# Conceptual Physics Fundamentals

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## Chapter 4:

## NEWTON’S LAWS OF MOTION

# Newton’s Laws of Motion

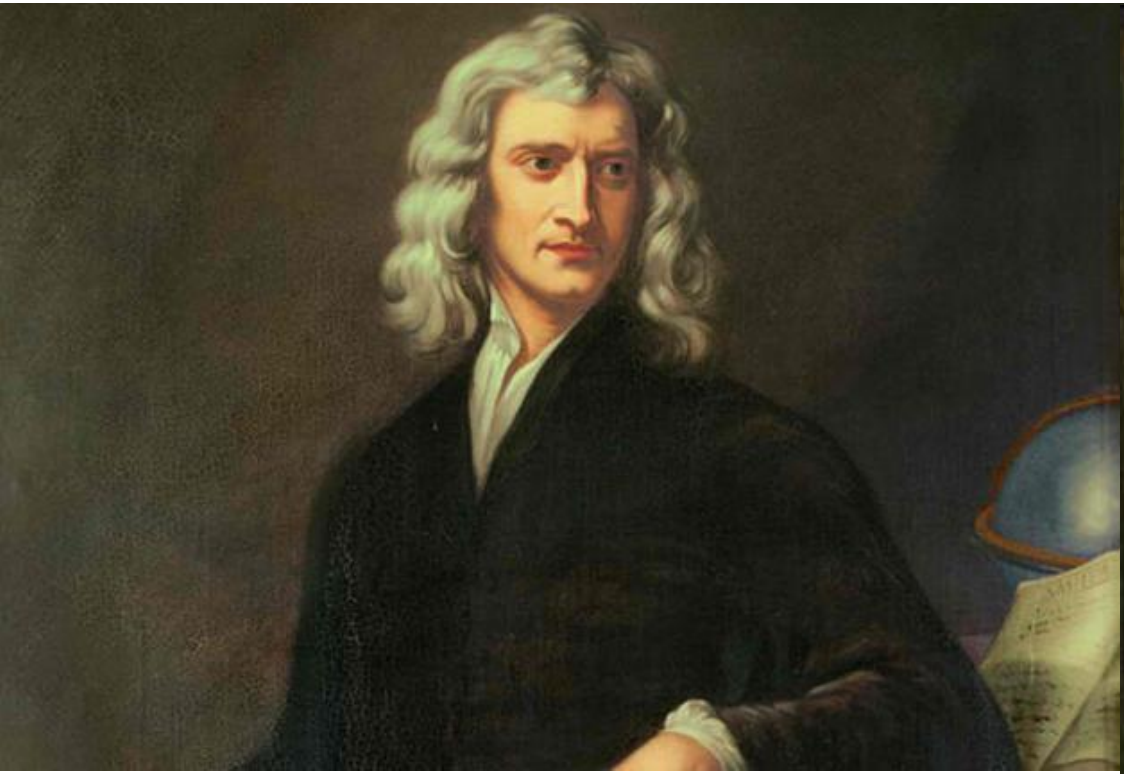
“I was only a scalar until you came along and gave me direction.”

—Barbara Wolfe

# This lecture will help you understand:

- Newton's First Law of Motion
- Newton's Second Law of Motion
- Forces and Interactions
- Newton's Third Law of Motion
- Vectors
- Summary of Newton's Laws of Motion

# Sir Isaac Newton (1642-1727)



- Newton invented calculus
- described the laws of universal gravitation (gravitas-weight) and the three laws of motion
- built the first reflecting telescope.

# Newton's First Law of Motion

Newton's First Law (the law of inertia)

- a restatement of Galileo's concept of inertia
- states that *every object continues in a state of rest or of uniform speed in a straight line unless acted on by a nonzero force*

# Newton's First Law of Motion

example: dishes remain in their initial state of rest when a tablecloth is whipped from beneath them


Inertia is the property of objects to resist changes in motion.

# Newton's First Law of Motion
# CHECK YOUR NEIGHBOR

A sheet of paper can be quickly withdrawn from under a soft-drink can without the can toppling, because

A. gravity pulls harder on the can than on the paper.
B. the can has weight.
C. the can has inertia.
D. none of the above

# Newton's First Law of Motion
## CHECK YOUR ANSWER

A sheet of paper can be quickly withdrawn from under a soft-drink can without the can toppling, because

A. gravity pulls harder on the can than on the paper.
B. the can has weight.
**C. the can has inertia.**
D. none of the above

# Newton's First Law of Motion
## CHECK YOUR NEIGHBOR

If you swing a stone overhead in a horizontal circle and the string breaks, the tendency of the stone is to follow a

A. curved path.
B. straight-line path.
C. spiral path.
D. vertical path.

# Newton's First Law of Motion
## CHECK YOUR ANSWER

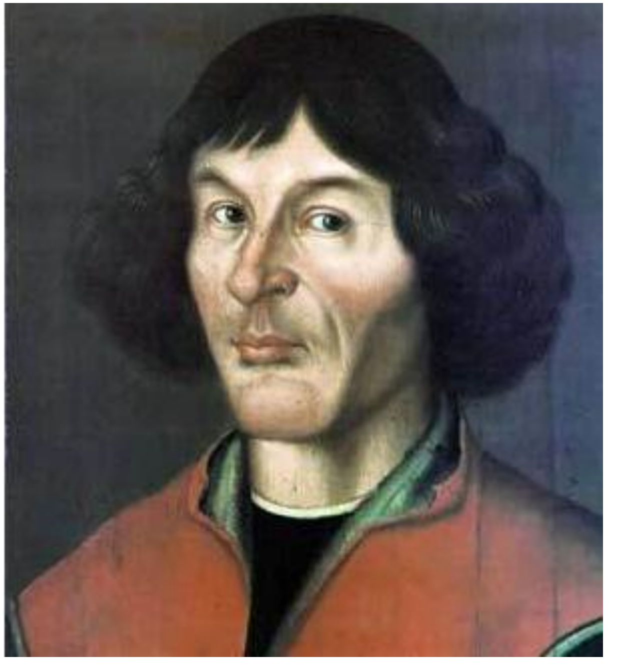
If you swing a stone overhead in a horizontal circle and the string breaks, the tendency of the stone is to follow a

A. curved path.
**B. straight-line path.**
C. spiral path.
D. vertical path.

# Newton’s First Law of Motion

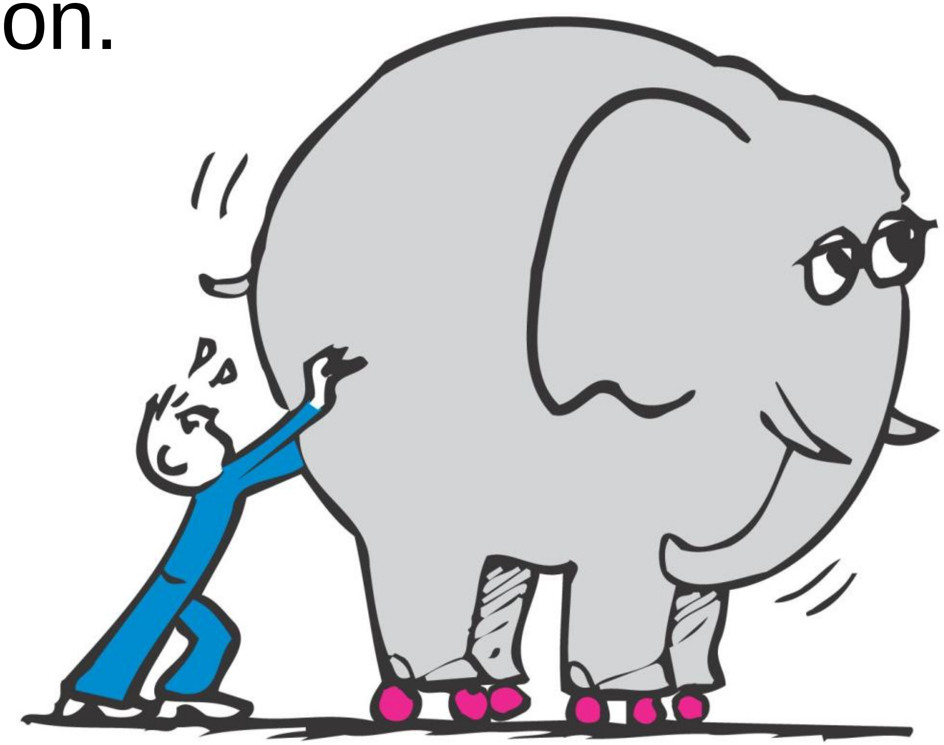
## The Moving Earth

- Theory of Earth revolving around the Sun was proposed by Copernicus, a Polish astronomer in 1543
- Newton



# Newton’s Second Law of Motion

Isaac Newton was the first to connect the concepts of force and mass to produce acceleration.



# Newton’s Second Law of Motion

## Newton’s Second Law (the law of acceleration)

- relates acceleration to force
- states that *the acceleration produced by a net force on an object is directly proportional to the net force, is in the same direction as the net force, and is inversely proportional to the mass of the object*

# Newton's Second Law of Motion

- in equation form:

$$acceleration = \frac{net\ force}{mass}$$

example: net force acting on object is doubled $\Rightarrow$ object's acceleration will be doubled

mass doubled $\Rightarrow$ acceleration halved

# Newton's Second Law of Motion

Force of hand
accelerates
the brick

Twice as much force
produces twice as
much acceleration

Twice the force on
twice the mass gives
the same acceleration

Force of hand
accelerates
the brick

The same force
accelerates 2 bricks
1/2 as much

3 bricks, 1/3 as
much acceleration

# Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

Consider a cart pushed along a track with a certain force. If the force remains the same while the mass of the cart decreases to half, the acceleration of the cart

A. remains the same.
B. halves.
C. doubles.
D. changes unpredictably.

# Newton’s Second Law of Motion
## CHECK YOUR ANSWER

Consider a cart pushed along a track with a certain force. If the force remains the same while the mass of the cart decreases to half, the acceleration of the cart

A. remains the same.
B. halves.
**C. doubles.**
D. changes unpredictably.

# Newton’s Second Law of Motion
## CHECK YOUR NEIGHBOR

Push a cart along a track so twice as much net force acts on it. If the acceleration remains the same, what is a reasonable explanation?

A. The mass of the cart doubled when the force doubled.
B. The cart experiences a force that it didn’t before.
C. The track is not level.
D. Friction reversed direction.

# Newton's Second Law of Motion
## CHECK YOUR ANSWER

Push a cart along a track so twice as much net force acts on it. If the acceleration remains the same, what is a reasonable explanation?

**A. The mass of the cart doubled when the force doubled.**

B. The cart experiences a force that it didn't before.

C. The track is not level.

D. Friction reversed direction.

# Newton's Second Law of Motion

When acceleration is *g*—free-fall

- Newton's second law provides an explanation for the equal accelerations of freely-falling objects of various masses
- acceleration is equal when air resistance is negligible
- acceleration depends on force (weight) and inertia

example: a double brick and a single brick fall at the same rate $\Rightarrow$ accelerate equally

# Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

At one instant, an object in free-fall has a speed of 40 m/s. Its speed one second later is

A. also 40 m/s.
B. 45 m/s.
C. 50 m/s.
D. none of the above

# Newton’s Second Law of Motion
## CHECK YOUR ANSWER

At one instant, an object in free-fall has a speed of 40 m/s. Its speed one second later is

A. also 40 m/s.
B. 45 m/s.
**C. 50 m/s.**
D. none of the above

*Comment*:
We assume the object is falling downward.

## Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

A 5-kg iron ball and a 10-kg iron ball are dropped from rest. For negligible air resistance, the acceleration of the heavier ball will be

A. less.
B. the same.
C. more.
D. undetermined.

# Newton’s Second Law of Motion
## CHECK YOUR ANSWER

A 5-kg iron ball and a 10-kg iron ball are dropped from rest. For negligible air resistance, the acceleration of the heavier ball will be

A. less.
**B. the same.**
C. more.
D. undetermined.

# Newton’s Second Law of Motion
## CHECK YOUR NEIGHBOR

A 5-kg iron ball and a 10-kg iron ball are dropped from rest. When the free-falling 5-kg ball reaches a speed of 10 m/s, the speed of the free-falling 10-kg ball is

A. less than 10 m/s.
B. 10 m/s.
C. more than 10 m/s.
D. undetermined.

## Newton's Second Law of Motion
## CHECK YOUR ANSWER

A 5-kg iron ball and a 10-kg iron ball are dropped from rest. When the free-falling 5-kg ball reaches a speed of 10 m/s, the speed of the free-falling 10-kg ball is

A. less than 10 m/s.
**B. 10 m/s.**
C. more than 10 m/s.
D. undetermined.

# Newton’s Second Law of Motion

When acceleration of fall is less than *g*—non-free fall

- occurs when air resistance is non-negligible
- depends on two things: speed and frontal surface area

# Newton’s Second Law of Motion

example: A skydiver jumps from plane.

Weight is the only force until air resistance acts.

As falling speed increases, air resistance on diver builds up, net force is reduced, and acceleration becomes less.

When air resistance equals the diver’s weight, net force is zero and acceleration terminates.

Diver reaches terminal velocity, then continues the fall at constant speed.

# Newton's Second Law of Motion

## Terminal speed

- occurs when acceleration terminates (when air resistance equals weight and net force is zero)

## Terminal velocity

- same as terminal speed, with direction implied or specified

# Newton’s Second Law of Motion
## CHECK YOUR NEIGHBOR

When a 20-N falling object encounters 5 N of air resistance, its acceleration of fall is

A. less than *g*.
B. more than *g*.
C. *g*.
D. terminated.

# Newton's Second Law of Motion
## CHECK YOUR ANSWER

When a 20-N falling object encounters 5 N of air resistance, its acceleration of fall is

**A. less than *g*.**
B. more than *g*.
*C.* *g*.
D. terminated.

*Comment*:

Acceleration of a nonfree-fall is always less than *g*. Acceleration will actually be (20 N – 5 N)/2 kg = 7.5 m/$s^2$.

# Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

If a 50-N person is to fall at terminal speed, the air resistance needed is

A. less than 50 N.
B. 50 N.
C. more than 50 N.
D. none of the above

# Newton's Second Law of Motion
## CHECK YOUR ANSWER

If a 50-N person is to fall at terminal speed, the air resistance needed is

A. less than 50 N.

**B. 50 N.**

C. more than 50 N.

D. none of the above

*Explanation*:

Then, $\Sigma F = 0$ and acceleration = 0.

# Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

As the skydiver falls faster and faster through the air, air resistance

A. increases.
B. decreases.
C. remains the same.
D. not enough information

## CHECK YOUR ANSWER

As the skydiver falls faster and faster through the air, air resistance

**A. increases.**
B. decreases.
C. remains the same.
D. not enough information

# Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

As the skydiver continues to fall faster and faster through the air, net force

A. increases.
B. decreases.
C. remains the same.
D. not enough information

# Newton's Second Law of Motion
## CHECK YOUR ANSWER

As the skydiver continues to fall faster and faster through the air, net force

A. increases.

**B. decreases.**

C. remains the same.

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# Newton's Second Law of Motion
## CHECK YOUR NEIGHBOR

As the skydiver continues to fall faster and faster through the air, her acceleration

A. increases.
B. decreases.
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# Newton's Second Law of Motion
## CHECK YOUR ANSWER

As the skydiver continues to fall faster and faster through the air, her acceleration

A. increases.

**B. decreases.**

C. remains the same.

D. not enough information

## Newton’s Second Law of Motion

A situation to ponder…

Consider a heavy and light person jumping together with the same-size parachutes from the same altitude.

# A situation to ponder…
# CHECK YOUR NEIGHBOR

Who will reach the ground first?

A. the light person
B. the heavy person
C. both will reach at the same time
D. not enough information

# A situation to ponder…
# CHECK YOUR ANSWER

Who will reach the ground first?

A. the light person
**B. the heavy person**
C. both will reach at the same time
D. not enough information

*Explanation*:

The heavier person has a greater terminal velocity. Do you know why?

# Newton’s Second Law of Motion

## Coin and feather fall

- feather reaches terminal velocity very quickly and falls slowly at constant speed, reaching the bottom after the coin does
- coin falls very quickly and air resistance doesn’t build up to its weight over short-falling distances, which is why the coin hits the bottom much sooner than the falling feather

# Newton’s Second Law of Motion
## CHECK YOUR NEIGHBOR

When the air is removed by a vacuum pump and the activity is repeated,

A. the feather hits the bottom first, before the coin hits.
B. the coin hits the bottom first, before the feather hits.
C. both the coin and feather drop together side-by-side.
D. not enough information

# Newton’s Second Law of Motion
## CHECK YOUR ANSWER

When the air is removed by a vacuum pump and the activity is repeated,

A. the feather hits the bottom first, before the coin hits.

B. the coin hits the bottom first, before the feather hits.

**C. both the coin and feather drop together side-by-side.**

D. not enough information

# Air Resistance

How to be a flying squirrel: [Jeb Corliss "Grinding the Crack"]

# Forces and Interactions

## Interaction

- is between one thing and another
- requires a pair of forces acting on two objects

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example: interaction of fingers and wall pushing on each other

force pair—you push on wall; wall pushes on you

# Newton’s Third Law of Motion

Newton’s Third Law (law of action and reaction)

states that *whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.*

# Newton's Third Law of Motion
# CHECK YOUR NEIGHBOR

A soccer player kicks a ball with 1500 N of force. The ball exerts a reaction force against the player's foot of

A. somewhat less than 1500 N.
B. 1500 N.
C. somewhat more than 1500 N.
D. none of the above

# Newton's Third Law of Motion
## CHECK YOUR ANSWER

A soccer player kicks a ball with 1500 N of force. The ball exerts a reaction force against the player's foot of

A. somewhat less than 1500 N.

**B. 1500 N.**

C. somewhat more than 1500 N.

D. none of the above

# Newton's Third Law of Motion

Action and reaction forces

- one force is called the action force; the other force is called the reaction force
- are copairs of a single interaction
- neither force exists without the other
- are equal in strength and opposite in direction
- always act on *different* objects

# Newton’s Third Law of Motion

- reexpression of Newton’s third law: **to every action there is always an opposed equal reaction**

example: tires of car push back against the road while the road pushes the tires forward

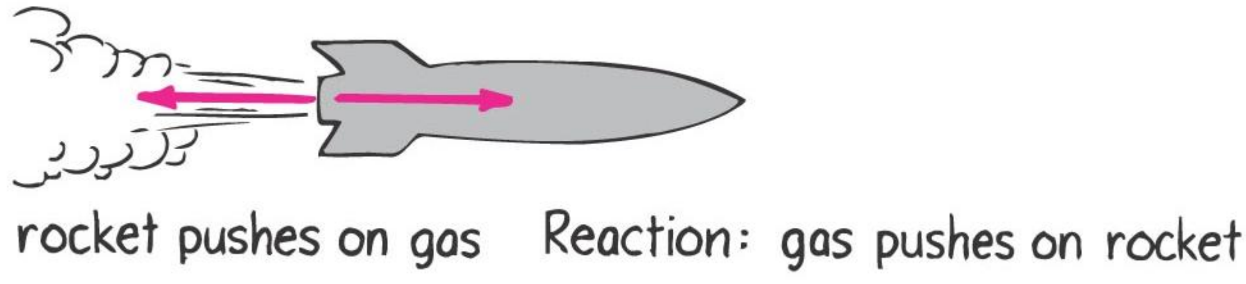
# Newton’s Third Law of Motion

Simple rule to identify action and reaction

- identify the interaction—one thing interacts with another
  - action: object A exerts a force on object B
  - reaction: object B exerts a force on object A

  example: action—rocket (object A) exerts force on gas (object B)

  reaction—gas (object B) exerts force on rocket (object A)



# Newton's Third Law of Motion
## CHECK YOUR NEIGHBOR

When you step off a curb, Earth pulls you downward. The reaction to this force is

A. a slight air resistance.
B. nonexistent in this case.
C. you pulling Earth upward.
D. none of the above

# Newton's Third Law of Motion
## CHECK YOUR ANSWER

When you step off a curb, Earth pulls you downward. The reaction to this force is

A. a slight air resistance.
B. nonexistent in this case.
**C. you pulling Earth upward.**
D. none of the above

# Newton's Third Law of Motion

## Action and Reaction on Different Masses

cannonball: $\frac{F}{m} = \mathbf{a}$

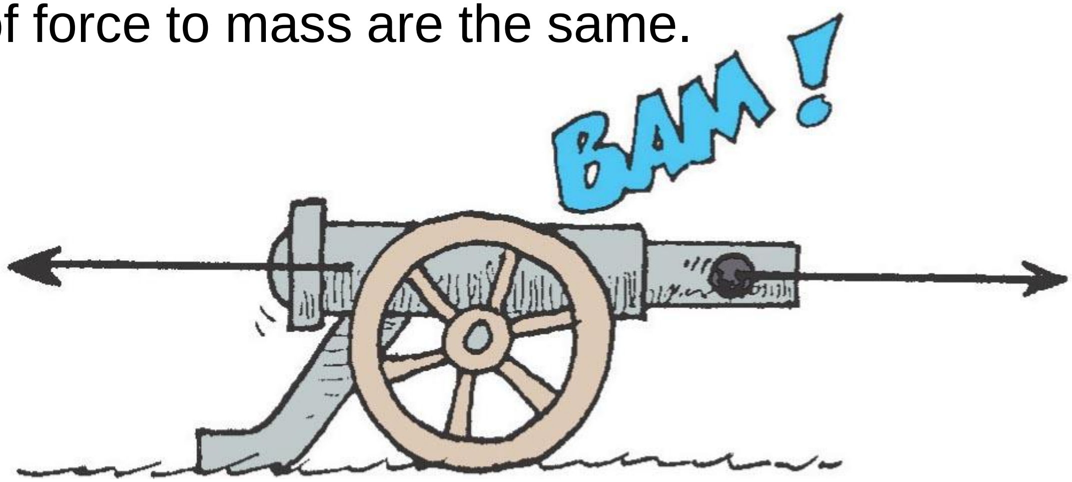
cannon: $\frac{F}{\mathbf{m}} = a$

- the same force exerted on a small mass produces a large acceleration
- the same force exerted on a large mass produces a small acceleration

# Newton's Third Law of Motion
## CHECK YOUR NEIGHBOR

When a cannon is fired, the accelerations of the cannon and cannonball are different because the

A. forces don't occur at the same time.
B. forces, although theoretically the same, in practice are not.
C. masses are different.
D. ratios of force to mass are the same.



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## CHECK YOUR ANSWER

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A. forces don’t occur at the same time.

B. forces, although theoretically the same, in practice are not.

**C. masses are different.**

D. ratios of force to mass are the same.

## Newton's Third Law of Motion

A situation to ponder…

Consider a high-speed bus colliding head-on with an innocent bug. The force of impact splatters the unfortunate bug over the windshield.

# A situation to ponder…
# CHECK YOUR NEIGHBOR

Which is greater, the force on the bug or the force on the bus?

A. bug
B. bus
C. both are the same
D. cannot say

# A situation to ponder…
# CHECK YOUR ANSWER

Which is greater, the force on the bug or the force on the bus?

A. bug
B. bus
**C. both are the same**
D. cannot say

*Comment*:

Although the forces are equal in magnitude, the effects are very different. Do you know why?

# Newton's Third Law of Motion
## CHECK YOUR NEIGHBOR

Two people of equal mass on slippery ice push off from each other. Will both move at the same speed in opposite directions?

A. yes
B. yes, but only if both push equally
C. no
D. no, unless acceleration occurs

# Newton’s Third Law of Motion
## CHECK YOUR ANSWER

Two people of equal mass on slippery ice push off from each other. Will both move at the same speed in opposite directions?

**A. yes**

B. yes, but only if both push equally

C. no

D. no, unless acceleration occurs

*Explanation*:

However they push, the result is equal-magnitude forces on equal masses, which produces equal accelerations; therefore, there are equal changes in speed.

# Newton's Third Law of Motion

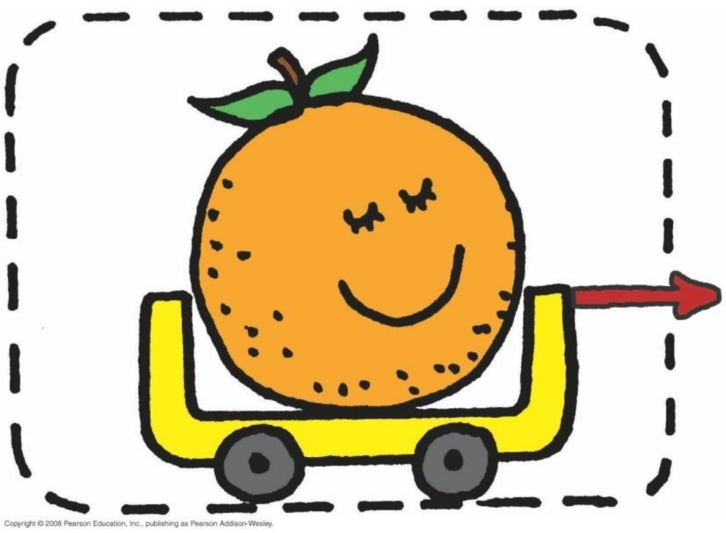
Myth busters video

– [two cars head on crash test]

# Newton's Third Law of Motion

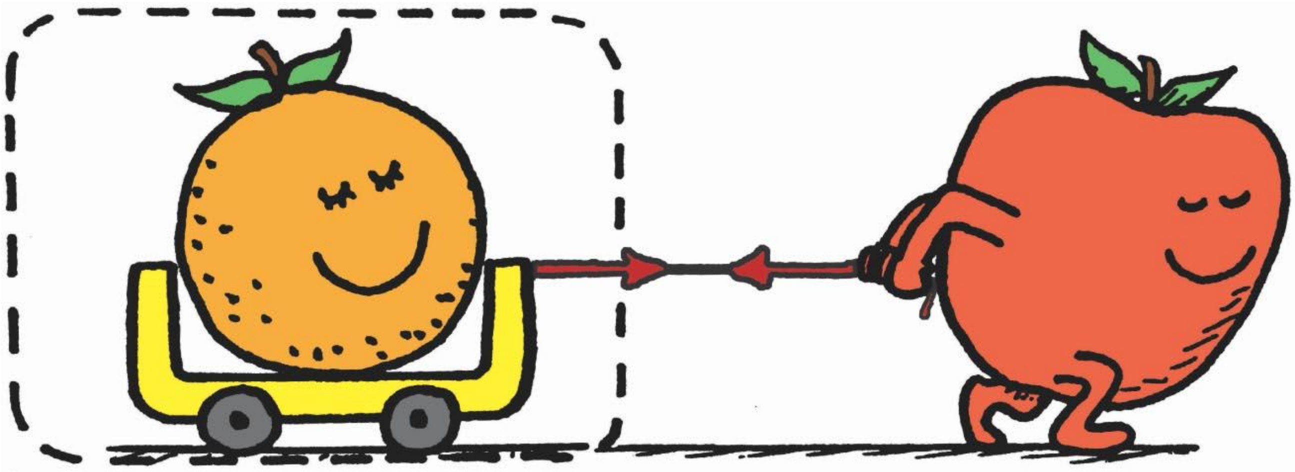
## Defining Your System

- consider a single enclosed orange
  - applied external force causes the orange to accelerate in accord with Newton's second law
  - action and reaction pair of forces is not shown



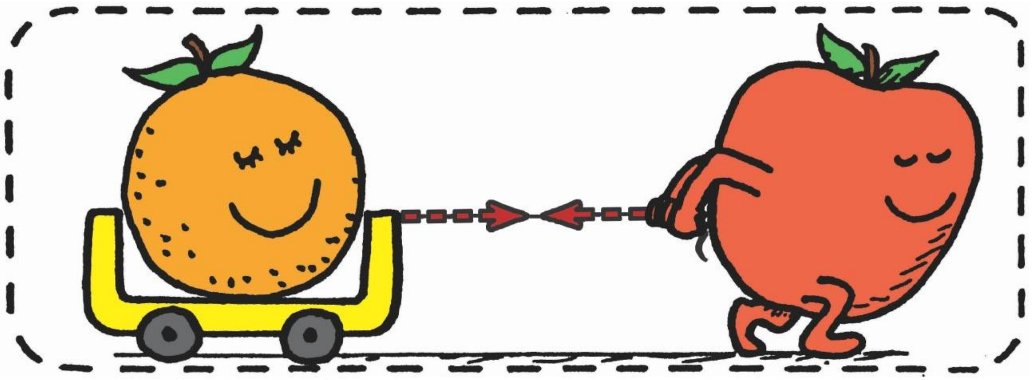
# Newton's Third Law of Motion

- consider the orange and the apple pulling on it
  - action and reaction do not cancel (because they act on different things)
  - external force by apple accelerates the orange



# Newton’s Third Law of Motion

- consider a system comprised of both the orange and the apple
  - the apple is no longer external to the system
  - force pair is internal to system, which doesn’t cause acceleration
  - action and reaction within the system cancel
  - with no external forces, there is no acceleration of system

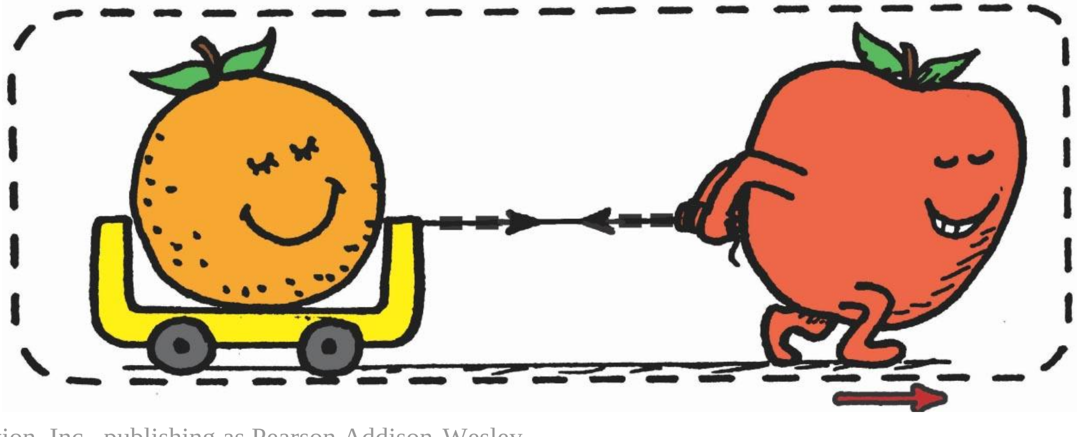


# Newton’s Third Law of Motion

- consider the same system, but with external force of friction on it
  - same internal action and reaction forces (between the orange and apple) cancel
  - a second pair of action-reaction forces (between the apple’s feet and the floor) exists

# Newton's Third Law of Motion

- one of these acts by the system (apple on the floor) and the other acts on the system (floor on the apple)
- external frictional force of floor pushes on the system, which accelerates
- second pair of action and reaction forces do not cancel



# Newton's Third Law
## CHECK YOUR NEIGHBOR

When lift equals the weight of a helicopter, the helicopter

A. climbs down.
B. climbs up.
C. hovers in midair.
D. none of the above

# Newton's Third Law
## CHECK YOUR ANSWER

When lift equals the weight of a helicopter, the helicopter

A. climbs down.
B. climbs up.
**C. hovers in midair.**
D. none of the above

# Newton’s Third Law
## CHECK YOUR NEIGHBOR

When lift is greater, the helicopter

A. climbs down.
B. climbs up.
C. hovers in midair.
D. none of the above

# Newton’s Third Law
## CHECK YOUR ANSWER

When lift is greater, the helicopter

A. climbs down.

**B. climbs up.**

C. hovers in midair.

D. none of the above

# Newton's Third Law
## CHECK YOUR NEIGHBOR

A bird flies by

A. flapping its wings.
B. pushing air down so that the air pushes it upward.
C. hovering in midair.
D. inhaling and exhaling air.

# Newton's Third Law
## CHECK YOUR ANSWER

A birds flies by

A. flapping its wings.

**B. pushing air down so that the air pushes it upward.**

C. hovering in midair.

D. inhaling and exhaling air.

# CHECK YOUR NEIGHBOR

Slightly tilted wings of airplanes deflect

A. oncoming air downward to produce lift.
B. oncoming air upward to produce lift.
C. both A and B
D. neither A nor B

# Newton's Third Law
# CHECK YOUR ANSWER

Slightly tilted wings of airplanes deflect

**A. oncoming air downward to produce lift.**

B. oncoming air upward to produce lift.

C. both A and B

D. neither A nor B

*Explanation*:

When a wing diverts air downward, it exerts a downward force on the air. The air simultaneously exerts an upward force on the wing. The vertical component of this upward force is lift. (The horizontal component is drag.)

# Newton's Third Law
## CHECK YOUR NEIGHBOR

Compared with a light-weight glider, a heavier glider would have to push air

A. downward with greater force.
B. downward with the same force.
C. downward with less force.
D. none of the above

# Newton’s Third Law
## CHECK YOUR ANSWER

Compared with a light-weight glider, a heavier glider would have to push air

**A. downward with greater force.**
B. downward with the same force.
C. downward with less force.
D. none of the above

*Explanation*:

The force on the air deflected downward must equal the weight of the glider.

# Vectors

## Vector quantity

- has magnitude and direction
- is represented by an arrow

example: velocity, force, acceleration

## Scalar quantity

- has magnitude

example: mass, volume, speed

# Vectors

## Resultant

- the sum of two or more vectors
  - for vectors in the same direction, add arithmetically
  - for vectors in opposite directions, subtract arithmetically
  - two vectors that don’t act in the same or opposite direction
    - use parallelogram rule
  - two vectors at right angles to each other
    - use Pythagorean theorem: $R^2 = V^2 + H^2$

# Vectors
# CHECK YOUR NEIGHBOR

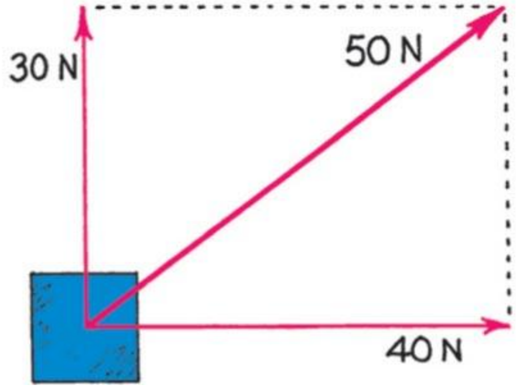
Referring to the figure, which of the following are true statements?

A. 50 N is the resultant of the 30 and 40-N vectors.

B. The 30-N vector can be considered a component of the 50-N vector.

C. The 40-N vector can be considered a component of the 50-N vector.

D. All of the above are correct.



# Vectors
## CHECK YOUR ANSWER

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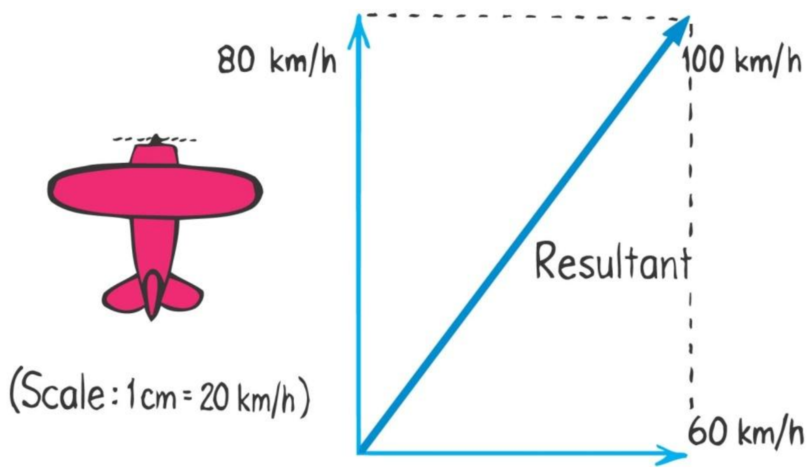
C. The 40-N vector can be considered a component of the 50-N vector.
**D. All of the above are correct.**

# Vectors
# CHECK YOUR NEIGHBOR

Referring to the figure, which of the following are true statements?

A. 100 km/h is the resultant of the 80 and 60-km/h vectors.
B. The 80-km/h vector can be considered a component of the 100-km/h vector.
C. The 60-km/h vector can be considered a component of the 100-km/h vector.
D. All of the above are correct.



# Vectors
## CHECK YOUR ANSWER

Referring to the figure, which of the following are true statements?

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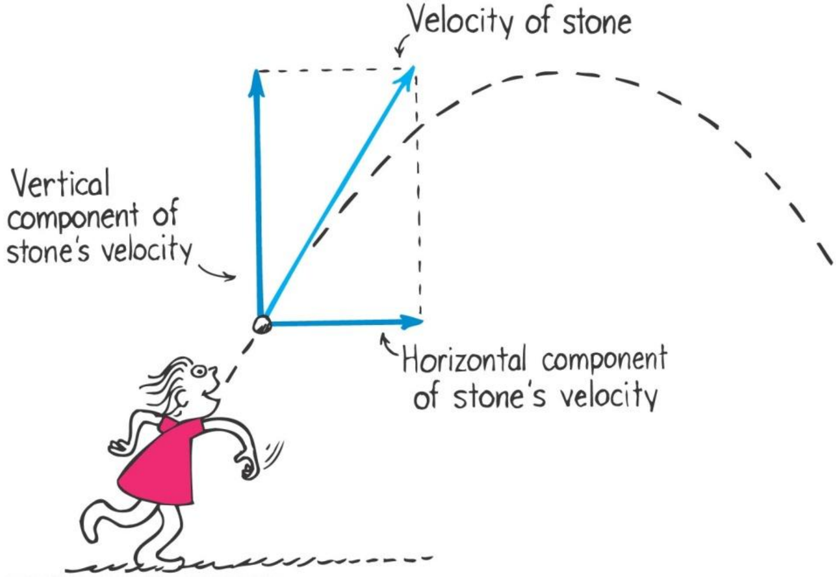
B. The 80-km/h vector can be considered a component of the 100-km/h vector.
C. The 60-km/h vector can be considered a component of the 100-km/h vector.
**D. All of the above are correct.**

# Vectors

## Vector Components

- vertical and horizontal components of a vector are perpendicular to each other
- determined by resolution



# Vectors
## CHECK YOUR NEIGHBOR

You run horizontally at 4 m/s in a vertically falling rain that falls at 4 m/s. Relative to you, the raindrops are falling at an angle of

A. 0°.
B. 45°.
C. 53°.
D. 90°.

## CHECK YOUR ANSWER

You run horizontally at 4 m/s in a vertically falling rain that falls at 4 m/s. Relative to you, the raindrops are falling at an angle of

A. 0°.

**B. 45°.**

C. 53°.

D. 90°.

*Explanation*:
The horizontal 4 m/s and vertical 4 m/s combine by the parallelogram rule to produce a resultant of 5.6 m/s at 45°.

# Summary of Newton's Three Laws of Motion

- Newton's first law of motion (the law of inertia)
  - An object at rest tends to remain at rest; an object in motion tends to remain in motion at constant speed along a straight-line path.
- Newton's second law of motion (the law of acceleration)
  - When a net force acts on an object, the object will accelerate. The acceleration is directly proportional to the net force and inversely proportional to the mass.
- Newton's third law of motion (the law of action and reaction)
  - Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.