three experiments that investigate the forces that two interacting objects exert on each other. Look for a pattern that relates the two forces to each other. For example: Place one probe at rest on the table and tap it with the second probe. Or attach the force probes to the carts and vary the amount of mass on one of the carts while rolling it so it collides with the other cart. *Remember that the probes are very delicate and if you use them to tap one another, you need to do it lightly*. Hint: Keep your experiments simple. Vary only one independent variable for each experiment.

For **each** of your three experiments, be sure to address the following points in your report:

a. Describe the design and set-up of your experiment, including what physical quantities you're varying and what variable(s) you're going to measure. Evaluate your designs.

b. Describe your findings, sketch the graphs that you see on the computer if necessary.

c. Find a pattern in the pairs of graphs representing the force-versus-time functions recorded by each probe during the time interval the interaction is taking place.

The pattern that students should find is that in all collisions the carts exert forces on each other that are the same in magnitude and opposite in direction.

When you have completed all three experiments:

d. Devise and state a general hypothesis about the relationship between the force that object A exerts on object B to the force that object B exerts on object A.

The force that object A exerts on object B is equal in magnitude and opposite in direction to the force that object B exerts on object A.

3.8.2 Test an idea

Class or lab: *Equipment per group:* 2 spring scales.

You and your friend each hold a spring scale and you hook the scales to each other. Use the rule relating the directions and magnitudes of the forces that two interacting objects exert on each other (formulated in Activity 3.8.1, part d.) to predict what your friend's spring scale reads if you pull yours with a force of 3 units. What if she pulls with a force of 5 units?

a. Describe what prediction you're making for each case and the hypothesis on which that prediction is based.

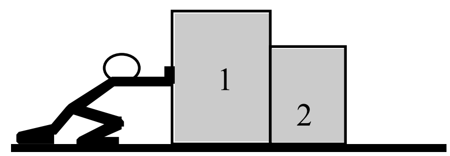
The scales should have the same reading (both 3 units or both 5 units). This prediction is based on the hypothesis above.

b. Conduct the experiment and record the outcomes. Do the results agree with the predictions?

c. Can you arrange it so that one of you pulls with 3 units and the other pulls with 5 units? Explain.

3.8.3 Represent and reason

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



You push horizontally on two crates of different mass. The surface on which the crates move is smooth. Draw separate force diagrams for crates 1 and 2 for the two scenarios **a.** and **b.** below. When drawing force diagrams, use the rule relating the forces that two interacting objects exert on each other (devised in Activity 3.8.1, part d.).

a. You first push crate 1, which pushes against the smaller crate 2.

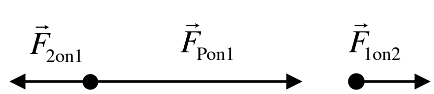
b. You now reverse the positions of the crates and push crate 2, which pushes against the larger crate 1.

c. Based on your diagrams in parts a. and b., should it be easier to push the crates in one situation or the other? Explain.

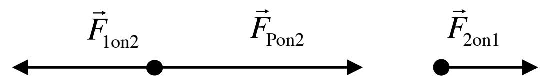
d. Is your answer to part c. consistent with the idea that you are pushing the same amount of matter, independent of the order of the crates?

e. If it is equally difficult to push the crates independent of their order, then how should the *sum* of the forces exerted by crate 1 on crate 2 and by crate 2 on crate 1 for part a. compare to the *sum* of these forces for part b.? What does this imply about the magnitude of the force that one crate exerts on the other and vice versa? (Note: the sum of the forces used here is the sum of the forces exerted on different objects, thus it does not determine the acceleration of any object.)

a. *You first push crate 1, which pushes against the smaller crate 2.*



b. *You now reverse the positions of the crates and push crate 2, which pushes against the larger crate 1.*



c. *Equally difficult.*

d. *Yes—pushing the same amount of matter.*

e. *The sum of forces 1 on 2 and 2 on 1 for a is zero as it is for b.*

3.8.4 Represent and reason

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

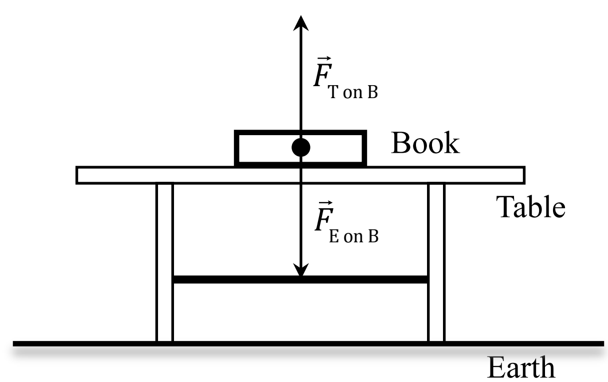
A book rests on a table.

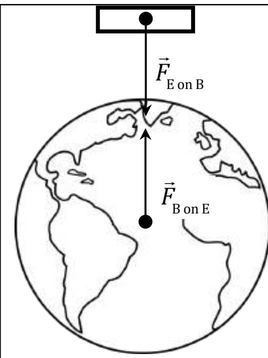
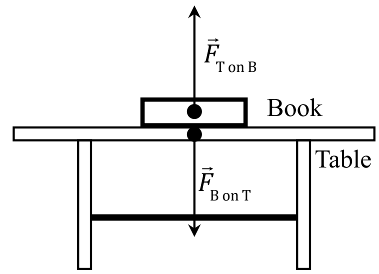
a. Draw a sketch of the situation and identify objects that interact with the book.

b. Draw forces representing these interactions (a force diagram for the book).

c. If the book is stationary, these forces are equal in magnitude and opposite in direction. Can we say that they represent a Newton's third law pair of forces? If not, why not?

d. Draw the Newton's third law force pair (using the same color pen for each pair) for each force shown in the force diagram in part b. and identify the cause of each of these forces and the objects on which each of these forces is exerted.

a. *The table pushes up on the book. Earth pulls down the book.* ***b.*** *A force diagram for the book is shown in the same figure.* **c.** *They are NOT a Newton's third law pair of forces. They are exerted on the one object of interest in the force diagram (the book) by other objects external to the book. They do not describe the same interaction.*	

d. *The N3 pair of $F_{E\ on\ B}$ is $F_{B\ on\ E}$. If Earth pulls down on the book, the book pulls up on Earth. $F_{B\ on\ E}$ is part of Earth's force diagram NOT the book's force diagram.* *The N3 pair of $F_{T\ on\ B}$ is $F_{B\ on\ T}$. If the table pushes up on the book, the book pushes down on the table. $F_{B\ on\ T}$ is part of the table's force diagram NOT the book's force diagram.*		

3.9 Seat belts and airbags

3.9.1 Real-world application

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

Work with your group to use the problem solving strategy to solve the following problem:

A 60-kg crash test dummy moving at 13.4 m/s (130 mi/h) stops during a collision over a distance of 0.65 m. Estimate the magnitude of the average force that the air bag and seat belt exert on the dummy.

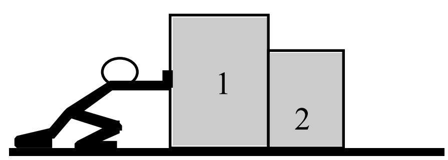
See example 3.9 in the textbook, it has a complete solution to this problem.

Sketch and translate ● Sketch the process. ● Choose the system. ● Choose a coordinate system. ● Label the sketch with everything you know about the situation. ● Identify the unknown that you need to find. Label it with a question mark on the sketch.	
Simplify and diagram ● Make appropriate simplifying assumptions about the process. For example, can you neglect the size of the system? Can you assume that forces or acceleration is constant?	

● Then represent the process with a motion diagram and/or force diagram(s). Make sure the diagrams are consistent with each other.	
Represent mathematically ● Convert these qualitative representations into quantitative mathematical descriptions of the situation using kinematics equations and Newton's second law for motion along the axis. Determine the signs for the force components in the equations. Add the force components (with either positive or negative signs) to find the sum of the forces.	
Solve and evaluate ● Substitute the known values into the mathematical expressions and solve for the unknowns. ● Finally, evaluate your work to see if it is reasonable (check units, limiting cases, and whether the answer has a reasonable magnitude). Check whether all representations—mathematical, pictorial, and graphical —are consistent with each other.	

3.9.2 Reason

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



Block 1 has a mass of 5 kg, block 2 has a mass of 3 kg. The person pushing the blocks exerts a force of 80 N on block 1. Assume the surface is smooth.

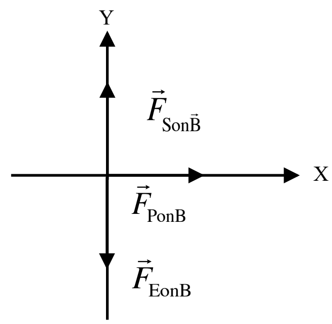
a. Treating the two blocks together as a system, draw a force diagram for the combined two-block system. Remember to mark the perpendicular *x*- and *y*-axes. Use your force diagram to apply Newton's second law to determine the acceleration of the system.

b. Now draw separate force diagrams for block 1 and block 2. Apply Newton's second law to block 1 and use the acceleration you found previously to determine the magnitude of $\vec{F}_{2\text{ on }1}$.

c. Evaluate the answer you found for $\vec{F}_{2\text{ on }1}$ by applying Newton's second law to block 2 to find the acceleration of block 2. (If you know $\vec{F}_{2\text{ on }1}$, you know $\vec{F}_{1\text{ on }2}$.) Make sure the acceleration you find is consistent with the other accelerations you found in earlier parts. If not, try figure out where you went wrong.

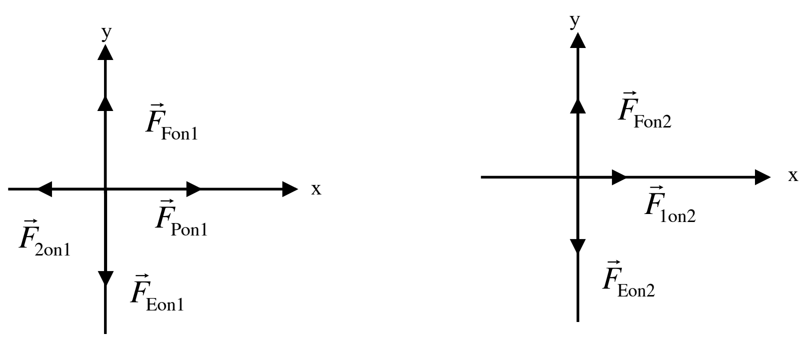
a.

$$a = \frac{80\text{ N}}{8\text{ kg}} = 10\text{ m/s}^2$$



b.

$$80\text{ N} - F_{2on1} = (5\text{ kg})(10\text{ m/s}^2)\text{ or }F_{\text{2on1}} = 30\text{ N}$$



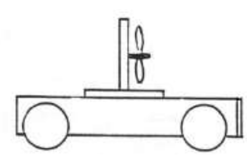
c.

$$a = \frac{30\text{ N}}{3\text{ kg}} = 10\text{ m/s}^2$$

3.9.3 Linearize

Class: *Equipment per group:* none.

Alex was investigating the motion of a low-friction fan cart on a horizontal track. As the fan blades rotate, they exert a force on the air and therefore the air exerts an equal and opposite force on the blades (see the sketch on the right). Using a motion detector, he found out



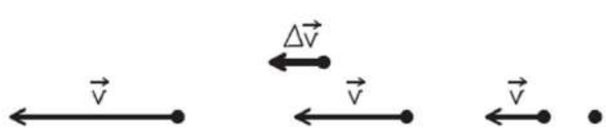
that the cart is moving with constant acceleration. He also measured how the acceleration of the cart depends on the mass of the weights that he added to the cart. His measurements are shown in the following table:

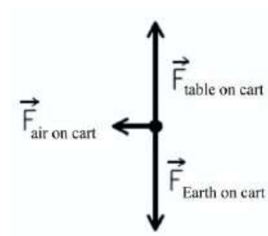
Added mass (kg)	**Acceleration of the cart (m/s^2)**
0	0.30
0.10	0.25
0.20	0.21
0.30	0.19
0.40	0.17
0.50	0.15

Which are the two unknown quantities in Alex's experiment that also determine the motion of the fan cart? Try to determine these two quantities using the data above. (Hint: rearrange the mathematical expression for the acceleration of the cart to obtain a linear dependence on added mass, and then plot the graph using the data in the table.)

We sketch the situation as shown on the right, choosing the cart as a system. The coordinate axis x points to the left, in the direction of motion.

We model the cart as a point-like object (a system) and construct the motion diagram and the force diagram for the cart:





The motion and the sum of the forces are along the x-axis, thus we use the x-component form of Newton's second law to analyze the process.

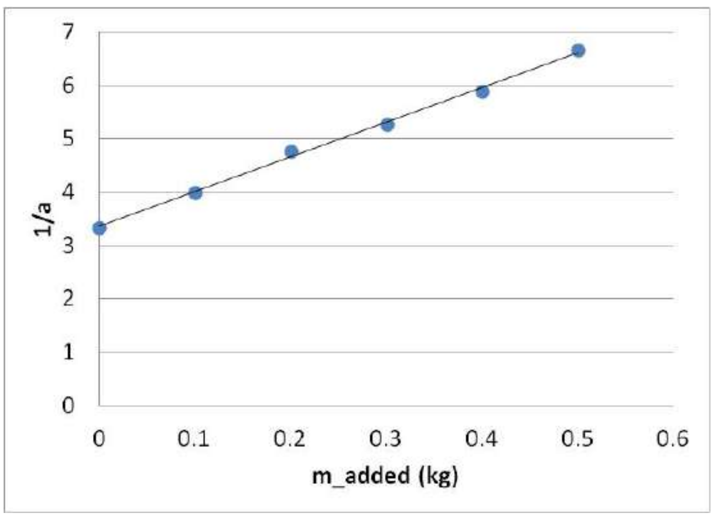
$$a_y = \frac{F_{\text{air on cart}}}{m_{\text{cart}} + m_{\text{added}}}$$

The two unknown quantities are the mass of the cart and the force exerted by air on the blades (because the fan is fixed on the cart this force is exerted on the whole cart). We can rearrange the equation to obtain a linear dependence on added mass:

$$m_{\text{cart}} + m_{\text{added}} = \frac{F_{\text{air on cart}}}{a_y}$$

$$\frac{1}{a_x} = \frac{m_{\text{added}}}{F_{\text{air on cart}}} + \frac{m_{\text{cart}}}{F_{\text{air on cart}}}$$

This is linear equation for variable $1/a_y$ *as a function of* m_{added}. *The slope of the line is equal to* $1/F_{\text{air on cart}}$ *and the intercept is equal to* $m_{\text{cart}}/F_{\text{air on cart}}$. *Now we plot* $1/a_y$ *against* m_{added} *and draw the best-fit line (see graph below)*



We can determine the slope and the intercept from the graph and get $1/F_{\text{air on cart}} = 6.52\ \text{N}^{-1}$ *and* $m_{\text{cart}}/F_{\text{air on cart}} = 3.35\ \text{kg/N}$. *Therefore,* $F_{\text{air on cart}} = 0.15\ \text{N}$ *and* $m_{\text{cart}} = 0.51\ \text{kg}$.

3.9.4 Application experiment

Lab: *Equipment per group:* 1 bathroom scale (or spring scale and hanging object), 1 stopwatch (or cellphone app.)

The elevator company that installed the elevators at your school is concerned that their elevators are running too slowly. They would like your group to estimate the starting and stopping acceleration and the speed when moving at constant speed between stops. You have a bathroom scale and a stopwatch. Answer the scaffolding questions that follow to help you design and execute your experiment.

a. Write a description of your proposed starting and stopping experiments. Indicate the location of the observer and whether the observer can use Newton's laws to analyze the motion of the elevator.

b. Draw a labeled sketch of each situation.

c. Draw a motion and a force diagram (as needed) for each situation. Make sure they are consistent with each other.

d. Write the physical quantities that you will measure and the quantities you will calculate.

e. Write the mathematical procedure you will use to calculate the acceleration.

f. List additional assumptions you need to make to implement your mathematical procedure.

g. List sources of experimental uncertainty and ways to minimize them.

h. Record your results, calculate the rate at which the elevator speeds up, slows down, and its speed in the constant speed portion of its motion; and the uncertainties in all of your estimates.

i. Imagine now that you are an observer inside the elevator. You are standing on the scale and all of a sudden you see the reading of the scale change. Can you explain this change if you are at rest with respect to the elevator?

I will consider a case where the elevator is moving upwards. Before the elevator is moving or accelerating, I will measure the force I exert on the scale in a non-accelerating reference frame. (For example, while elevator is stationary.) For example, I might find that the scale reads 784 N. I deduce from this reading that my mass is 80 kg.

Analysis when starting.	***Analysis when stopping***
Method: I will stand on the scale in the elevator. As the elevator starts accelerating upwards, I will carefully note what the scale reads and compare this reading against the 784 N I read when I was not accelerating in order to determine the upward acceleration of the elevator.	*Method: As the elevator approaches its stopping point, I will remain standing on the scale. As the elevator starts slowing down, I will note any changes in the reading on the scale. I will compare this with the known 784 N I measured when the elevator was not moving and from that, determine the acceleration of the elevator.*
Put labeled sketch here	*Put labeled sketch here*

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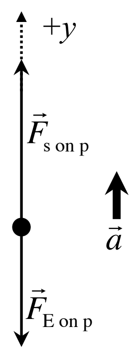

Force diagram for person on scale while the elevator is accelerating upwards

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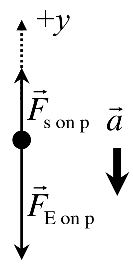

Force diagram for person on scale while the elevator is slowing down as it goes up (accelerating downwards).

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To be measured: The reading on the scale. This is the force exerted by the person on the scale and should be the same magnitude as $F_{s\ on\ p}$ by Newton's third law.

To be calculated: The acceleration of the elevator.

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To be measured: The reading on the scale. This is the force exerted by the person on the scale and should be the same as $F_{s\ on\ p}$ by Newton's third law.

To be calculated: The acceleration of the elevator

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Mathematical procedure:

$$\vec{a} = \frac{\vec{F}_{\text{E on p}} + \vec{F}_{\text{s on p}}}{m_{\text{p}}}$$

$$a = \frac{-784\ \text{N} + F_{\text{s on p}}}{80\ \text{kg}}$$

In this case, I should get a positive answer for the acceleration because the scale should read more than 784 N when the elevator is speeding up as it goes upwards.

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Mathematical procedure:

$$\vec{a} = \frac{\vec{F}_{\text{E on p}} + \vec{F}_{\text{s on p}}}{m_{\text{p}}}$$

$$a = \frac{-784\ \text{N} + F_{\text{s on p}}}{80\ \text{kg}}$$

In this case, I should get a negative answer for the acceleration because the scale should read less than 784 N when the elevator is slowing down as it goes upwards.

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I have ignored all other interactions other than those considered. I will assume that any other interactions are negligibly small. I will assume that the acceleration is roughly constant. I will also make sure the

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Assumptions are the same.

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scale is properly zeroed before I do the experiment.	
Sources of uncertainty: The main difficulty will be to read the scale precisely. Small fluctuations in the acceleration and the short time period may make reading the scale very difficult. *Ways to minimize: I will use a video camera pointed at the dial on the scale. Once the experiment is over, I can step the video frame by frame and read the scale much more easily.*	*Uncertainties are the same*