Section 4 Newton's Second Law of Motion: The Rear-End Collision

Performance Expectation

The following *Performance Expectation* is targeted in this section:

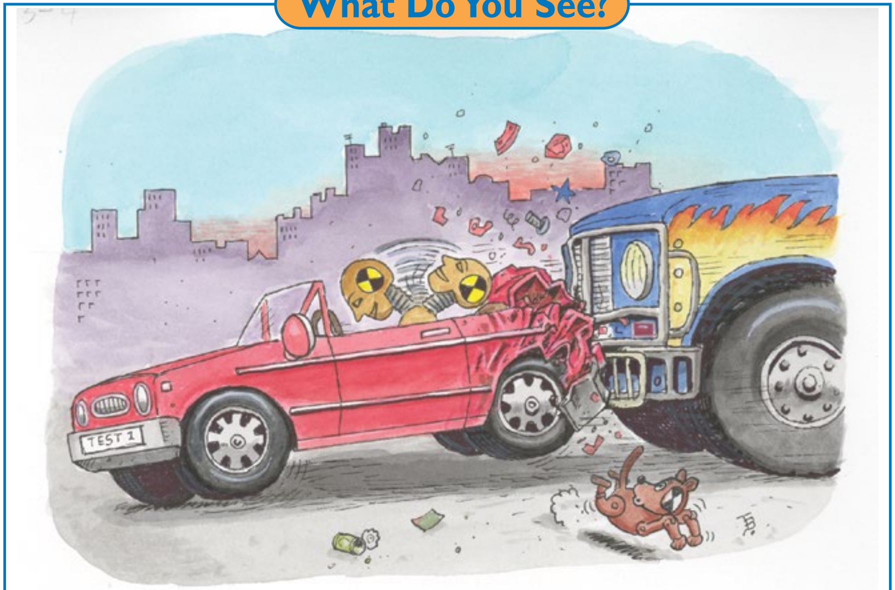
- Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

Learning Outcomes

In this section, you will

- **Evaluate,** from simulated collisions, the effect of rear-end collisions on the neck muscles.
- **Describe** the causes of whiplash injuries.
- **Provide** examples of Newton's first and second laws of motion in automobile crashes.
- **Analyze** the role of safety devices in preventing whiplash injury.

What Do You See?



What Do You Think?

The whiplash effect is a serious injury that is caused by a rear-end collision. It is the focus of many lawsuits, the inability to work, and discomfort.

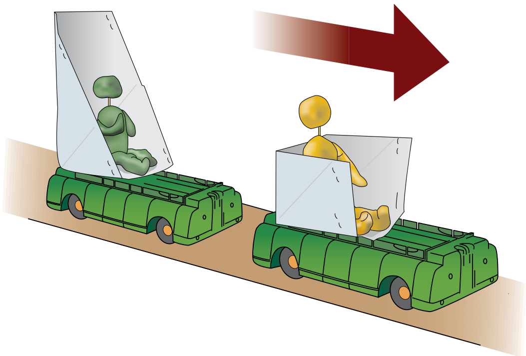
- **What is whiplash?**
- **Why is it more prominent in rear-end collisions?**

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

Investigate

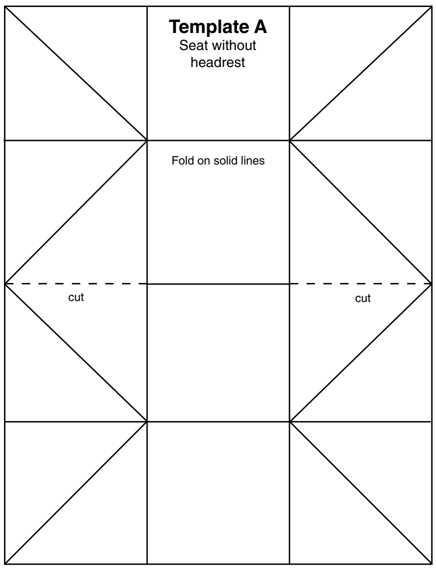
Whiplash injury can occur in automobile collisions at surprisingly low speeds—as low as 2.7 m/s (6 mi/h). In this section, you will plan and carry out an investigation to simulate a rear-end collision between two carts—a "bullet" cart and a "target" cart. The bullet cart will be moving at a speed of approximately 2.7 m/s (6 mi/h) and will strike a stationary target cart. You will use the data you collect to help you design your solution to the *Chapter Challenge*.

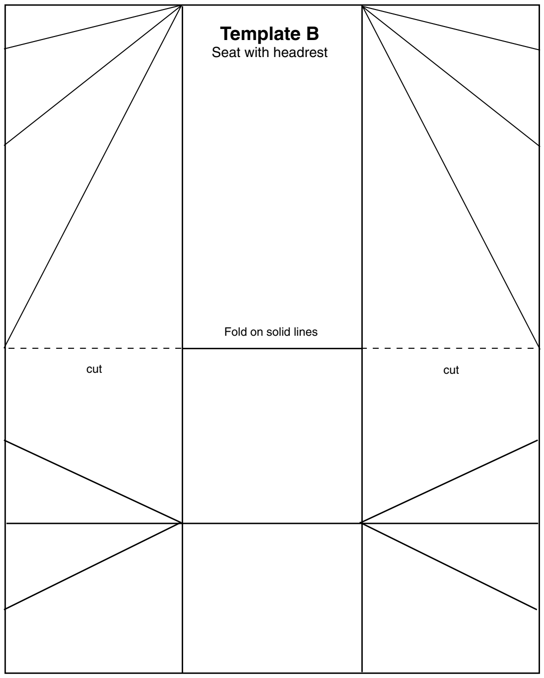
You will need to create two clay passengers and two different driver's seats—one with a headrest and one without a headrest.



1. Your teacher will provide you with a set of two templates to create driver's seats. Use Template A to create a driver's seat with no headrest. The clay passenger should fit into this seat so that the shoulders of the passenger are level with the top of the seat. (There is no built-in support for the head.)
2. Create the clay passenger in two sections. In the first section, create the torso and legs out of clay.

   In the second section, create the head and connect it to the torso with a small piece of clay rolled in the shape of a neck so that the head is not sitting directly on the shoulders. Use a 2.5 cm piece of # 26 wire to fasten the head-neck-torso combination. The wire represents the spinal column in the neck. Do not press the head onto the neck, but rather allow it to rest on it held in place by the wire. The passenger and seat will go in the target cart.
3. Create a similar second clay passenger to go in the bullet cart. Use Template B to create a driver's seat with a headrest.
4. Use masking tape to create seat belts for both dummies.
5. Set up a ramp about 40 cm high, as shown in the diagram on the following page. Use a piece of stiff paper (like card stock) at the bottom of the ramp to smooth out the bump when the cart comes off the ramp.





Release the bullet cart from the position on the ramp. This produces an average speed of approximately 2.7 m/s (6 mi/h). This may take several trials.

6. Now place the target cart about 50 cm from the end of the ramp.

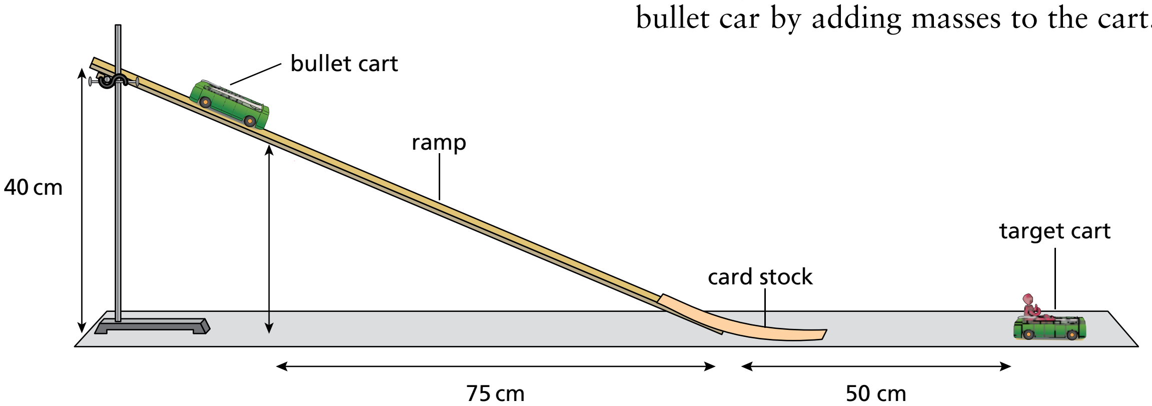
7. Release the bullet cart from the same position on the ramp to produce a 2.7 m/s (6 mi/h) collision with the target cart.

a) What happens to the clay passenger's head in the target cart?

b) Use Newton's first law of motion to explain your observations.

8. Repeat this experiment (*Steps 1-7*) by exchanging the carts so that the cart with the headrest is the target cart.

9. Repeat this experiment using a bullet cart with a mass two to three times the mass of the target cart. You may be able to tape two or three carts together or one on top of the other to get a cart with about two to three times the mass. You may also increase the mass of the bullet car by adding masses to the cart.



Physics Talk

NEWTON'S SECOND LAW OF MOTION

Newton's first law informs us what happens to objects if no net force acts upon them. Knowing that objects at rest have a tendency to remain at rest and that objects in motion will continue in motion does not provide enough information to analyze collisions. **Newton's second law of motion** allows you to make predictions about what happens when an unbalanced external force is applied to an object. If you were to place a collision cart on a level surface, it would not move. However, if you begin to push the cart, it will begin to move.

Newton's second law of motion states:

> If a body is acted on by an unbalanced force, it will accelerate in the direction of the unbalanced force. The acceleration will be larger for smaller masses. The acceleration can be an increase in speed, a decrease in speed, or a change in direction.

Newton's second law of motion indicates that the change in motion is determined by the net force acting on the object, and the mass of the object itself. Physicists are never satisfied with a verbal explanation and always ask, "Is there an equation that can describe this precisely?"

Physics Words

Newton's second law of motion: if a body is acted on by an unbalanced force, it will accelerate in the direction of the unbalanced force. The acceleration will be larger for smaller masses. The acceleration can be an increase in speed, a decrease in speed, or a change in direction.

Newton's second law does have such an equation that can be written as:

$$F = ma \text{ or } a = \frac{F}{m}$$

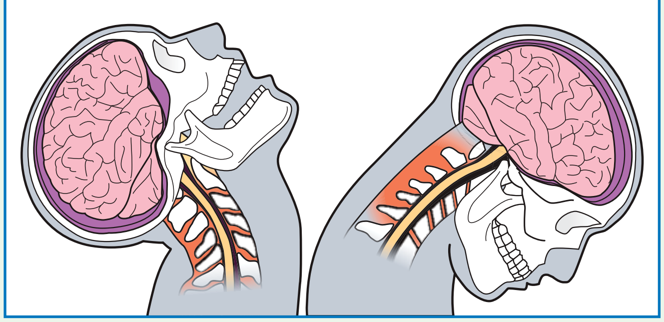
From this equation, one can see that "if a body is acted upon by an unbalanced force, it will accelerate in the direction of the unbalanced force." One can also see that the "acceleration will be larger for smaller masses."

What is Whiplash?

In the collision in the investigation you completed, where the target cart did not have a headrest, the clay head swung back during the collision. **Whiplash** is a serious injury that can be caused by a rear-end collision. The back of the automobile seat pushes forward on the torso of the driver and the passengers and their bodies lunge forward. The head remains still for a very short time. The body moving forward and the head remaining still causes the head to snap backward. The neck muscles and bones of the vertebral column (spine) become damaged. The same muscles must then snap the head back to its place atop the shoulders.

Physics Words

whiplash: the common name for a type of neck injury to muscles of the neck.



A headrest can prevent whiplash injury. The headrest must be adjusted for the height of the passenger.

Newton's First and Second Laws of Motion and Whiplash

The activity in this section demonstrated the effects of a rear-end collision. Newton's first law and Newton's second law can help explain the "whiplash" injury that passengers suffer during this kind of collision.

Imagine looking at the rear-end collision in slow motion. Think about all that happens.

- An automobile is stopped at a red light. This is the automobile in which the driver is going to receive a whiplash injury. It was the target cart in your investigation. The driver is at rest within the automobile.

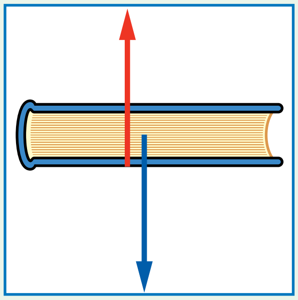
- The stopped automobile gets hit from the rear.
- The automobile begins to move. The back of the seat pushes the driver forward and the driver's torso moves with the automobile. The driver's head is not supported and tends to stay back where it is.
- The neck muscles hold the head to the torso as the body moves forward. The muscles then "whip" the head forward. The head keeps moving until it gets ahead of the torso. The neck muscles stop the head, and pull it back to its usual position. Ouch!

Let's repeat the description of the collision and insert all of the places where Newton's first law and Newton's second law apply (in color).

- An automobile is stopped at a red light. This is the automobile in which the driver is going to receive a whiplash injury. The driver is at rest within the automobile. Newton's first law: An object at rest stays at rest, and an object in motion stays in motion unless acted upon by an unbalanced, outside force.
- The stopped automobile gets hit from the rear.
- The automobile begins to move. Newton's second law: The automobile accelerates because of the unbalanced, outside force from the rear: $F = ma$. The back of the seat pushes the driver forward and the driver's torso moves with the automobile. Newton's second law: The torso accelerates because of the unbalanced, outside force from the back of the seat: $F = ma$. The driver's head is not supported and stays back where it is. Newton's first law: an object (the driver's head) at rest stays at rest.
- The neck muscles hold the head to the body as the body moves forward. The muscles then "whip" the head forward. Newton's second law: The head accelerates because of the unbalanced force of the muscles: $F = ma$. The head keeps moving until it gets ahead of the torso. Newton's first law: An object (the head) in motion stays in motion. The head is stopped by the neck muscles. The muscles pull the head back to its usual position. Newton's second law: The head accelerates (slows down) because of the unbalanced force from the neck muscles: $F = ma$. Ouch!

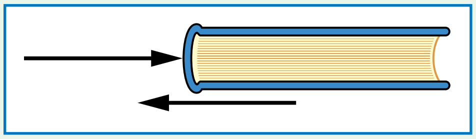
Newton's second law informs you that all accelerations are caused by *unbalanced, outside* forces. It does not say that all forces cause accelerations, only those that are unbalanced.

An object at rest may have many forces acting upon it. When you hold a book in your hand, the book is at rest. There is a force of gravity pulling the book down. There is a force of your hand pushing the book up. These forces are equal and opposite. The "net" force on the book is zero because the two forces balance each other. There is no acceleration because there is no "net" force.



As an automobile moves down the highway at a constant speed, there are forces acting on the automobile but there is no acceleration. No acceleration indicates that the net force must be zero. The force of the engine on the tires and road moving the automobile forward must be equal in magnitude and opposite in direction to the force of the air pushing backward on the automobile. These forces balance each other in this case, where the speed is not changing. There is no net force and there is no acceleration. The automobile stays in motion at a constant speed.

A similar situation occurs when you push a book across a table at constant speed. The push is to the right and the friction is to the left, causing opposing motion. If the forces are equal in size, there is no net force on the book. The book does not accelerate—it moves with a constant speed.



Checking Up

1. What type of safety devices can prevent a whiplash injury?
2. Describe how a whiplash injury occurs in a vehicle collision.
3. Use Newton's first and second laws of motion to analyze how a whiplash injury occurs during a rear-end collision.

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
◆			

Using Equations to Analyze a Whiplash Injury

1. Using the model of whiplash and assuming that the driver's head has a mass of 5 kg, calculate the force on the driver's neck muscles during the collision when the target vehicle gets hit and moves at 3 m/s, 5 m/s, 10 m/s, and 15 m/s. (To give a better sense of these speeds, 27 m/s = 60 mi/h.) Assume this change in motion occurs in 0.2 s (seconds).
2. Draw a graph showing the relationship between force on the neck muscles versus speed of the automobile coming from behind.
3. Repeat the analysis assuming that the time is only 0.1 s (seconds).

What Do You Think Now?

At the beginning of the section, you were asked

- **What is whiplash?**
- **Why is it more prominent in rear-end collisions?**

Revisit your initial ideas about whiplash and rear-end collisions. Based on your investigation of Newton's first and second laws, how would you answer these questions now?

What Do You See Now?

Look at the cartoon at the beginning of this section. Now that you have completed this section, what additional features do you see that demonstrate you have a better understanding of the physics?

Physics Essential Questions

What does it mean? (Disciplinary Core Ideas)

Use Newton's second law of motion to explain what happens to a passenger in a rear-end collision.

How do you know? (Connect Core Ideas and Practices)

How do you know that headrests can improve passenger safety during a rear-end collision?

Why do you believe? (Connect Core Ideas and Crosscutting Concepts)

Connects with Other Physics Content (Disciplinary Core Ideas)	Fits with Big Ideas in Science (Crosscutting Concepts)	Meets Physics Requirements (Nature of Science)
Forces and motion	Cause and effect Systems and system models Stability and change	Optimal prediction and explanation *

* In physics, there is often more than one correct way to describe an event. Describe a rear-end collision using Newton's first law and compare it with your explanation using Newton's second law.

Why should you care?

How can the possibility of a rear-end collision be factored into the design of your safety system?

Reflecting on the Section and the Challenge

Whiplash is a serious injury that can occur during rear-end collisions. The bones that attach the spinal column to the skull are called attachment bones. They are supported by the least amount of muscle. Unfortunately, these smaller bones, with less muscle support, make this area particularly susceptible to injury. The brainstem is very susceptible to damage following whiplash. The brainstem is vital because it regulates blood pressure and breathing movements. By restraining the movement of the head and neck muscles, you can protect against the most severe aspects of whiplash.

Physics 3D Question

Performance Expectation (with Disciplinary Core Idea)	Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.
Science and Engineering Practices	Constructing explanations and designing solutions
Crosscutting Concepts	Structure and function

A seat belt is helpful if your car hits a tree head-on. A headrest is helpful when your car gets hit from behind. Use Newton's first and second laws to explain how these technologies minimize injury in an accident.

Physics to Go

1. Why are neck injuries common during rear-end collisions?
2. Explain why packages in the back of a truck move forward if it comes to a quick stop.
3. As a bus accelerates, the passengers on the bus are jolted toward the back of the bus. Explain what causes the passengers to be apparently pushed backward.
4. Why would the rear-end collision demonstrated in the *Investigate* be more dangerous for someone driving a motorcycle than driving an automobile?
5. Explain in which type of collision headrests serve the greater benefit: during a head-on collision or a rear-end collision?
6. What additional devices have been placed in automobiles to help reduce the impact of rear-end collisions?
7. Consider how your safety device will help prevent whiplash injuries following a collision. What part of the restraining device prevents the movement of the head?
8. As a way to help you learn more about whiplash, rate your whiplash knowledge by taking this whiplash quiz and then check your knowledge against the answers given at the end.

Whiplash Quiz

1. The range of collision speed in which most (nearly 80 percent) rear-impact whiplash injuries occur is:
   a) 10-25 mi/h (4.5 – 11 m/s or about 16-40 km/h)
   b) 15-30 mi/h (7 – 13 m/s or about 25-47 km/h)
   c) 1-5 mi/h (0.5 – 2.3 m/s or about 2-8 km/h)
   d) 6-12 mi/h (2.7 – 5.4 m/s or about 10-19 km/h)
2. Human-volunteer crash testing, which simulated rear-impact collisions, was conducted at University of California, Los Angeles, and demonstrated the following relationships:
   a) The volunteer's head was subjected to 2 ½ times the acceleration as the vehicle itself.
   b) The volunteer's head was subjected to about ½ the acceleration as the vehicle itself.
   c) The volunteer's acceleration was roughly equivalent to stepping off a curb.
   d) In low-speed collisions, under 8 mi/h (about 12 km/h), no acceleration of the human head can be measured.
3. Regarding the outcome of whiplash injuries, which of the following statements is most accurate?
   a) The vast majority of whiplash injuries resolve in about 6 weeks.
   b) The vast majority of whiplash injuries resolve in 6-12 weeks.
   c) About 25-50 percent of whiplash injuries fail to resolve completely.
   d) Whiplash injuries rarely resolve completely.
4. Although a fairly large percentage of persons will have symptoms on a permanent basis following whiplash injury, what proportion of whiplash patients will have disability?
   a) 2% b) 5% c) 10% d) 18% e) 59%
5. The majority of modern automobiles behave relatively stiffly in low-speed, rear-impact collisions. Permanent damage to bumper systems begins to occur at which range of collision speeds?
   a) 20-25 mi/h (9-11 m/s or about 32-40 km/h)
   b) 2-7 mi/h (1-3 m/s or about 4-11 km/h)
   c) 8-12 mi/h (3.6-5.4 m/s or about 13-19 km/h)
   d) 25-30 mi/h (11-14 m/s or about 40-50 km/h)

6. According to the authors of one series of full-scale, rear-impact crash tests using human volunteers, the threshold for cervical spine soft tissue injury (whiplash injury) occurs at speeds of:

   a) 12 mi/h (5.4 m/s or about 19 km/h)

   b) 5 mi/h (2.3 m/s or about 8 km/h)

   c) 2 mi/h (0.9 m/s or about 3 km/h)

   d) 15 mi/h (7 m/s or about 25 km/h)

(Source: *Dynamic Chiropractic*, August 11, 1997, volume 15, issue 17)

Answers:

1. (d) **2.** (a) **3.** (c) **4.** (e) **5.** (c) **6.** (b)

Inquiring Further

Crash-test dummies

Investigate crash-test dummies on the Internet. Prepare a 5-minute presentation for the class or a paper including information about how much they cost, their functions, and the variety that exist.