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PHYSICS 11

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Contents

5 Newton's Laws of Motion

In this chapter the focus will be on the Big Ideas:

An object's motion can be predicted, analyzed and described.
Forces influence the motion of an object.

The content learning standards will include:

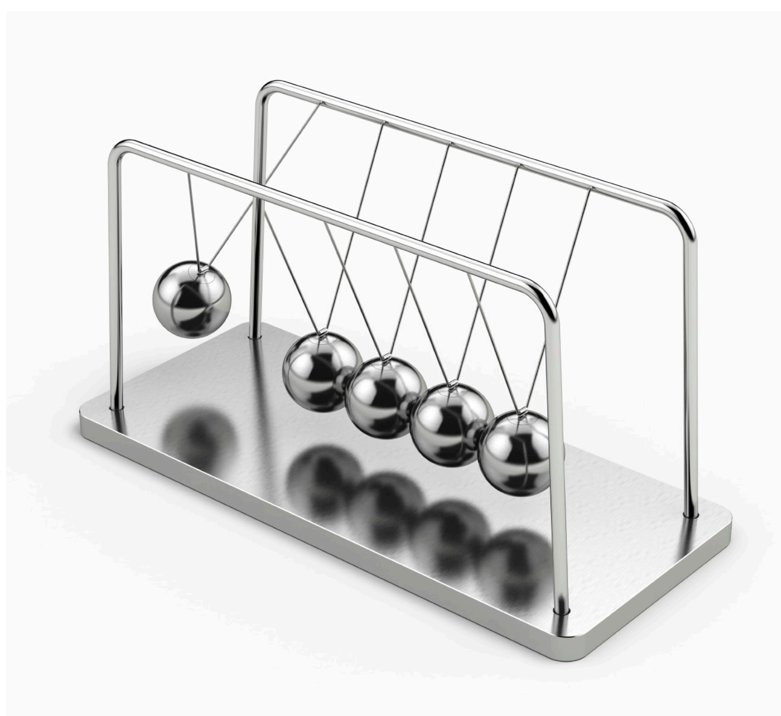
- Newton's laws of motion and free-body diagrams
- Balanced and unbalanced forces in systems

By the end of this chapter, you should know the meaning to these **key terms**:

- action force
- gravitational mass
- impulse
- inertia
- inertial mass
- law of action and reaction
- law of conservation of momentum
- law of inertia
- momentum
- newton
- Newton's first law of motion
- Newton's second law of motion
- Newton's third law of motion
- reaction force

By the end of this chapter, you should be able to use and know when to use the following formulae:

$F = ma$ $\quad p = mv$ $\quad \Delta p = F\Delta t$



This device is called Newton's cradle, named after Sir Isaac Newton, the British scientist. When a ball at one end is lifted and released, it hits the ball next to it but that ball doesn't move. Only the ball at the end of the row is pushed upward as shown here. In this chapter you'll learn about Newton's laws of motion and momentum, which help to explain how this device works.

5.1 Inertia and Newton's First Law

Warm Up

You are attending a magic show and the magician stands beside a table set with fancy plates, cups, and silverware. Grabbing the edge of the tablecloth she quickly pulls the cloth out, and the plates, cups, and silverware stay in place. Is this magic or just physics in action? Explain your answer.

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Inertia

Imagine you are a passenger in a car, and the driver makes a sudden left turn. What sensation do you feel during the left turn? From your own experience, you might recall that you feel as if you are being pushed to the right. Contrary to what you feel, you are not being pushed to the right at all.

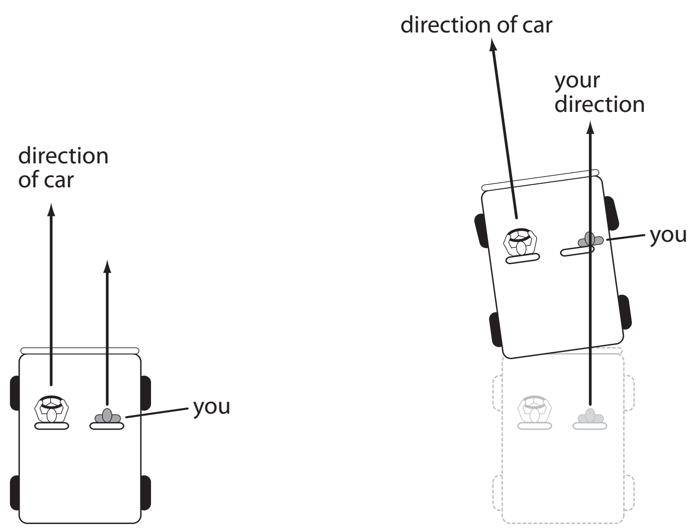

Figure 5.1.1 *As the car turns, your body wants to keep moving straight ahead.*

Figure 5.1.1 illustrates what happens and explains why you feel the force acting on your body. The car starts out by going straight and then the driver steers the car to the left. The car is moving to the left but your body wants to carry on in a straight line. What's stopping you? The door of the car is moving left with the rest of the car so it is pushing you in the direction the car is going. You feel as if you are pushing against the door, but this feeling is not what is happening. What is happening is that your body is trying to continue along its original straight path while the car is turning left. The result is that you are being pulled along with the car rather than continuing in a straight line.

As a general rule, any object tends to continue moving with whatever speed and direction it already has. This can include zero speed. When a driver accelerates a car, a body in the car tends to keep doing what it was already doing. So if the car is stopped, you are stopped. As the car starts to move and speeds up, you feel as if you are being pushed back into your seat.

The tendency that all objects have to resist change in their states of motion is called **inertia**. Every object in the universe that has mass has this property of inertia. Galileo Galilei (1564–1642) was the first person to describe this property of nature, which is called the **law of inertia**.

Some objects have more inertia than others because they have more mass. A logging truck has much more inertia than a mountain bike. Because it has so much more inertia, the logging truck is

(a) more difficult to get moving,
(b) more difficult to stop,
(c) more difficult to turn at a corner.

Measuring Inertia

Is there a way to measure inertia? You have measured it many times in science class. The way to measure inertia is to measure the object's mass. When you measure the mass of an object using a balance, that mass is equal to the object's **inertial mass**.

Strictly speaking, what the balance measures is called **gravitational mass**. This is because the unknown object is placed on one pan, and a standard mass is placed on the other pan. The masses are assumed to be equal when the force of gravity on the unknown mass balances the force of gravity on the standard mass. Gravitational mass is numerically equal to inertial mass, so a balance can be used to measure inertial mass as well.

Quick Check

1. Why does it hurt more to kick a rock shaped like a soccer ball than a soccer ball?

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2. When astronauts are living in the International Space Station (ISS) they are in orbit around Earth at a minimum altitude of 278 km. They live in an environment of apparent weightlessness. Compare the inertial mass of the astronauts when they live on the ISS to their inertial mass when they are on Earth.

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Newton's First Law

Isaac Newton (1642–1727) is considered one of the greatest scientists of all time. In any physics class you ever take, you will come across his name at some time. This is impressive, given that all his work was done more than 350 years ago. Newton is probably best known for his laws of motion. Newton's three laws describe motion as we experience it on Earth. They are also the foundation for helping to send humans to the Moon and deep-space vehicles out beyond our solar system.

Newton's first law of motion incorporated Galileo's law of inertia. The first law of motion, or law of inertia, can be stated this way:

> A body will continue to move at the same speed and in the same direction for as long as there are no unbalanced forces acting on it.

Ideal Conditions

Put another way, an object wants to keep doing what it is already doing. This means if a basketball is placed on the floor, it will not move until another force acts on it. Someone picking up the ball is an example of a force acting on the ball.

Sometimes it appears that Newton's first law does not apply. For example, when coasting on your bicycle along a flat part of the road, you have probably noticed that you slow down even though it appears no forces are acting on the bicycle. In fact, the force of friction between the road and tires is responsible for slowing the bicycle. If there were no friction, the bicycle would continue at the same speed until another force acted on it. That is why in many physics problems about motion, you will see the assumption that there is no friction. A situation that is assumed to have no friction is called *ideal conditions*. Using ideal conditions, we can focus on the motion being observed. By specifying ideal conditions, we also show we know that friction would have to be considered under normal conditions.

Quick Check

1. A car you are driving in encounters a patch of ice just as the car enters a corner turn. Using your knowledge of Newton's first law of motion, explain what will happen to the car.

2. You are a judge listening to an injury claim from a bus passenger. The passenger claims to have been hurt when the bus driver slammed on the brakes and a suitcase came flying from the front of the bus to hit the passenger. Do you believe the passenger's description of what happened? Explain your answer.

3. When you receive a drink for a take out order, usually there is a lid on the cup. Use Newton's first law to explain why the lid is necessary to prevent spills.

Investigation 5.1.1 Investigating Inertia

Purpose

To answer problems that will help you develop an understanding of inertia and Newton's first law of motion

Problem 1: How does a seatbelt work?

Figure 5.1.2 *Problem 1*

Procedure

1. Place a small toy human figure on a toy car or truck as shown in Figure 5.1.2. Do not fasten the figure to the vehicle. Let the vehicle move toward an obstruction like another toy vehicle or a brick and collide with it. Observe what happens to the unattached passenger.
2. Repeat step 1, but this time give the toy human figure a "seatbelt" by taping it to the vehicle.

Questions

1. How does this procedure illustrate inertia?
2. How does a seatbelt work?
3. Why are you more likely to survive a collision with a seatbelt than without one?

Problem 2: Does air have inertia?

Procedure

1. Fill a large garbage bag with air, and hold it as shown in Figure 5.1.3.
2. Quickly jerk the bag to one side. What happens to the air in the bag
   (a) when you start moving the bag?
   (b) when you stop moving the bag?

Question

1. What evidence have you observed from this procedure that supports the claim that air has inertia?

Figure 5.1.3 *Problem 2*

Problem 3: Inertia on an air track

Procedure

1. Place a glider on an air track as shown in Figure 5.1.4. Turn on the compressed air supply and check that the track is absolutely level. When the track is level the glider should have no tendency to move in one direction or the other. It should sit still.
2. Place the glider at one end of the track. Give it a slight nudge, and let it go.
3. Observe the motion of the glider.

Questions

1. Are there any unbalanced forces on the glider?
2. Describe its motion.
3. How does this demonstration illustrate Newton's first law?

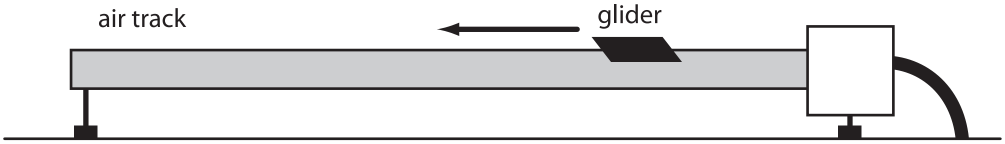


Figure 5.1.4 *Problem 3*

Problem 4: Get on the right track.

Procedure

1. Place a battery-powered toy train on a circular track, and let it run a few full circles.
2. Predict which way the train will go if one of the sections of curved track is removed. Which one of the following will the train do? Explain your answer.
   (a) continue to move in a circle
   (b) move off along a radius of the circle
   (c) move off in a straight line tangent to the circle
   (d) follow some other path
3. Now test your prediction by setting up a section of track as shown in Figure 5.1.5.

Question

1. What happens to the toy train when it leaves the track? Explain this in terms of inertia.

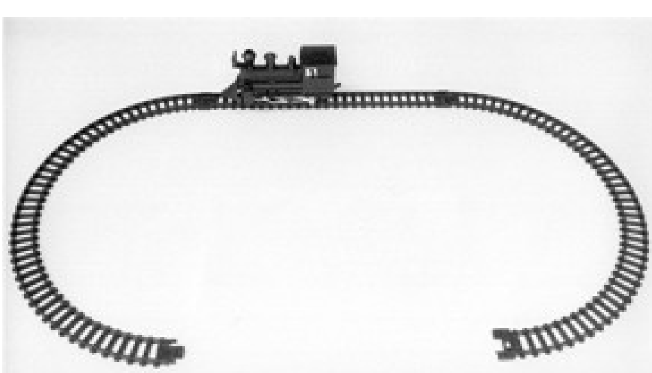


Figure 5.1.5 *Problem 4*

Problem 5: Where will the string break? Getting the "hang" of inertia

Procedure

1. Attach two equal masses, either 500 g or 1 kg, to a supporting rod, as shown in Figure 5.1.6. Use string that is strong enough to support the hanging masses, but not so strong that you cannot break it with a moderate pull with your hand. Add a 50 cm length of the same kind of string to the bottom of each mass.
2. Predict where each string will break, above or below the mass, if you pull on the end of the string first gently and then abruptly. Test your predictions by experiment.

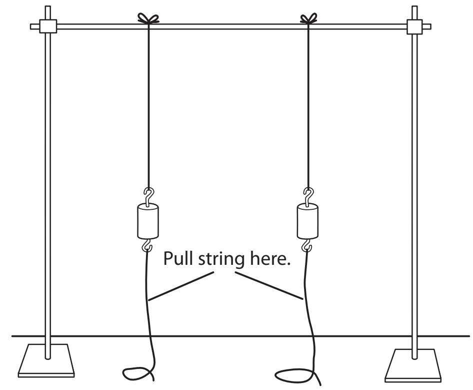
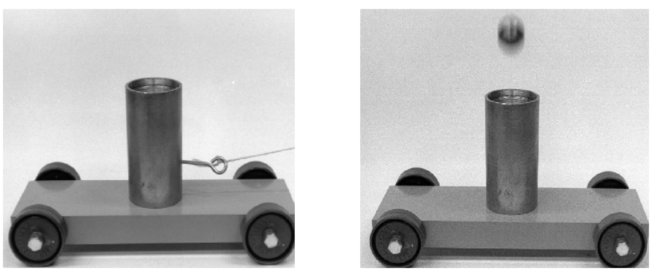


Figure 5.1.6 *Problem 5*

Questions

1. Explain what happened, in terms of inertia.
2. Which action illustrates the weight of the ball and which illustrates the mass of the ball?

Problem 6: The pop-up coaster



(a) (b)

Figure 5.1.7 *Problem 6*

Procedure

1. The cart in Figure 5.1.7 contains a spring that can fire a steel ball straight up in the air. The cart is given a steady horizontal speed when pulled with a string. This also activates the trigger for the spring-loaded cannon. When the cart is moving with a steady speed, giving the string a sudden pull will release the spring and fire the ball up in the air.
2. Predict whether the ball will land ahead of the cannon, behind the cannon, or in the cannon. Explain your prediction.
3. Test your prediction.

Questions

1. What forces are acting on the ball when it is in the air?
2. How does this procedure illustrate Newton's first law of motion?
3. Why does the ball sometimes miss the cart after it is released? Does this mean Newton's first law sometimes does not apply?

Concluding Question

Use your understanding of inertia to explain the following situation: You are carrying a carton of milk with one hand and need to get a section of paper towel off the roll in your kitchen. You can only use one hand to tear off the paper towel. Why does a quick, jerking motion work better than a slow pulling motion when removing the paper towel section from the roll?

5.1 Review Questions

1. In the Warm Up of this section, you were asked to explain why the magician was able to pull the tablecloth out from the under the plates, cups and silverware. Using the concepts of inertia and Newton's first law, explain why this "magic act" succeeds.

2. Does 2 kg of apples have twice the inertia or half the inertia of 1 kg of apples? Explain your answer.

3. If the pen on your desk is at rest, can you say that no forces are acting on it? Explain your answer.

4. If the forces acting on the pen are balanced, is it correct to say that the pen is at rest? Explain your answer.

5. If you place a ball in the centre of a wagon and then quickly push the wagon forward, in what direction does the ball appear to go? Why?

6. Why do headrests in cars help protect a person from head and neck injury in a car accident?

7. A hockey puck moving a constant velocity across the ice eventually comes to a stop. Does this prove the Newton's first law does not apply to all situations?

8. You are travelling in a school bus on a field trip. The driver has to apply the brakes quickly to prevent an accident. Describe how your body would move in response to this rapid braking action.

9. While travelling in Africa you are chased by a very large elephant. Would it make more sense to run in a straight line to get away or in a zigzag motion? Explain your answer.

5.2 Newton's Second Law of Motion

Warm Up

Take an empty spool of thread and wrap a string or thread around it three or four times, leaving the end loose so you can pull on it. Place the spool on the floor and pull on the thread horizontally to make the spool move to the right.

1. Based on your observations, what can you say about the direction of the force applied to the spool and the acceleration of the spool?

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2. Would the direction of the force or the acceleration of the spool be affected if the thread were wrapped around the spool in the opposite direction? Explain your answer.

   ____

   ____

Defining Newton's Second Law of Motion

In his second law of motion, Newton dealt with the problem of what happens when an unbalanced force acts on a body. **Newton's second law of motion** states: If an unbalanced force acts on a body, the body will accelerate. The rate at which it accelerates depends directly on the unbalanced force and inversely on the mass of the body.

$$\boldsymbol{a} = \frac{F}{m}$$

The direction in which the body accelerates will be the same direction as the unbalanced force. The measuring unit for force is the **newton (N)**. The measuring unit for mass is the kilogram (kg) and for acceleration is m/s^2. Therefore, using $F = ma$, one newton can be defined as the force needed to accelerate one kilogram at a rate of one metre per second per second.

Whenever Newton's second law is used, it is understood that the force F in the equation $F = ma$ is the unbalanced force acting on the body. This unbalanced force is also called the net force. To calculate the unbalanced force acting on a 1.0 kg mass falling due to gravity, you use Newton's second law:

$$F = ma = 1.00 \text{ kg} \times 9.81 \text{ m/s}^2 = 9.81 \text{ kg•m/s}^2 = 9.81 \text{ N}$$

To calculate the rate at which the mass accelerates, you rearrange Newton's second law to give:

$$a = \frac{F}{m} = \frac{9.81 \text{ N}}{1.00 \text{ kg}} = \frac{9.81 \text{ kg•m/s}^2}{1.00 \text{ kg}} = 9.81 \text{ m/s}^2$$

The acceleration of the mass is g or 9.81 m/s^2.

Quick Check

1. A single engine plane has a mass of 1500 kg and acceleration of 0.400 m/s^2. What is the thrust, or unbalanced force on the plane?

2. What is the mass of a rocket that accelerates at 2.0 m/s^2 and has a net force of 25 000 N?

3. Find the acceleration of a passenger jet that has a mass of 250 000 kg and provides an unbalanced force of 50 000 N.

Multiple Forces

The example and problems in the Quick Check above involve only one unbalanced force. In other situations, like Sample Problem on the next page, there are more forces to consider.

Remember that, in these problems, it is important to identify the forces that create the unbalanced force. Figure 5.2.1 shows four different forces acting on a block. The two vertical forces are the force of gravity and the normal force (the force exerted by the floor on the block). The two horizontal forces are the applied force and the force of friction.

The two vertical forces balance each other because the force of gravity and the normal force equal each other in size and act in opposite directions. The unbalanced force is the difference between the applied force and the friction force opposing the applied force.

Sample Problem — Multiple Forces Acting on a Body

A 45.0 N block is being pushed along a floor, where the coefficient of kinetic friction is 0.333. If a force of 25.0 N is applied, at what rate will the block accelerate? The mass of the block is 4.60 kg.

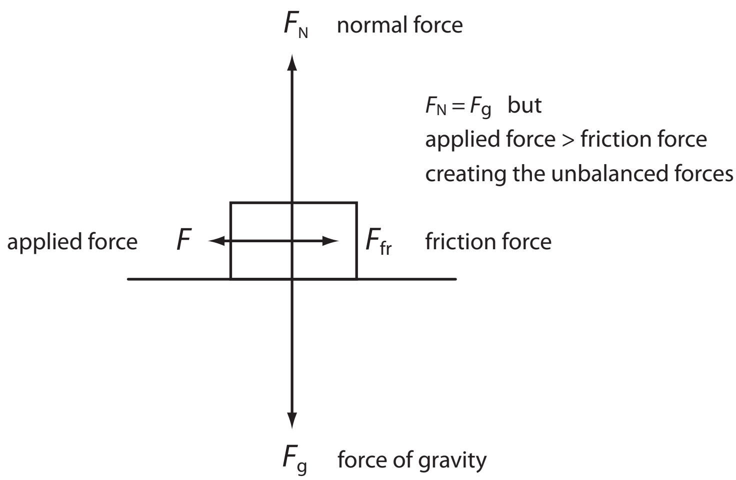

Figure 5.2.1 *Forces acting on block*

What to Think About	How to Do It
1. Find the force of friction.	$F_{fr} = \mu F_N = \mu F_g = (0.333) \times (45.0\ \text{N}) = 15.0\ \text{N}$
2. Find the unbalanced force.	unbalanced force = applied force – friction force $F = 25.0\ \text{N} - 15.0\ \text{N} = 10.0\ \text{N}$
3. Find the acceleration.	$a = \frac{F}{m} = \frac{10.0\ \text{N}}{4.60\ \text{kg}} = 2.17\ \text{m/s}^2$

Practice Problems — Multiple Forces Acting on a Body

1. A net force of 20 N is acting on a falling object. The object experiences air resistance of 6.0 N. If acceleration due to gravity is 9.8 m/s^2, what is the mass of the object?

2. A 900 N person stands on two scales so that one foot is on each scale. What will each scale register in Newtons?

3. What is the mass of a paratrooper who experiences an air resistance of 400 N and an acceleration of 4.5 m/s^2 during a parachute jump.

4. A force of 50 N accelerates a 5.0 kg block at 6.0 m/s^2 along a horizontal surface.
   (a) What is the frictional force acting on the block?

   (b) What is the coefficient of friction?

Investigation 5.2.1 Newton's Second Law of Motion

Purpose

To investigate how the change in speed of a cart is affected by
(a) the amount of unbalanced force, and (b) the amount of mass in the cart

Procedure

Part 1: Setting up and moving the cart

1. Set up the apparatus as shown in Figure 5.2.2(a). Start with three 200 g masses in the cart. Suspend a mass of 200 g from the end of a string, which passes over a pulley at the end of the bench. The force of gravity on this mass is 1.96 N or approximately 2.0 N.
2. Lift one end of your laboratory table so that the cart rolls toward the pulley at a steady speed. This can be checked with a ticker tape and your recording timer. If your bench cannot be lifted, do the experiment on a length of board, which can be raised at one end. What this lifting does is balance friction with a little help from gravity.
3. The class will now share the task of preparing and analyzing ticker-tape records of speed vs. time for each of the situations in Figure 5.2.2. Each lab group of two students will choose one of the eight set-ups and prepare two tapes or one for each partner. Note that the whole system of cart-plus-string-plus-hanging-mass moves as one unit. The mass of the whole system must be kept constant. This means that once you build your system you must not add any additional masses.

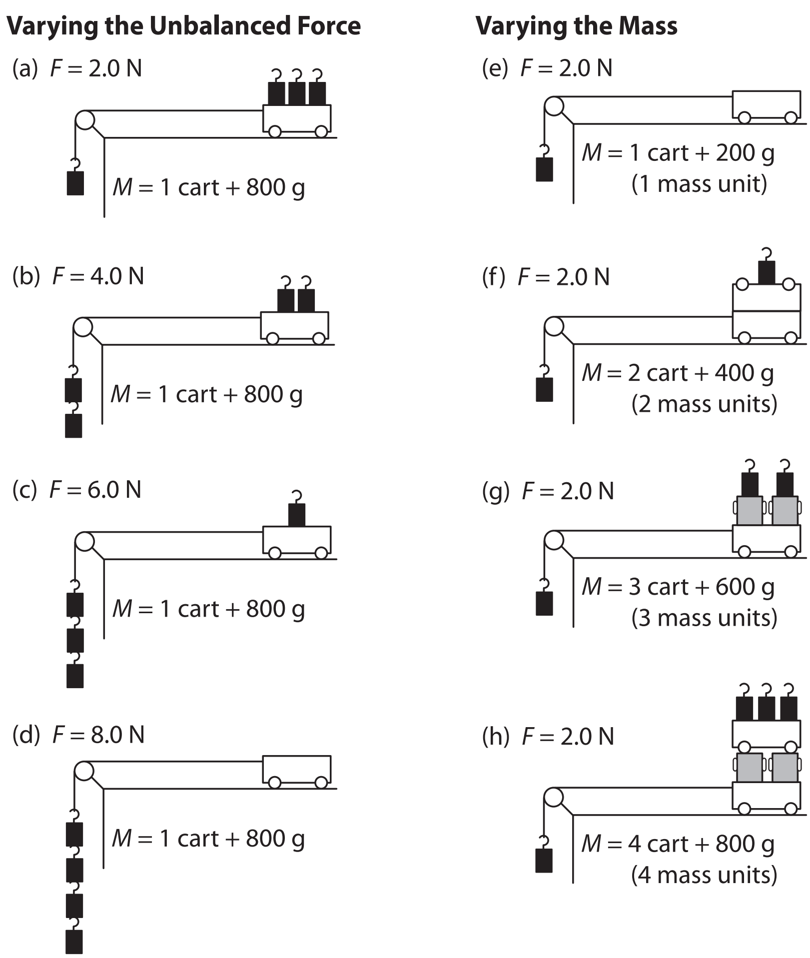

Figure 5.2.2 *Cart and mass set-ups*

Part 2: Preparing Your Own Tape

1. The class as a team will prepare and analyze tapes for each of the situations in Figure 5.2.2. If your class is large enough, compare duplicated data for any potential sources of error.
2. Use the technique you used to measure acceleration in an earlier chapter. Remember that a group of six dots represents 0.10 s and that the average speeds for each interval are plotted mid-way through each time interval and not at the end of the interval.
3. Prepare your graph. Label it carefully with the unbalanced force used (2.0 N, 4.0 N, 6.0 N, or 8.0 N) and the mass of the cart system.
4. The most important measurement you need is the acceleration of the cart. You get this from the slope of the graph. Express the acceleration in cm/s^2. You will share this information with the rest of the class.

Part 3: Analyzing Class Data

1. Prepare the following tables of data, summarizing class results.

Table 5.2.1 *Acceleration vs. Unbalanced Force (mass constant)*

Unbalanced Force F (N)	**Acceleration** a (cm/s^2)
0	0
2.0	
4.0	
6.0	
8.0	

Table 5.2.2 *Acceleration vs Mass (unbalanced force constant)*

Mass, m (mass units)	**Acceleration**, a (cm/s^2)	$\frac{1}{\text{mass}}, \frac{1}{m}$ (mass units^{-1})
1.0		1.0
2.0		0.50
3.0		0.33
4.0		0.25

2. Plot a graph of acceleration (y-axis) against unbalanced force (x-axis).
3. Plot a graph of acceleration against mass.
4. Plot a graph of acceleration against the reciprocal of mass ($1/m$).

Concluding Questions

1. Describe how the speed of a cart changes when a constant unbalanced force pulls it.
2. According to your first graph (a vs. F), how does acceleration depend on unbalanced force? Does your graph suggest that acceleration is directly proportional to unbalanced force? Support your answer with your data.
3 According to your second and third graphs, how does the acceleration of the cart vary when the mass is doubled, tripled, and quadrupled?
4 Write an equation for the third graph, complete with the numerical value and units for the slope.
5 What were some of the experimental difficulties you encountered in this investigation, which would make it difficult to obtain ideal results?

5.2 Review Questions

1. What unbalanced force is needed to accelerate a 5.0 kg cart at 5.0 m/s^2?

2. A net force of 7.5×10^4 N acts on a spacecraft of mass 3.0×10^4 kg.
   (a) At what rate will the spacecraft accelerate?

   (b) Assuming constant acceleration is maintained, how fast will the spacecraft be moving after 25 s, if its initial speed was 5.0×10^3 m/s?

3. A model rocket has a mass of 0.12 kg. It accelerates vertically to 60.0 m/s in 1.2 s.
   (a) What is its average acceleration?

   (b) What is the unbalanced force on the rocket?

   (c) If the force of gravity on the rocket is 1.2 N, what is the total thrust of its engine?

4. What is the mass of a rock if a force of 2.4×10^3 N makes it accelerate at a rate of 4.0×10^1 m/s^2?

5. A fully loaded military rocket has a mass of 3.0×10^6 kg, and the force of gravity on it at ground level is 2.9×10^7 N.
   (a) At what rate will the rocket accelerate during lift-off, if the engines provide a thrust of 3.3×10^7 N?

   (b) Why will this acceleration not remain constant?

6. A boy and his skateboard have a combined mass of 60.0 kg. After an initial shove, the boy starts coasting at 5.5 m/s along a level driveway. Friction brings him to rest in 5.0 s. The combined force of gravity on the boy and skateboard is 5.9×10^2 N. What is the average coefficient of rolling friction between the driveway and the skateboard wheels?