Topic 4.1

Linear Momentum

Learning Objectives

- Describe the linear momentum of an object or system.
- Recognize that linear momentum is a vector.

Topic Questions

- What is momentum?
- How is the direction of the momentum of an object determined?

4.1.01 Linear Momentum as a Vector

[4.1.A.1 4.1.A.2 4.1.A.3]

This unit describes the notions of **momentum** and **impulse**, which can be used to describe the motion of objects before and after a force is exerted on them. The first topic addresses the idea of **linear momentum**, which applies to any object with mass in motion relative to some reference frame. An object of mass m moving with a velocity $\vec{v}$ has a linear momentum $\vec{p}$ equal to the product of m and $\vec{v}$ (see Figure 4.1):

$$\vec{p} = m\vec{v}$$

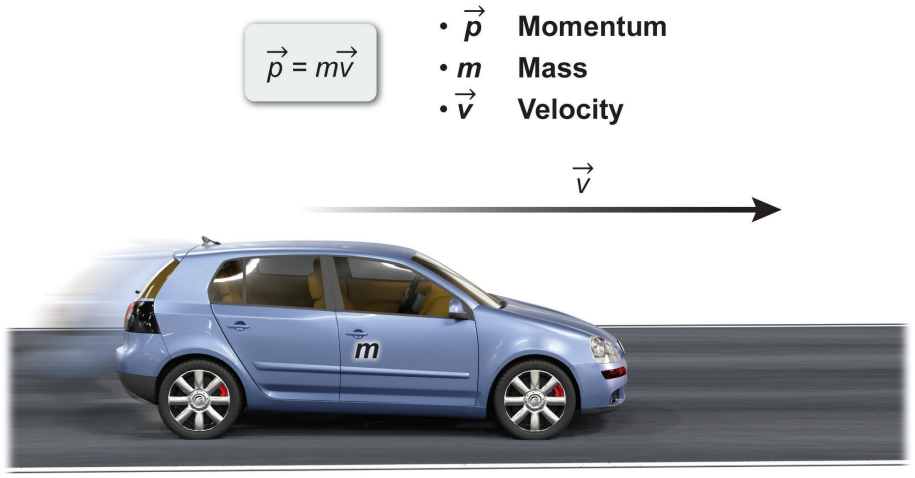

Figure 4.1 The linear momentum of a moving object.

Linear momentum $\vec{p}$ is a vector quantity that has both a magnitude and a direction. An object's $\vec{p}$ is directly proportional to its mass and its velocity. The SI unit for linear momentum does not have its own identity. The definition of linear momentum implies that the units are the product of mass (kg) and velocity (m/s):

$$[\vec{p}] = [\text{kg}]\left[\frac{\text{m}}{\text{s}}\right]$$

For example, consider the $\vec{p}$ for a 2.5 kg lab cart, as shown in Figure 4.2. A student gives the cart a push and measures the velocity of the cart to be 5.0 m/s to the right as it travels on a straight and level track. The magnitude of the linear momentum $|\vec{p}|$ of the cart equals:

$$|\vec{p}| = (2.5\ \text{kg})\left(5.0\ \frac{\text{m}}{\text{s}}\right)$$

$$|\vec{p}| = 12.5\ \frac{\text{kg} \cdot \text{m}}{\text{s}}$$

Because $\vec{p}$ is a vector with magnitude and direction, the direction of the cart's $\vec{p}$ is the same as the direction of its $\vec{v}$. Hence, the $\vec{p}$ is directed to the right.

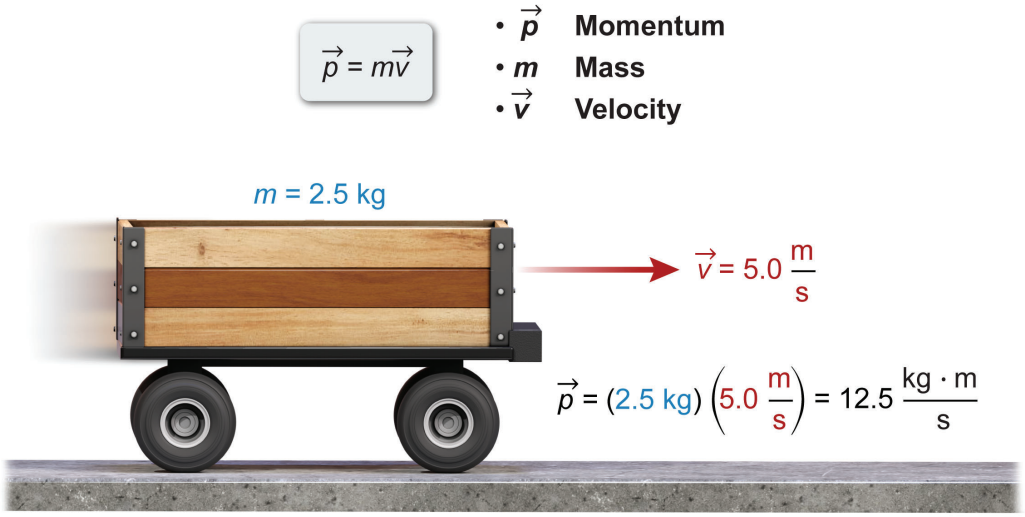

Figure 4.2 Linear momentum of a cart on a track.

The student investigates a different example by taking a 0.25 kg baseball and throwing it straight up with some velocity v. The student wants to know the direction of the momentum vector $\vec{p}$ when the baseball reaches its maximum height at the top of its path (see Figure 4.3):

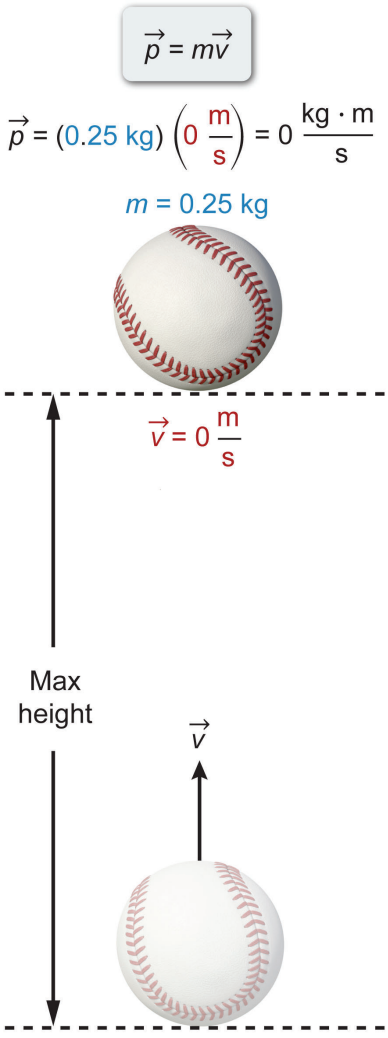

Figure 4.3 Linear momentum of a baseball when reaching the top of the of its path.

Since the velocity of the baseball at the top of its path is 0 m/s, the linear momentum is equal to 0 (kg·m)/s:

$$\vec{p} = (0.25\ \text{kg})\left(0\ \frac{\text{m}}{\text{s}}\right) = 0\ \frac{\text{kg} \cdot \text{m}}{\text{s}}$$

Therefore, the baseball does not have a linear momentum vector when it reaches its maximum height.

An object's linear momentum can be useful when trying to quantify an object in motion, much like an object's kinetic energy (see Topic 3.1). Linear momentum differs from kinetic energy because it is a vector quantity. This characteristic makes it useful for describing how easy or difficult it is for an object to change its motion, including when it changes direction or changes speed. This description can apply to a single object or a system of objects when experiencing a force, colliding with one another, or undergoing an explosion.

Topic 4.1 Linear Momentum

Check for Understanding Quiz

1. A car begins to merge onto a highway with a speed of 15 m/s. To complete the merge safely, the car increases its speed to 30 m/s, matching the other cars already on the highway. By what factor has the car's momentum increased?

   A. 0.5

   B. 2

   C. 4

   D. 15

2. A baseball player swings a bat at a baseball and pops the ball straight upward. The baseball travels upward to a maximum height, where it momentarily stops and then begins accelerating downward. What direction does the baseball's linear momentum vector point right before it hits the ground?

   A. Up

   B. Down

   C. Right

   D. It has no momentum vector.

Note: Answers to this quiz are in the back of the book (appendix).