Lesson 3
Forces

Introduction: Connecting Your Learning

The previous lesson introduced kinematics, the study of motion without regard to the forces that produce it. When forces are considered, the study is then of dynamics. Lesson 3 examines forces and their actions and reactions in regards to motion. This lesson also expands the concept of force and describes how the net force on an object is related to the acceleration (or change in the motion) of the object. Newton's three laws of motion are described in detail. The concept of a vector is introduced and applied to both one-dimensional and two-dimensional motions.

Readings, Resources, and Assignments	
Required Textbook Readings	*Newtonian Physics* Chapter 4 Chapter 5, Section 5.1, pp. 123-149

Check Prior Knowledge

Check your prior knowledge by seeing if you can correctly determine if each statement is true or false.

True or False

1. The object with the most forces on it moves the fastest.
2. Forces on an object will always cause the object to accelerate.
3. Mass has no effect on an object's tendency to accelerate.

Focusing Your Learning

Lesson Objectives

By the end of this lesson, you should be able to:

1. Discuss Newton's 1st Law of Motion and explain why this law is often referred to as the Law of Inertia.
2. Recognize the basic quantities that describe motion and forces, identify whether the quantities are vectors or scalars, and match the quantities with their respective units of measurement.

3. Discuss Newton's 2nd Law of Motion and explain why this law is often referred to as the link between net force and acceleration.

4. Calculate the net force, mass, or acceleration of an object, given two of the three variables.

5. Analyze the forces acting on an object in terms of the vector components of the forces.

6. Draw a free body diagram showing the various forces that may act on an object such as weight, normal force, applied force, and frictional force.

7. Distinguish between action and reaction forces in the context of Newton's 3rd Law.

Approaching the Objectives

This lesson is comprised of six sections:

Section 1: Forces and Equilibrium

Section 2: Newton's 1st Law of Motion

Section 3: Vectors and Vector Components

Section 4: Newton's 2nd Law of Motion

Section 5: Air Resistance and Terminal Velocity

Section 6: Newton's 3rd Law of Motion

Section 1: Forces and Equilibrium

Begin this section by reading Chapter 4, Section 4.1, pp. 124 to 126 in the *Newtonian Physics* textbook. View the video from Khan Academy on Forces.

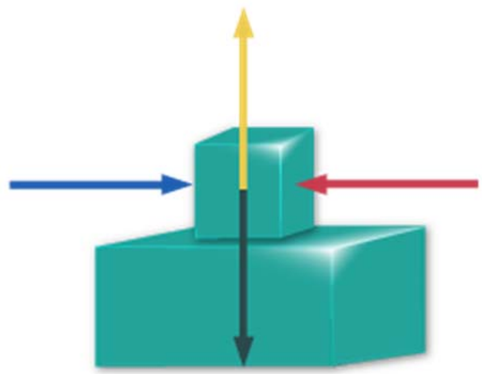
There are two broad categories of forces. The first category includes the contact forces. Examples of contact forces are pushes, pulls, tension in a rope attached to an object, forces of contact between two objects (e.g., a box sitting on a table), and the normal force (if the force of one surface on another is perpendicular to the surface).

Forces are vector quantities. This means that the direction of the force on an object influences the change in the motion of the object that results from the application of the force. The magnitude of the force (how strong or weak the force is) also influences the change in motion. Notice that the key word is change. More than one force can act on an object at once. The vector sum of these forces produces the net force on the object. When an object has a net force acting on it, this produces an acceleration (or change in the motion).

The net force and the acceleration are always in the same direction.

When the net force on the object is zero, the object is said to be in equilibrium. If the object happens to be at rest, this is referred to as static equilibrium. An object can be in dynamic equilibrium, even if the object is moving, as long as the velocity is constant. A constant velocity implies zero acceleration, which further implies there is no net force on the object. These relationships are explored in more detail in the next lesson.

The second category of forces is sometimes referred to as the "action at a distance" forces. Gravity is a prime example. When an object is dropped near the surface of the Earth, there is no contact seen between the object and the Earth. The object just falls. The force that is acting is an attractive force between the object and the Earth. The force due to gravity is included here because it appears in the free body diagram below as one of the forces acting on the box shown sitting on a table.



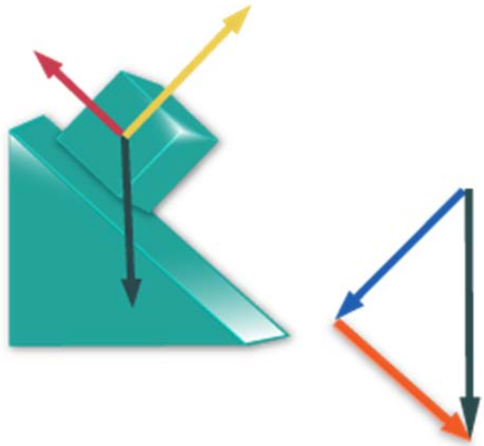
The diagram above represents a box sitting motionless on a table. The four arrows represent the forces acting on the box. The blue vector represents an applied force (a push in this case). The red vector represents the force due the friction between the box and the table (always in a direction that opposes intended motion). The yellow vector represents the normal force. This is the force of the table on the box, which acts perpendicular the surface of the table. Lastly, the black vector represents the force due to gravity. This force acts downward toward the center of the earth.

When the vectors are drawn on a coordinate system, all of the vector tails are usually placed together at the coordinate system origin.

Activity: Fill in the table below based on the free body diagram used in the activity above. Answers are located at the end of the lesson.

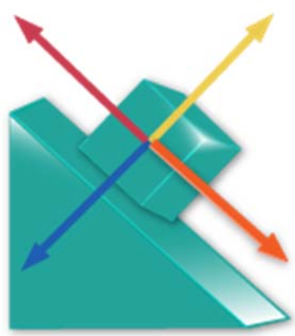
Question	**Your Description / Explanation**
Describe the net force in the horizontal direction	
Describe the net force in the vertical direction	
If the box started moving at a constant velocity, how would the vector picture change?	
Could the force due to gravity ever be larger than the normal force?	

If an object is sitting on a ramp, the force due to gravity is still directed downward. The normal force is directed perpendicular to the surface. This means that only a component of the weight is used to balance the normal. The other perpendicular component of the weight is directed down the ramp.



The force of gravity (black vector) can be broken down into two perpendicular components that when added together as vectors represent the same black vector.

Vectors are added head (the tip of the arrow) to tail (the other end of the arrow). This means the dark blue vector plus the orange vector equals the black vector. So, the black vector can be replaced in the free body diagram by the dark blue vector and the orange vector.



Activity:

Based on the free body diagram shown above, determine what each vector represents. Answers are found at the end of the lesson.	
Vector	**What Does the Vector Represent?**
Red	
Yellow	
Orange	
Blue	

Based on the free body diagram shown above, respond to each of the items in the left hand column below.	
Describe the net force in the direction parallel with the plane	
Describe the net force in the direction perpendicular with the plane	
If the box started moving at a constant velocity, how would the vector picture change?	
Could the force due to gravity ever be larger than the normal force?	

The next section introduces the three primary variables used to completely describe uniformly accelerated motion in a straight line.

Section 2: Newton's 1st Law of Motion

Begin this section by reading Chapter 4, Section 4.2, pp. 127 to 131 in the *Newtonian Physics* textbook. View the video from Khan Academy on Newton's 1st Law of Motion.

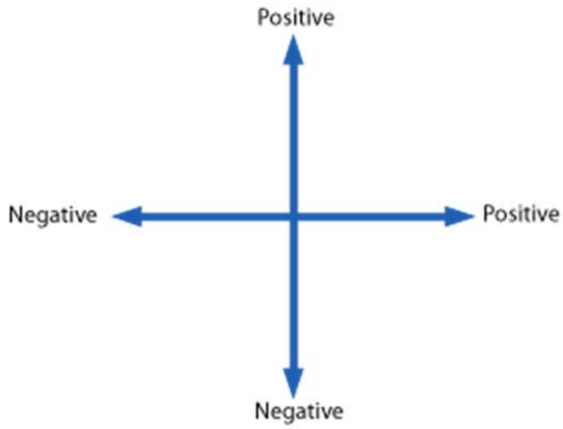
As you learned in a previous lesson, early Greek philosophers believed that objects need some sort of force or impetus to sustain motion. Newton's 1st Law of Motion completely turns this thought around. Objects that are in motion will stay in motion forever unless some net force acts on the object to cause a change in the motion. Likewise, if the object is at rest, the object will remain at rest unless a net force on the object causes it to start moving. This experimentally observed phenomenon has been a cornerstone of classical mechanics for several hundred years and today remains the defining principle that relates mass and inertia. Newton's 1st Law is sometimes referred to as the Law of Inertia.

View demonstrations of Newton's 1st Law from WonderHowTo

Section 3: Vectors and Vector Components

Quantities that have both magnitude (amount) and direction are referred to as vectors. Vectors are usually represented by drawing an arrow where the length of the arrow represents the magnitude, and the direction of the arrow represents the direction that the quantity is acting. The motion of objects must be related to a frame of reference. Reference frames are usually stationary; however, for some problems it might be convenient to define a moving reference frame.

For most problems in the class, the normal reference frame is defined by the X-Y coordinate system. Motion in the X-direction is positive to the right and negative to the left. In the vertical direction, motion upward is positive and motion downward is negative.



Examples of vector quantities include:

Quantity	Units (SI)	Symbol	Definition
Displacement	Meters (m)	x or y	The vector difference between the final position of an object and the initial position of the object.
Velocity	meters/second (m/s)	v	The rate at which the displacement is changing with respect to (WRT) time.
Acceleration	meters per second per second (m/s^2)	a	The rate at which the velocity is changing with respect to (WRT) time.
Force	$kg{\cdot}m/s^2$ or Newton (N)	F	One Newton of force is the force required to cause a 1 kg object to change its velocity by 1 m/s each second.

Activity: Using the reference frame defined above, predict if the vector quantity is positive, negative, or zero. Answers can be found at the end of the lesson.

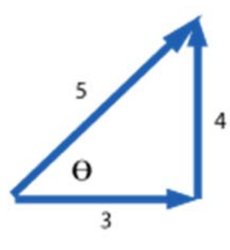
Motion	Displacement	Velocity	Acceleration
Object moving to the right and constant velocity			
Object moving to the left, speeding up			
Object moving to the right, slowing down			
Object moving to the left, slowing down			

Any vector can be resolved into two vectors that are perpendicular to each other. This is very convenient for solving problems that involve motion in two directions, such as the motion of a golf ball after being hit or the motion of a baseball after the bat hits it.

Vector addition and subtraction are different from adding or subtracting scalar quantities unless the vectors are collinear (acting in the same or opposite directions along a straight line).

For example, consider a velocity vector that represents 5 cm/s at some angle (WRT) to the X-axis. This vector can be resolved into a 3 cm/s vector along the X-axis and a 4 cm/s vector along the Y-axis. Remember the 3-4-5 right triangle.

In this illustration, when the 3 m/s vector is added to the 4 cm/s vector (head to tail), the resultant vector is 5 m/s NOT 7 m/s. **The mathematics required to resolve vectors at any angle requires the use of simple right angle geometry/trigonometry.**



Sin Θ =	Opposite side/hypotenuse	= 4/5 = 0.8
Cos Θ =	Adjacent side/hypotenuse	= 3/5 = 0.6
Tan Θ =	Opposite side/adjacent side	= 4/3 = 1.333

Note: If the resultant vector is R, then the x-component of R is R cos Θ.

If the resultant vector is R, then the y-component of R is R sin Θ.

This is a very important result, because it demonstrates that any vector can be resolved into two perpendicular components using simple ratios (i.e., sin and cos). This tool is invaluable when it comes to analyzing motion in two directions (i.e., projectile motion).

The next section represents perhaps the most important relationship in all of classical mechanics. Newton's 2nd Law establishes the relationship between the net force on an object and the resulting change in the object's motion (acceleration).

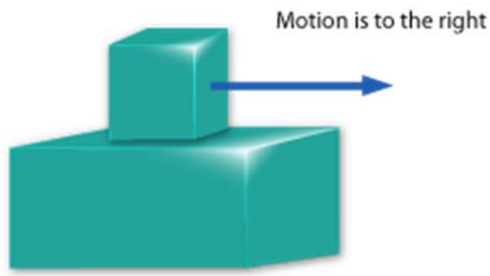
Section 4: Newton's 2nd Law of Motion

Begin this section by reading Chapter 4, Section 4.3, pp. 131 to 134 in the *Newtonian Physics textbook.* View the video from Khan Academy on Newton's 2nd Law of Motion.

Newton's 2nd Law relates the acceleration of an object to the net force acting on the object and the mass of the object. Acceleration and net force are directly proportional, which means if the net force increases, then the acceleration will also increase and vice versa. Acceleration and net force are both vector quantities, and the direction of the two vectors will always be the same. A common method to determine the net force on an object is to draw a free body diagram. This is a vector sketch showing all the forces acting on an object. **Note:** The sketch does not have to be drawn to scale unless the free body diagram is intended to quantitatively solve the problem. Below is a table showing some of the common forces that can be used in the free body diagram.

Force	Symbol	Definition	Direction
Normal	F_N	The contact force exerted by a surface on an object.	Perpendicular and away from the surface
Weight	F_g	The product of the mass of the object and the acceleration due to gravity (mg).	Straight down toward the center of the Earth
Tension	F_T	The pull exerted by a rope or cable attached to an object.	Away from the object (in the same direction as the rope or cable.
Applied	F_A	A push or pull on the object.	Direction of the push or pull.
Friction	F_f	A contact force that opposes motion.	In the direction that opposes motion.

In the illustration below, a box is sliding across a table from left to right. The surfaces are rough and friction is present. The box is moving at constant velocity.

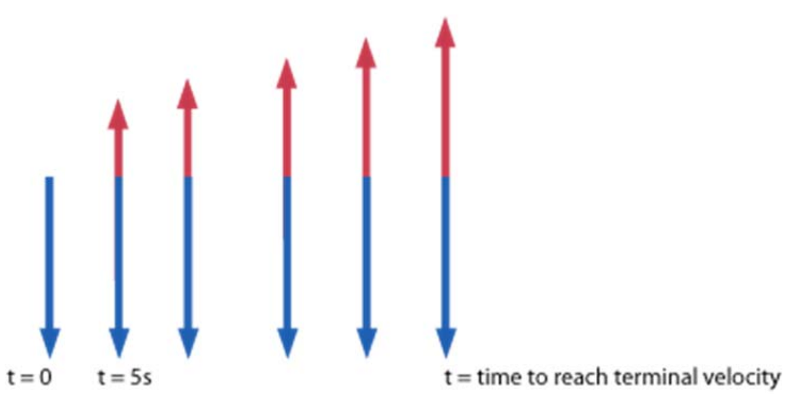


Complete the following statements as positive, negative, or zero: (Answers are found at the end of the lesson.)

1. The displacement is __________
2. The velocity is __________
3. The acceleration is __________

Section 5: Air Resistance and Terminal Velocity

Free fall is a special case of uniformly accelerated straight-line motion where the acceleration is provided by the force of attraction between an object and the massive Earth. Beginning problems in introductory physics usually ignore the frictional force between the object and the air around it. In the absence of air resistance, objects will fall freely at the same rate regardless of the object's mass, size, or shape. In the real world, air resistance must be addressed. The amount of air resistance is a function of how fast the object is traveling. Consider a large box dropped from a very tall building. At first, the air resistance is negligible, and the box starts to accelerate at $-9.8\ m/s^2$. The blue vector in the diagram below represents the weight. The red vector represents the air resistance. The weight vector stays constant, while the air resistance vector keeps increasing until it has the same magnitude as the weight vector. When these two vectors are equal in magnitude, the net force is zero, and the box continues to fall at a final constant velocity. The acceleration is then zero. This velocity is referred to as the terminal velocity.



True or False

(Check your answers at the end of the lesson.)

1. When the terminal velocity equals the weight of an object (in magnitude), the velocity of the object decreases to zero.
2. If the weight equals 10 N and the air resistance equals 2 N, the net force on the object is 12 N.
3. A net force of 8 N on the object will cause a 4 kg object to accelerate 2 m/s^2.
4. A net force of 8 N on the object will cause a 8 kg object to accelerate 1 m/s^2.
5. All objects in free fall will achieve terminal velocity prior to hitting the ground.

The next section focuses on Newton's 3rd Law. This law is perhaps the easiest to remember, but it is often the least understood. For every action force, there is an equal but opposite reaction force. What does this really mean?

Section 6: Newton's 3rd Law of Motion

Begin this section by reading Chapter 5, Section 5.1, pp. 145 to 149 in the *Newtonian Physics* textbook. View the video from Khan Academy on Newton's 3rd Law of Motion.

When you push on a wall, the wall pushes back on you. This is an example of a Newton's 3rd Law, action-reaction pair of forces. These forces are equal in magnitude and opposite in direction. However, unlike the weight and the normal force, which can cancel each other (or create a balanced force condition), the Newton's 3rd Law action-reaction pair never cancel each other out because these forces act on different objects. These action-reaction forces never appear in the same free body diagram.

When a force is identified: Force OF hand ON wall.

To obtain the 3rd Law reaction force, just switch the words hand and wall.

This yields Force OF wall ON hand. In this case, which force goes on the free body diagram? It depends on whether the motion of the wall is under consideration or the motion of the hand is being analyzed.

Free body diagrams contain all the forces on the object being studied.

When a ball is dropped, it heads for the ground because of the force of the Earth on the ball. There is an equal but opposite force of the ball on the Earth. So, why doesn't the Earth rush up to meet the ball? The forces are equal! The Earth does, in fact, experience acceleration, because of the force the ball exerts on the Earth. However, it is so small that this force can't be measured. The force exerted by the ball on the Earth is not nearly enough to overcome the huge inertia of the Earth.

Summarizing Your Learning

This lesson established the link between the description of motion and the forces that cause the motion to change. Newton's 1st Law is the law of inertia and dispels the ancient notion that bodies require a force to keep them moving. In fact, just the opposite is true. Newton's 2nd Law, (F = ma), is perhaps the most powerful physical law governing the motion of objects in the Universe. Finally, Newton's 3rd Law explains how action and reaction forces always exist in pairs. The next lesson continues the journey of classical mechanics by discussing two of the most powerful conservation laws in science: the conservation of momentum and the conservation of energy.

Practice Answers

Check Prior Knowledge

The object with the most forces on it moves the fastest. FALSE

Forces on an object will always cause the object to accelerate. FALSE

Mass has no effect on an object's tendency to accelerate. FALSE

Section 1: Forces and Equilibrium

Describe the net force in the horizontal direction	The net force is the applied force (blue vector) subtracted from the friction vector (red vector).
Describe the net force in the vertical direction	The net force is normal force (yellow vector) subtracted from the weight (black vector).
If the box started moving at a constant velocity, how would the vector picture change?	The magnitude of the applied force vector would be the same as the magnitude of the friction vector. The net force in the horizontal direction would be zero.
Could the force due to gravity ever be larger than the normal force?	Yes. If the object was on an inclined plane, the weight would be larger than the normal force. The weight would equal (**mg cos** θ) where θ is the angle of inclination

Based on the free body diagram shown above, determine what each vector represents.	
Vector	What Does the Vector Represent?
Red	Friction
Yellow	Normal force
Orange	Parallel component of the weight of the box
Blue	Perpendicular component of the weight of the box.

Based on the free body diagram shown above, respond to each of the items in the left hand column below.	
Describe the net force in the direction parallel to the plane.	This is the magnitude of the orange vector minus the magnitude of the red vector. The net force is directed down the plane.
Describe the net force in the direction perpendicular to the plane.	This is the magnitude of the yellow vector minus the magnitude of the blue vector. The net force is zero in this direction.
If the box started moving at a constant velocity, how would the vector picture change?	This is the magnitude of the orange vector minus the magnitude of the red vector. The box would continue moving at constant velocity.
Could the force due to gravity ever be larger than the normal	Yes. Only a component of the force due to gravity is needed to balance the normal force.

force?	

Section 3: Vectors and Vector Components

Motion	Displacement	Velocity	Acceleration
Object moving to the right and constant velocity	POSITIVE	POSITIVE	ZERO
Object moving to the left, speeding up.	NEGATIVE	NEGATIVE	NEGATIVE
Object moving to the right, slowing down	POSITIVE	POSITIVE	NEGATIVE
Object moving to the left, slowing down.	NEGATIVE	NEGATIVE	POSITIVE

Section 4: Newton's 2nd Law of Motion

- The displacement is POSITIVE.
- The velocity is POSITIVE.
- The acceleration is ZERO.

Section 5: Air Resistance and Terminal Velocity

When the terminal velocity equals the weight of an object (in magnitude), the velocity of the object decreases to zero. FALSE

If the weight equals 10 N and the air resistance equals 2 N, the net force on the object is 12 N. FALSE

A net force of 8 N on the object will cause a 4 kg object to accelerate 2 m/s2. TRUE

A net force of 8 N on the object will cause an 8 kg object to accelerate 1 m/s2. TRUE

All objects in free fall will achieve terminal velocity prior to hitting the ground. FALSE