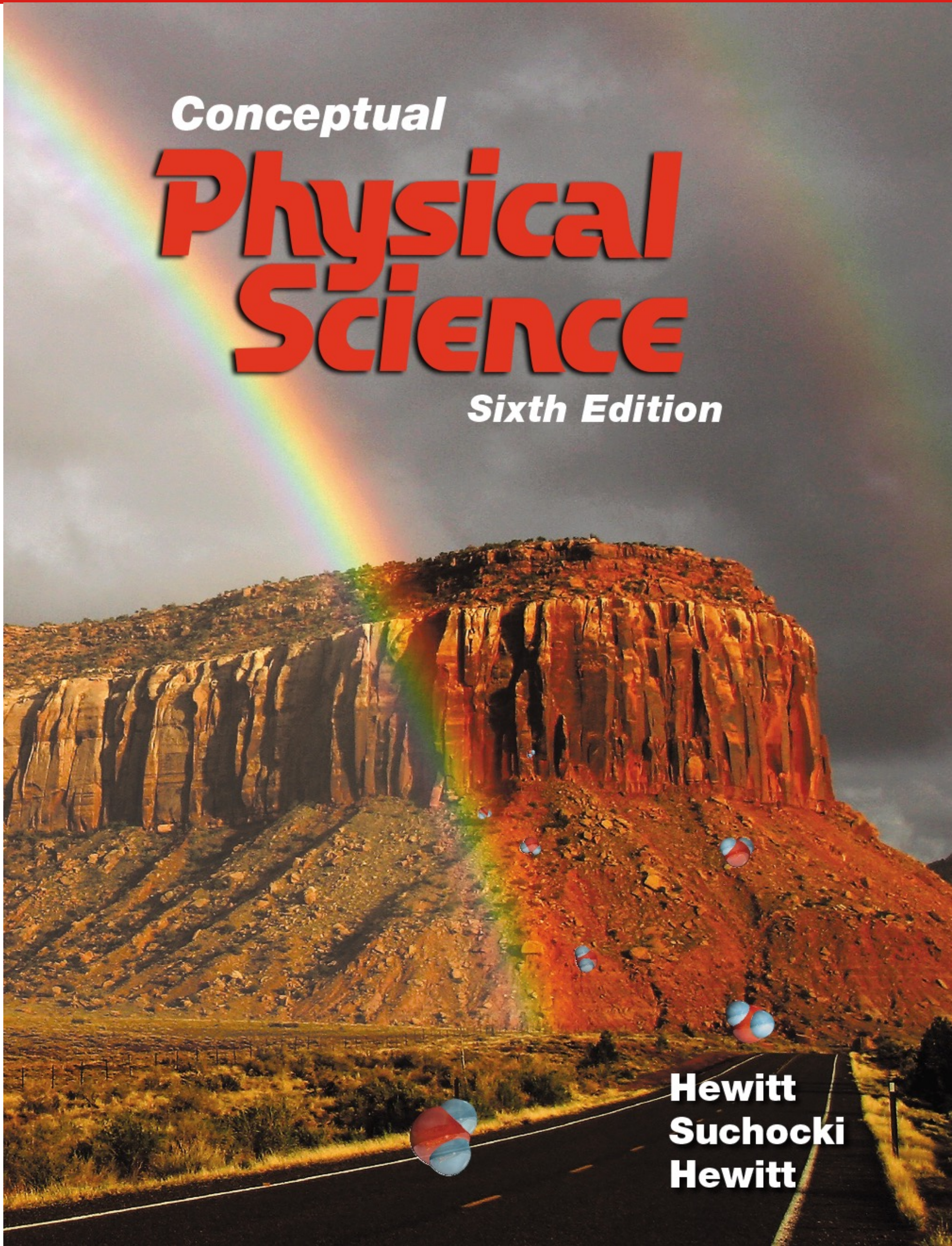
Chapter 1: Patterns of Motion and Equilibrium



This lecture will help you understand:

- Aristotle on Motion
- Galileo's Concept of Inertia
- Mass—A Measure of Inertia
- Net Force
- The Equilibrium Rule
- Support Force
- Dynamic Equilibrium
- The Force of Friction
- Speed and Velocity
- Acceleration

Aristotle on Motion

- Aristotle classified motion into two kinds:
  - Natural motion—motion that is straight up or straight down
  - Violent motion—imposed motion resulting from an external push or pull
- Aristotle believed that natural laws could be understood by logical reasoning
- Two assertions of Aristotle (held for ~ 2000 years):
  1) Heavy objects necessarily fall faster than lighter objects.
  2) Moving objects must necessarily have forces exerted on them to keep them moving

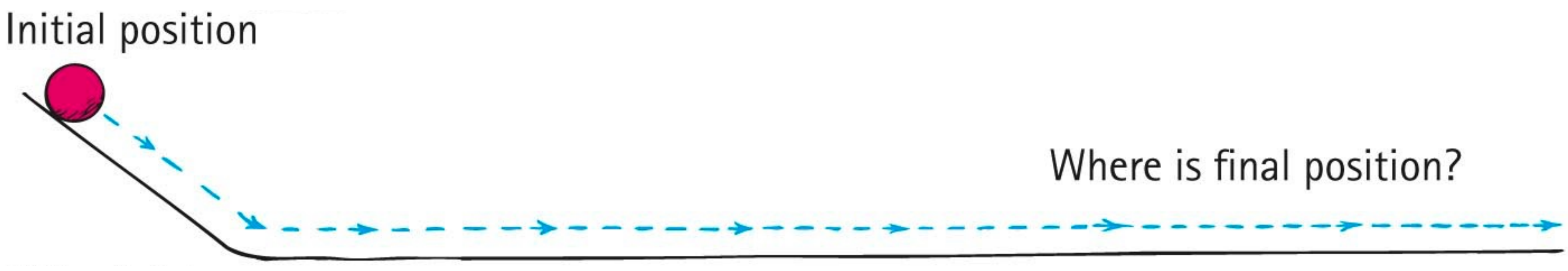
CHECKPOINT

- **Isn't it common sense to think that Earth is in its proper place and that a force to move it is inconceivable, as Aristotle held, and that the Earth *is* at rest in this universe?**

- "Common sense is relative to one's time and place. Aristotle's views were logical and consistent with everyday observations. So unless you become familiar with the physics to follow, Aristotle's views about motion *do* make common sense (and are held by many uneducated people today). But as you acquire new information about nature's rules, you'll likely find your common sense progressing beyond Aristotelian thinking"

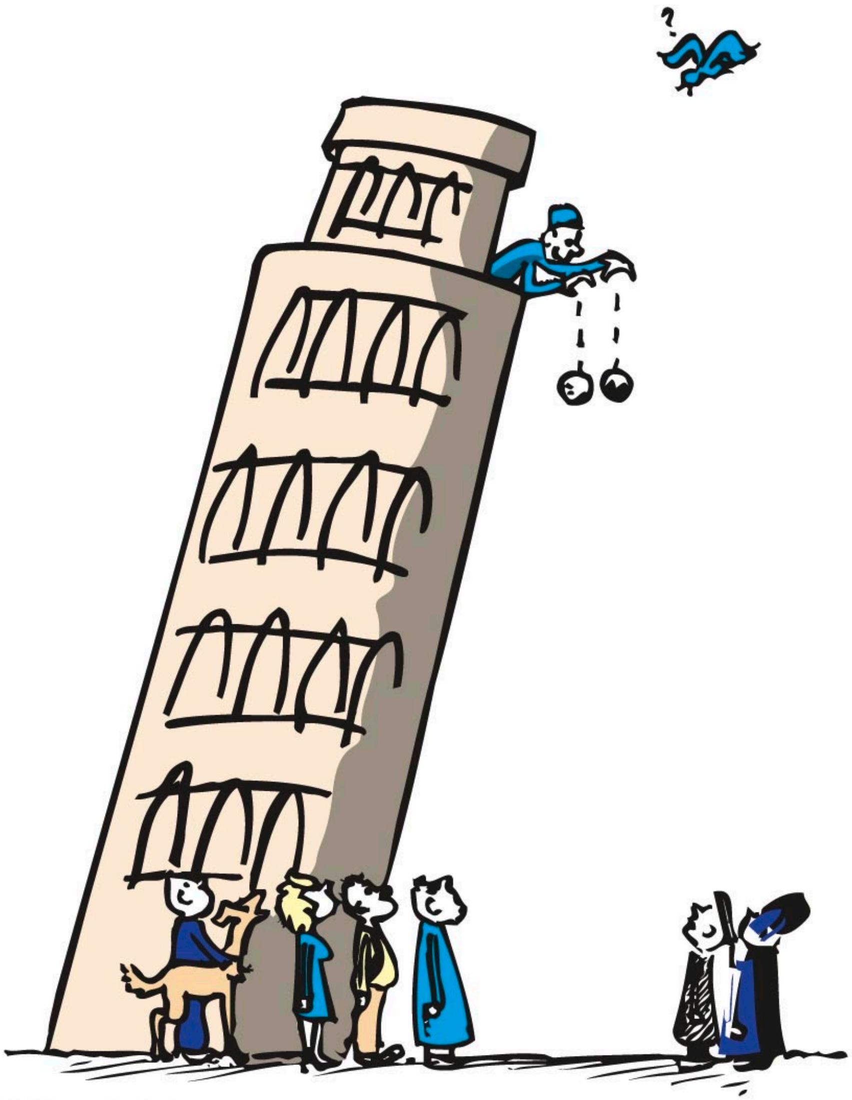
Galileo's Concept of Inertia

- Italian scientist Galileo demolished Aristotle's assertions in early 1500s.
- In the absence of a force, objects once set in motion tend to continue moving indefinitely.



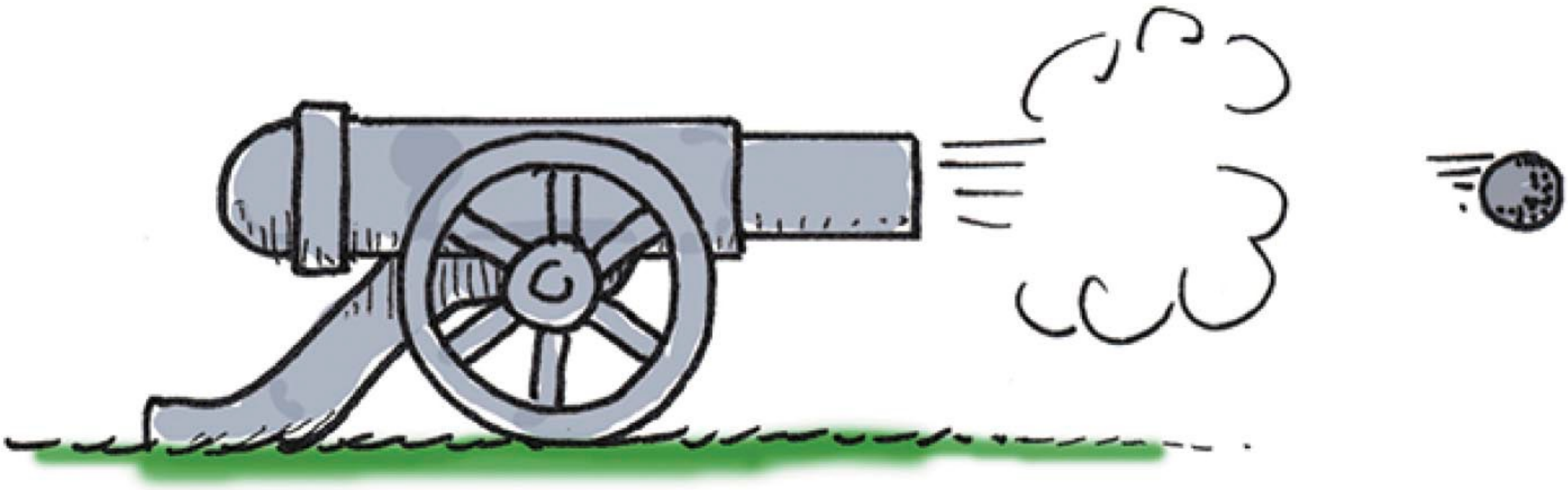
Galileo's Concept of Inertia

- Legend of the Leaning Tower of Pisa:
  - Galileo showed that dropped objects fall to the ground at the same time when air resistance is negligible.



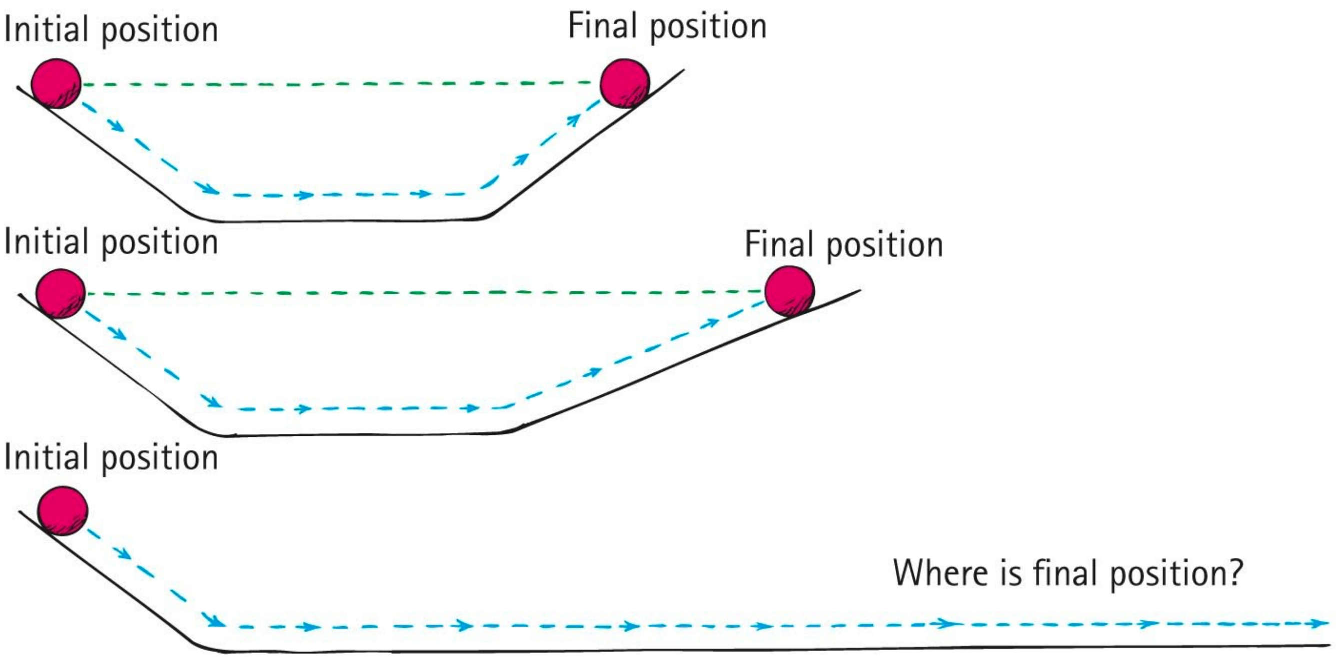
Galileo's Concept of Inertia

- Discovery:
  - In the absence of friction, no force is necessary to keep a horizontally moving object moving.



Galileo's Concept of Inertia

- Experiment:
  - Balls rolling down inclined planes and then up others tend to roll back up to their original heights.



Galileo's Concept of Inertia

- Conclusion:
  - The tendency of a moving body to keep moving is natural—every material object resists *change* in its state of motion. This property of things to resist change is called **inertia**.

Galileo's Concept of Inertia
CHECK YOUR NEIGHBOR

The use of inclined planes for Galileo's experiments helped him to

A. eliminate the acceleration of free fall.

B. discover the concept of energy.

C. discover the property called inertia.

D. discover the concept of momentum.

Galileo's Concept of Inertia
CHECK YOUR ANSWER

The use of inclined planes for Galileo's experiments helped him to

A. eliminate the acceleration of free fall.

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C. discover the property called inertia.

D. discover the concept of momentum.

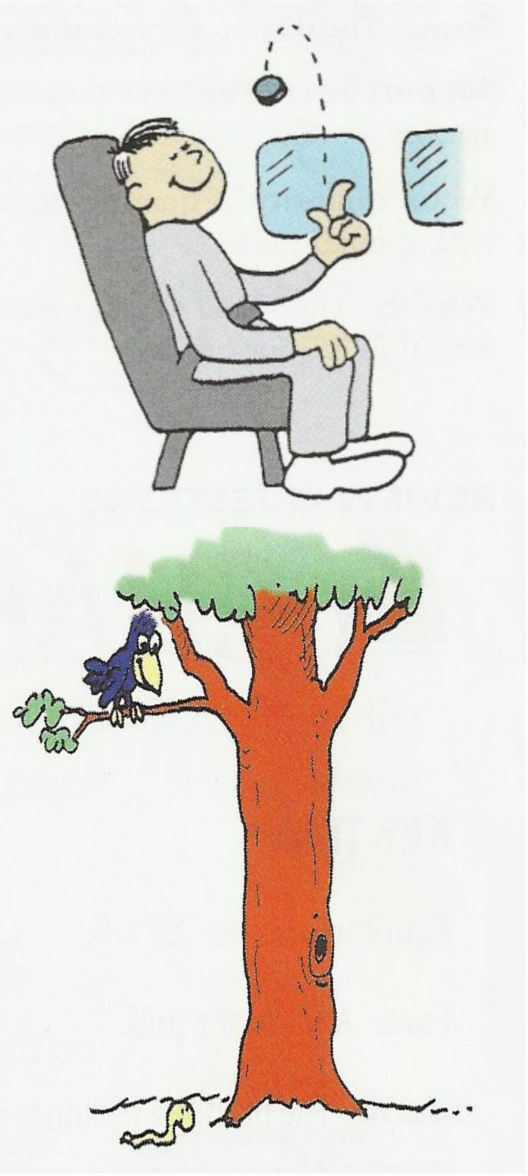
Explanation:

Note that inertia is a property of matter, not a reason for the behavior of matter.

Inertia: Additional Examples

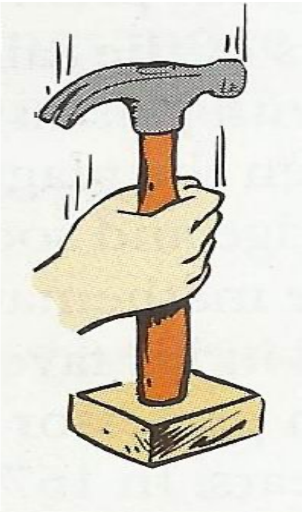
- When we flip a coin in a high speed car, we catch the moving coin as we would if the car was at rest. This happens because of the coin’s inertia and its forward motion at the speed of the car.

- Birds move from the tree branch vertically below and catch the worm. If inertia is neglected this would be impossible and the worm would be swept far away with the moving earth. The actual situation is that when the bird drops from the branch its initial sideways motion remains unchanged. It catches the worm quite unaffected by the motion of its environment.



Inertia: Additional Examples

- Rapid deceleration is sensed by the driver who is pushed forward when the brakes are applied.
- The downward motion and sudden stop of the hammer hand tightens the hammer hand
- A tablecloth is whipped from beneath dishes sitting on a table, leaving the dishes in their initial state of rest.

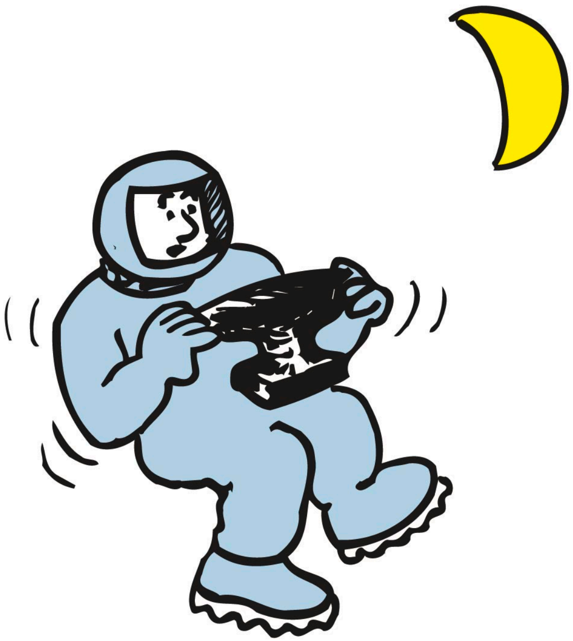


Mass—A Measure of Inertia

- The amount of inertia possessed by an object depends on the amount of matter—the amount of material that composes it—its **mass:**

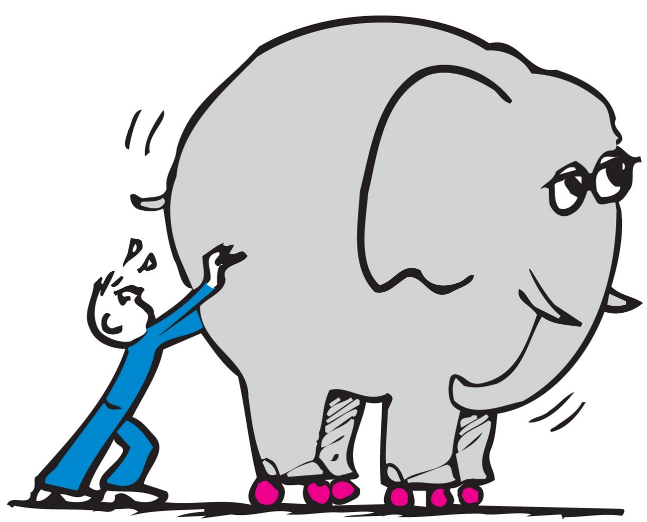
greater mass ⇒ greater inertia

smaller mass ⇒ smaller inertia



Mass—A Measure of Inertia

- Mass
  - Quantity of matter in an object
  - Measure of inertia or sluggishness that an object exhibits in response to any effort made to start it, stop it, or change its state of motion in any way



Mass—A Measure of Inertia

- Weight
  - Amount of gravitational pull on an object
  - Proportional to mass

Twice the **mass** $\Rightarrow$ twice the **weight**

Half the mass $\Rightarrow$ half the weight

$$\text{Weight} = \text{mass} \times \text{acceleration of gravity}$$

$$\boldsymbol{w = mg}$$

m: mass in kg

g: acceleration of gravity $\cong 10\ \mathrm{m}/s^2$

Weight is a force and has units of Newton (N). **Direction of weight is downwards always.**

A note on units

- Most physical quantities have units. It is necessary to indicate the units used.
- We use the international system of units (**SI-units**). There are **three basic units in mechanics. In SI-units these are**:
  - **Length in meters (m)**
  - **Mass in kilograms (kg)**
  - **Time in seconds (s)**
- Other physical quantities have derived units, for example:
  - Speed in $\mathrm{m/s}$,
  - Acceleration in $\mathrm{m/s^2}$
  - Force in N $(\mathrm{N} \equiv \mathrm{kg.\,m/s^2})$
  - Volume in $\mathrm{m^3}$
- One cannot mix different systems of units. **It is recommended to use SI-units.** Carry unit conversion when necessary

Example (including unit conversion)

- Calculate the weight of a 200 gram object.

  (Hint: check if the units are consistent and make proper unit conversion!)

- Calculate the mass of a man who weighs 600 N

Mass—A Measure of Inertia

- Mass versus volume:
  - **Mass** involves how much *matter* an object contains
  - **Volume** involves how much *space* an object occupies
- Density: Measure of compactness
  - **Density** is the measure of how much mass occupies a given space

Mass—A Measure of Inertia
CHECK YOUR NEIGHBOR

The concept of inertia mostly involves

A. mass.
B. weight.
C. volume.
D. density.

Mass—A Measure of Inertia
CHECK YOUR ANSWER

The concept of inertia mostly involves

A. **mass.**

B. weight.

C. volume.

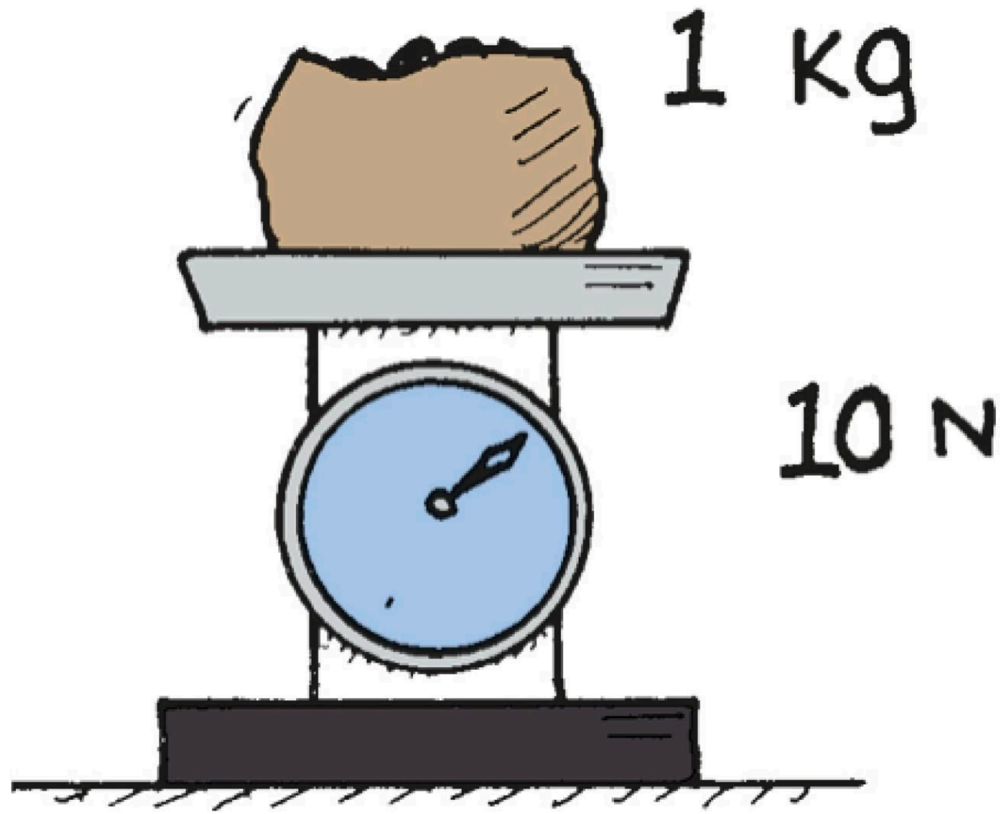
D. density.

Explanation:

Anybody get this wrong? Check the title of this slide! :-)

Mass—A Measure of Inertia

- Kilogram
  - **standard unit of measurement for mass**
  - on Earth's surface, 1 kg of material weighs 10 newtons
  - away from Earth (on the Moon), 1 kg of material weighs less than 10 newtons



Mass—A Measure of Inertia
CHECK YOUR NEIGHBOR

The density of 1 kilogram of iron is

A. less on the Moon.

B. the same on the Moon.

C. greater on the Moon.

D. All of the above.

Mass—A Measure of Inertia
CHECK YOUR ANSWER

The density of 1 kilogram of iron is

A. less on the Moon.

B. the same on the Moon.

C. greater on the Moon.

D. All of the above.

Explanation:

Both mass and volume of 1 kilogram of iron is the same everywhere, so density is the same everywhere.

Force

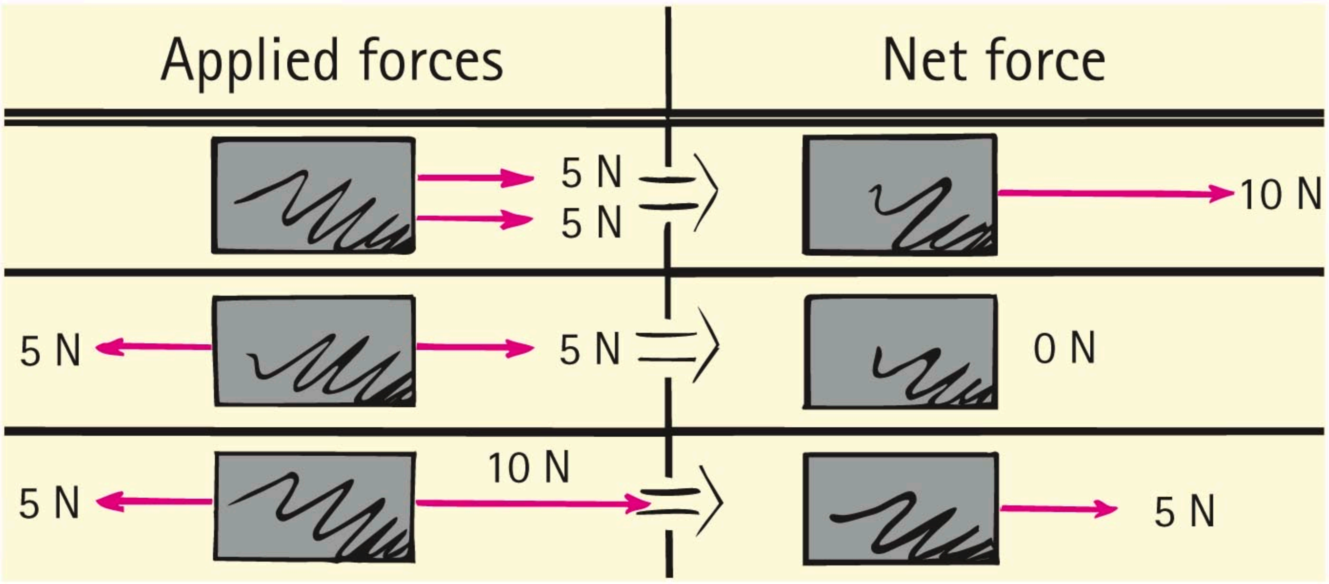
- **Force**: **simply a push or a pull**
  - Results from an interaction between two objects
  - Units of force is Newton (N)
  - Forces are vector quantities: They have direction
- Some common forces:
  1. **Weight**
  2. **Support/Normal force**
  3. **Friction force**

A note on vector and scalar quantities

- Physical quantities are divided into two main types:
  1) Vector Quantities: quantities that have magnitude and direction. (Velocity, acceleration, force, weight, …)
  2) Scalar Quantities: quantities that have magnitudes only. (Time, temperature, mass, speed, work, energy, power…)

Net Force

- Net force
  - combination of all forces that act on an object
  - changes an object's motion



Net Force
CHECK YOUR NEIGHBOR

A cart is pushed to the right with a force of 15 N while being pulled to the left with a force of 20 N. The net force on the cart is

A. 5 N to the left.

B. 5 N to the right.

C. 25 N to the left.

D. 25 N to the right.

Net Force
CHECK YOUR ANSWER

A cart is pushed to the right with a force of 15 N while being pulled to the left with a force of 20 N. The net force on the cart is

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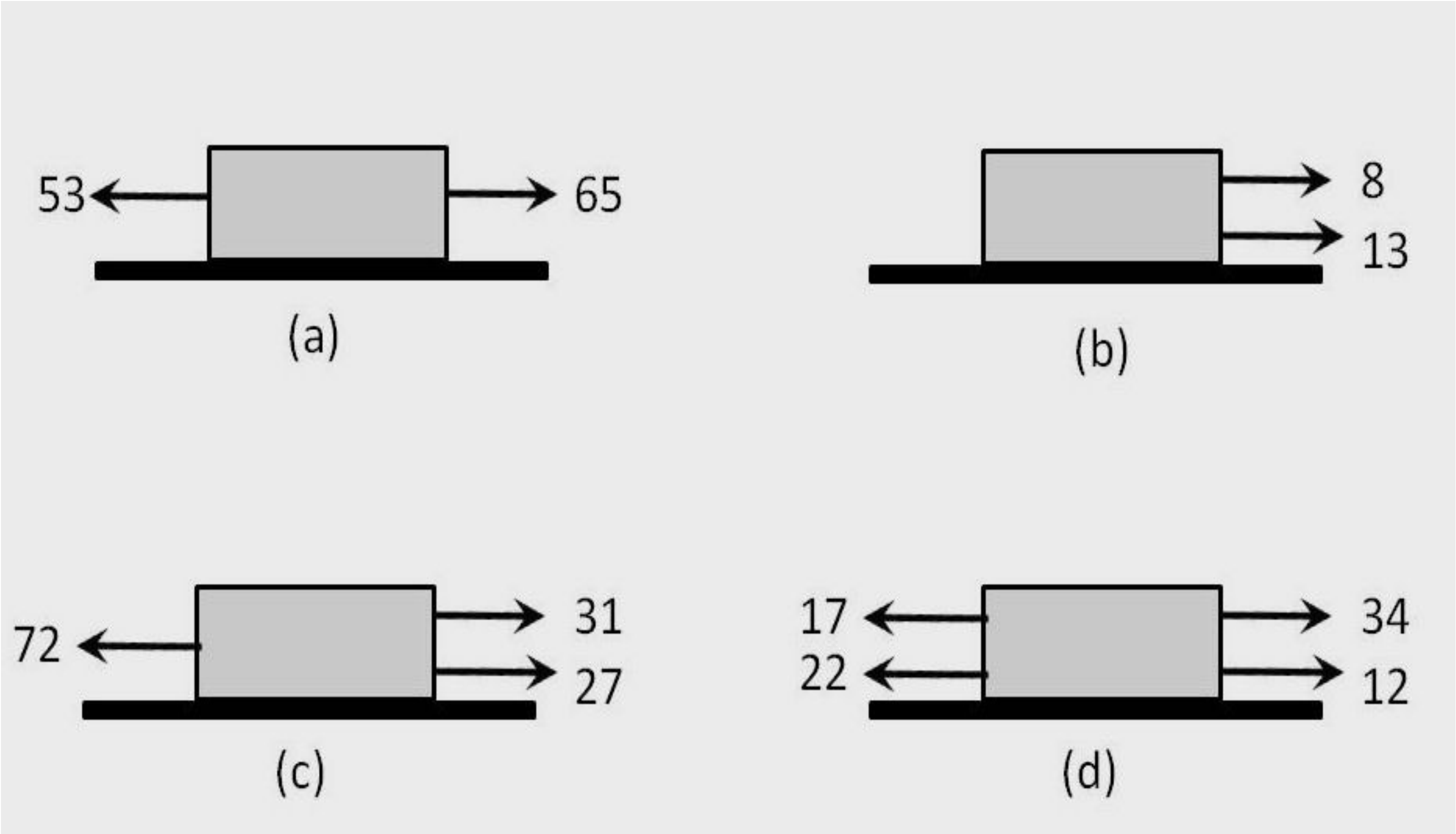
C. 25 N to the left.

D. 25 N to the right.

Example

- Find the net force is the following cases:



a) 12 N (right), b) 21 N (right), c) 14 N (left), d) 7 N (right)

The Equilibrium Rule

- The **equilibrium rule:**

  The vector sum of forces acting on a non-accelerating object or system of objects equals zero.

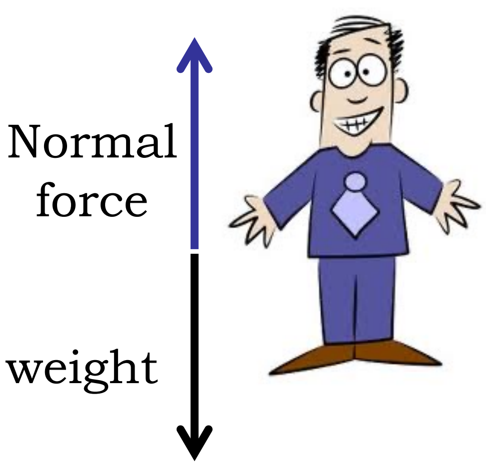
  Mathematical notation: $\boldsymbol{\Sigma F = 0}$.

Types of Equilibrium

1. **Static equilibrium**: objects at rest (stationary objects)
2. **Dynamic equilibrium**: objects moving at a constant velocity

(**constant velocity = *constant speed in a straight line***).

When two or more forces cancel to zero on a moving object, then the object is in equilibrium.



The Equilibrium Rule
CHECK YOUR NEIGHBOR

The equilibrium rule, $\Sigma F = 0$, applies to

A. vector quantities.
B. scalar quantities.
C. Both of the above.
D. Neither of the above.

The Equilibrium Rule
CHECK YOUR ANSWER

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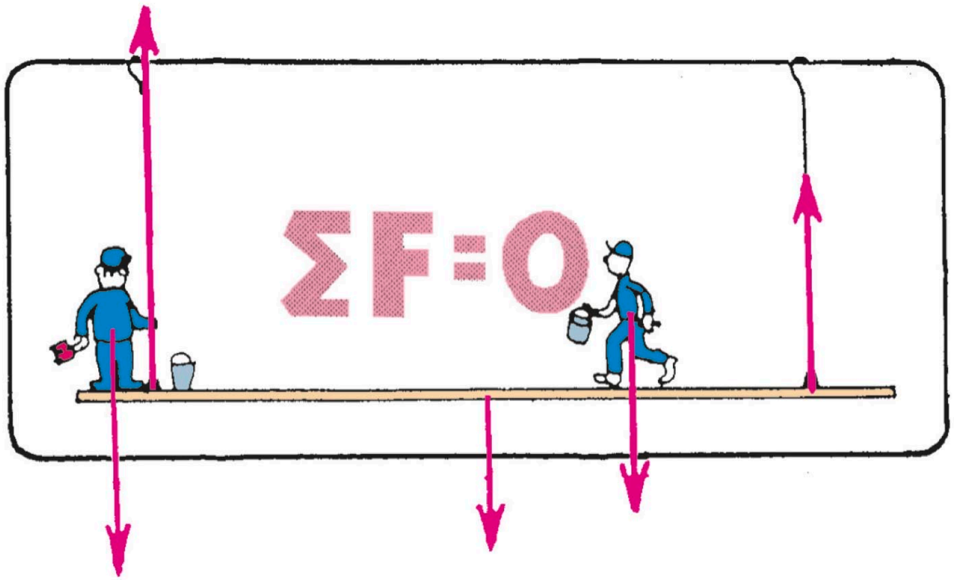

Explanation:

Vector addition takes into account + and – quantities that can cancel to zero. Two forces (vectors) can add to zero, but there is no way that two masses (scalars) can add to zero.

Dynamic Equilibrium
CHECK YOUR NEIGHBOR

A bowling ball is in equilibrium when it

A. is at rest.

B. moves steadily in a straight-line path.

C. Both of the above.

D. None of the above.

Dynamic Equilibrium
CHECK YOUR ANSWER

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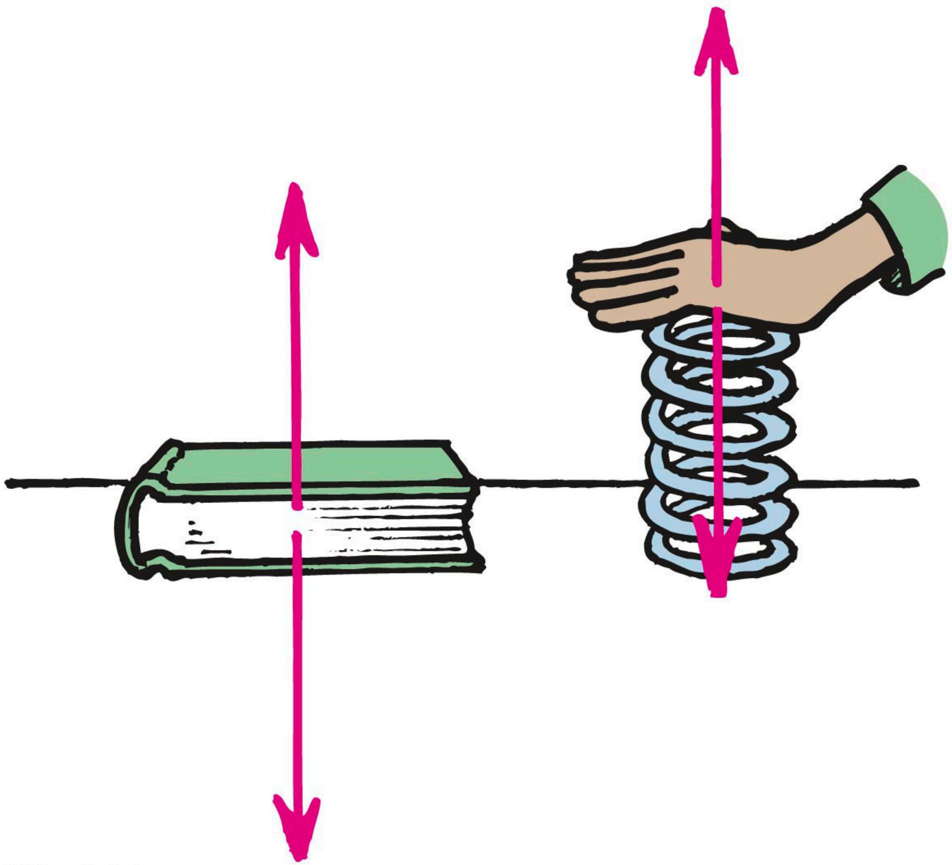
Weight

- Weight is the force due to gravity.
  - measured in Newton (SI-unit is N)
  - always **points downwards** (towards the center of the Earth)

- Recall: $\boldsymbol{w = mg}$

Support Force

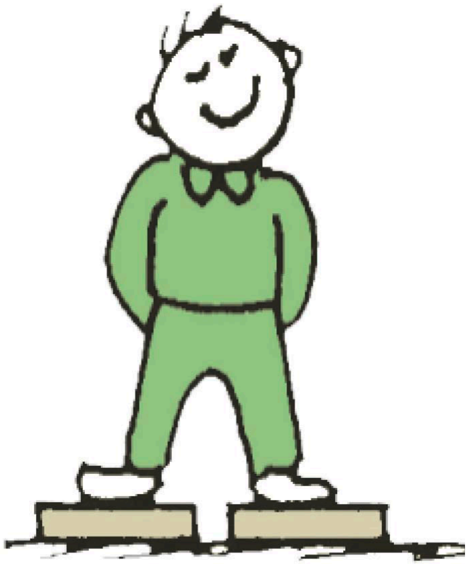
- **Support force**
  - is force that supports an object on the surface against gravity
  - is also normal force (perpendicular to the surface)



Support Force
CHECK YOUR NEIGHBOR

When you stand on two bathroom scales, with one foot on each scale and weight evenly distributed, each scale will read

A. your weight.
B. half your weight.
C. zero.
D. actually more than your weight.



Support Force
CHECK YOUR ANSWER

When you stand on two bathroom scales, with one foot on each scale and weight evenly distributed, each scale will read

A. your weight.

B. half your weight.

C. zero.

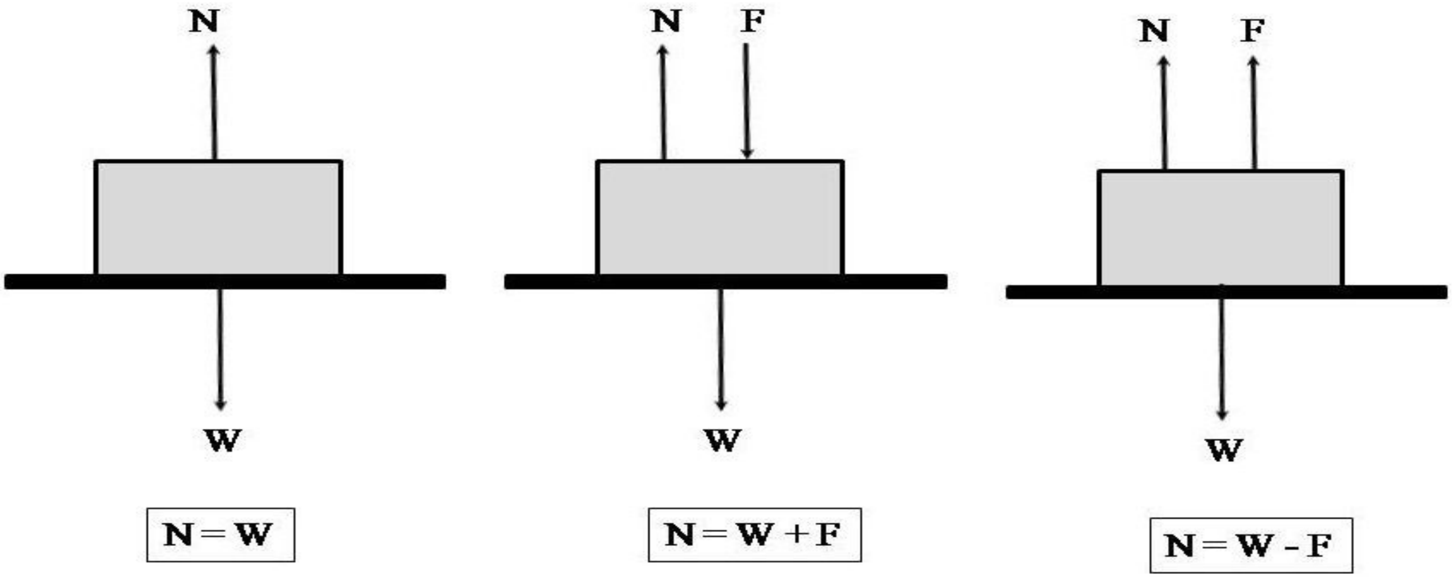
D. actually more than your weight.

Explanation:

You are at rest on the scales, so $\Sigma F = 0$. The sum of the two upward support forces is equal to your weight.

Support Force

- Note: the support (normal) force is **NOT necessarily equal to the weight**

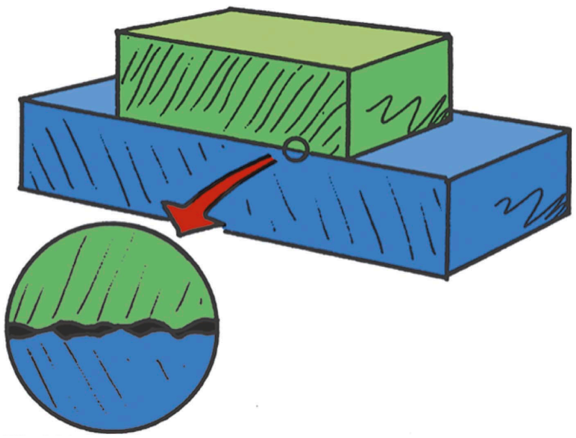


The Force of Friction

- **Friction**
  - the resistive force that **opposes the motion** or attempted motion of an object through a fluid or past another object with which it is in contact
  - always acts in a direction to oppose motion

The Force of Friction

- Friction (continued)
  - between two surfaces, the amount depends on the kinds of material and how much they are pressed together
  - due to surface bumps and also to the stickiness of atoms on the surfaces of the two materials



The Force of Friction
CHECK YOUR NEIGHBOR

The force of friction can occur

A. with sliding objects.

B. in water.

C. in air.

D. All of the above.

The Force of Friction
CHECK YOUR ANSWER

The force of friction can occur

A. with sliding objects.

B. in water.

C. in air.

D. All of the above.

Explanation:

Friction can also occur for objects at rest. If you push horizontally on your book and it doesn't move, then friction between the book and the table is equal and opposite to your push.

The Force of Friction
CHECK YOUR NEIGHBOR

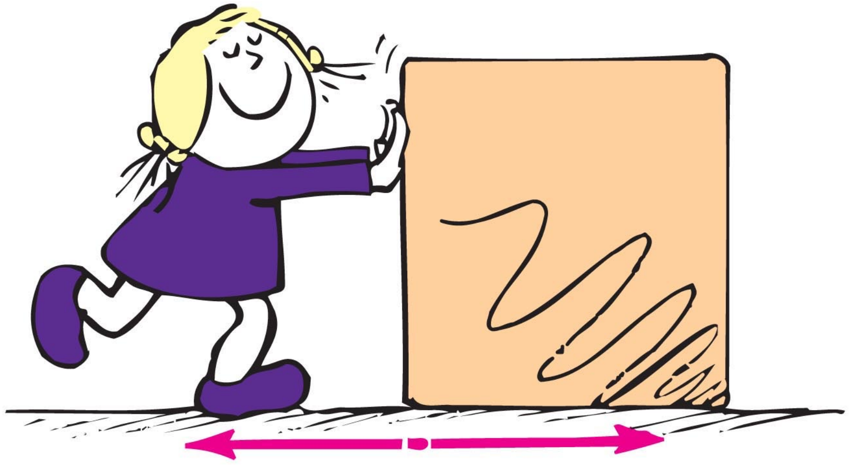
When Nellie pushes a crate across a factory floor at constant speed, the force of friction between the crate and the floor is

A. less than Nellie's push.

B. equal to Nellie's push.

C. equal and opposite to Nellie's push.

D. more than Nellie's push.



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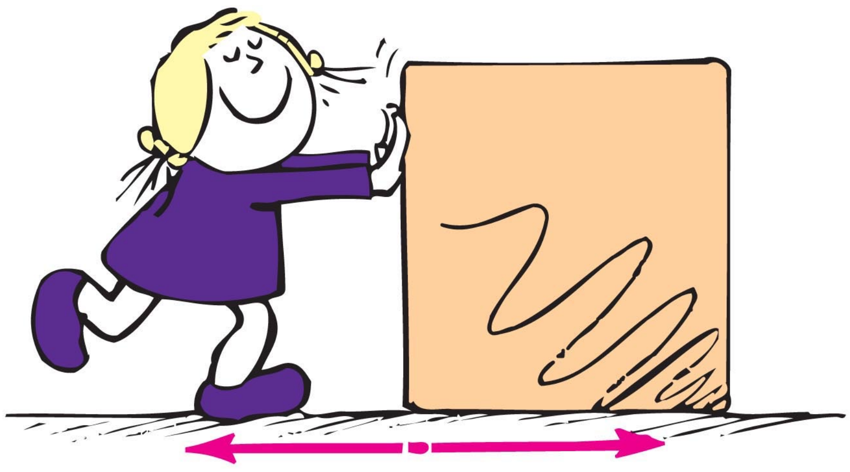


The Force of Friction
CHECK YOUR NEIGHBOR

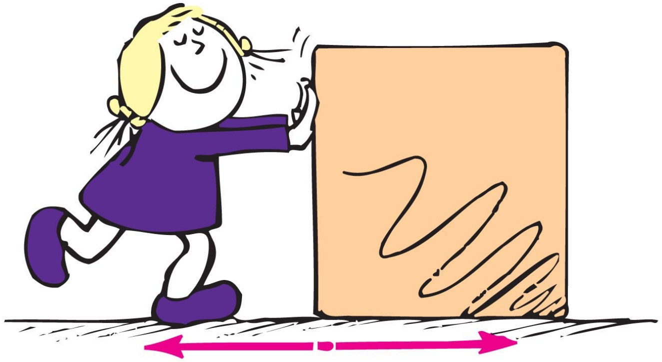
When Nellie pushes a crate across a factory floor at an *increasing speed*, the amount of friction between the crate and the floor is

A. less than Nellie's push.

B. equal to Nellie's push.

C. equal and opposite to Nellie's push.

D. more than Nellie's push.



The Force of Friction
CHECK YOUR ANSWER

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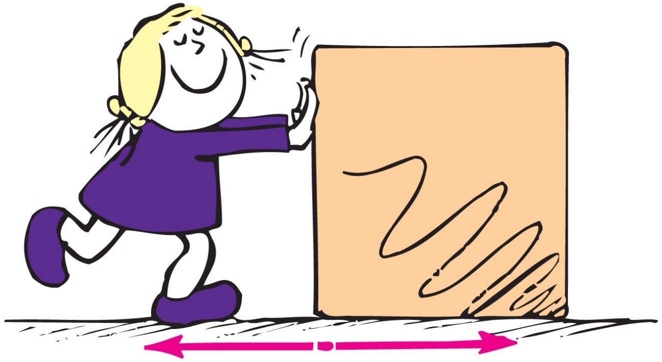

Explanation:

The increasing speed indicates a net force greater than zero. Her push is greater than the friction force. The crate is not in equilibrium.

Speed and Velocity

- **Speed** is described as the distance covered per amount of travel time

speed is measured in units of m/s or km/h

Unit conversion:

- $1\,\frac{\text{km}}{\text{h}} = \frac{1000\ \text{m}}{60\times60\ \text{s}} = \frac{5}{18}\frac{\text{m}}{\text{s}}$
- $1\,\frac{\text{m}}{\text{s}} = \frac{18}{5}\frac{\text{km}}{\text{h}}$

Speed and Velocity

- Average speed
  - is total distance traveled divided by travel time
  - equation:

$$\text{average speed} = \frac{\text{total distance covered}}{\text{travel time}}$$

- Instantaneous speed
  - is speed at any instant of time; the speedometer of your car shows the instantaneous speed not the average speed

Speed and Velocity
CHECK YOUR NEIGHBOR

The average speed in driving 30 km in 1 hour is the same average speed as driving

A. 30 km in one-half hour.

B. 30 km in two hours.

C. 60 km in one-half hour.

D. 60 km in two hours.

Speed and Velocity
CHECK YOUR ANSWER

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Exercises

- A car is moving with a speed of 90 km/h, what is its speed in m/s

- A horse is running with a speed of 15 m/s what is its speed in km/h

Exercises

- A man runs at 8 m/s; find the distance he travels in half an hour.

- A boy swims at 3 m/s, what time is needed for him to travel a distance of 105 m?

Exercises

- A driver is to travel 500 km in 4 hours. If his average speed in the first 275 km was 110 km/h, at what average speed must he travel during the remaining distance?

- If you drive your car at a speed of 80 km/h for 20 km then at a speed of 100 km/h for another 20 km, what is your average speed in the overall distance?

Velocity

- When we know both the speed and the direction of motion of an object, then we know its **velocity**.

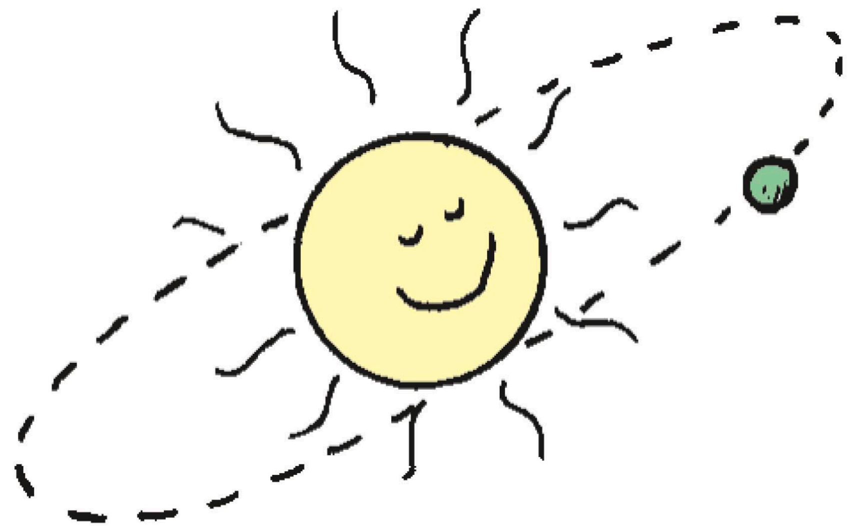
Velocity = speed and direction

- For example, if a car is moving at 80 km/h to the west, then its speed is 80 km/h and its direction is to the west.
- **Constant velocity:** means that the object is neither speeding up nor slowing down and at the same time is moving in the same direction (along a straight line).

- **Question**: Can you round a curve with your car at constant velocity? Explain.

Motion is Relative

- Everything is always moving.
- At this moment, your speed relative to the Sun is about 100,000 kilometers per hour.
- When we say a space shuttle travels at 30,000 kilometers per hour, we mean relative to the Earth.
- When we discuss the speed or velocity of something, we mean the speed or velocity with respect to something else



Relative velocity

- The velocity along a straight line can be expressed with a **number** (indicating its value or magnitude) and a **sign** (+ or − to indicate the direction). For example, right (East) is usually taken to be positive
- Example: $v = -2\ \mathrm{m}/s$ means the object is moving in the negative direction at 2 m/s.
- The Relative velocity of object A with respect to B:

$$v_{AB} = v_A - v_B$$

  - **Note:** v_A *and* v_B **should contain the correct sign (e.g. right: positive, left: negative, or up positive, down negative)** [we study here only one dimensional motion (horizontal OR vertical)]
  - **The sign of the answer indicates the direction of the relative velocity**
- A general note: when two objects move in same direction the relative velocity of one with respect to the other will be the difference between their velocities, and when they move in opposite direction it will be the sum. (only as **magnitudes**)

Relative velocity Example

A car moving to the east at 8 m/s and a truck is moving to the west at 5 m/s. Calculate: (a) The velocity of the truck relative to the car. (b) The velocity of the car relative to the truck.

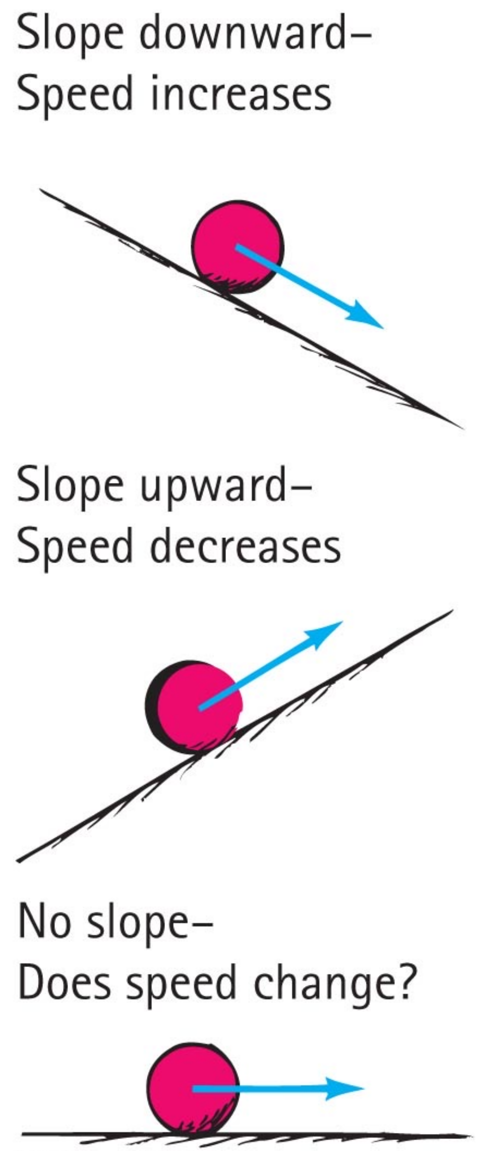
Solution:

(a) $v_{tc} = v_t - v_c = (-5) - (8) = -13\frac{m}{s}$ (13 m/s to the west)

(b) $v_{ct} = v_c - v_t = (8) - (-5) = 13\frac{m}{s}$ (13 m/s to the east)

Acceleration

- Galileo first formulated the concept of acceleration in his experiments with inclined planes.

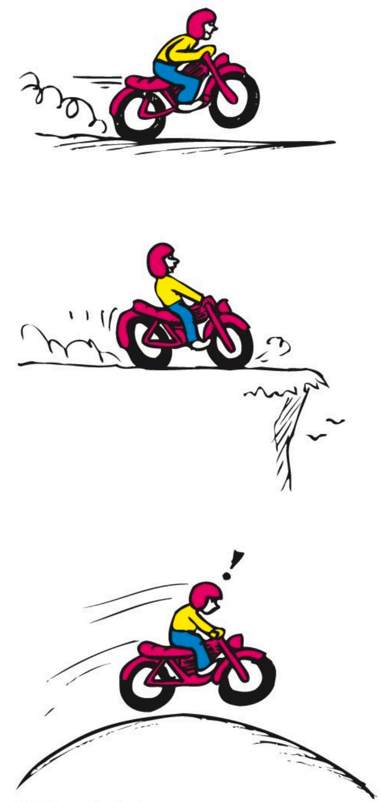


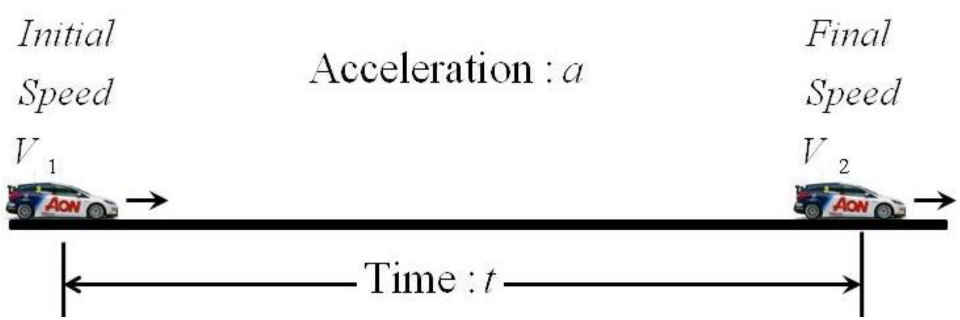
Acceleration

- **Acceleration** is the rate at which velocity changes with time. The change in velocity may be in magnitude, in direction, or both.
  - Equation for acceleration:

$$\text{Acceleration} = \frac{\text{Change in velocity}}{\text{time interval}}$$

$$a = \frac{\Delta v}{t} = \frac{v_f - v_i}{t}$$





Acceleration
CHECK YOUR NEIGHBOR

An automobile cannot maintain a constant velocity when

A. accelerating.
B. rounding a curve.
C. Both of the above.
D. None of the above.

Acceleration
CHECK YOUR ANSWER

An automobile cannot maintain a constant velocity when

A. accelerating.

B. rounding a curve.

C. Both of the above.

D. None of the above.

Explanation:

When rounding a curve, the automobile is accelerating, for it is changing direction.

Acceleration
CHECK YOUR NEIGHBOR

Acceleration and velocity are actually

A. much the same as each other.
B. rates, but for different quantities.
C. the same when direction is not a factor.
D. the same for free-fall situations.

Acceleration
CHECK YOUR ANSWER

Acceleration and velocity are actually

A. much the same as each other.

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D. the same for free-fall situations.

Explanation:

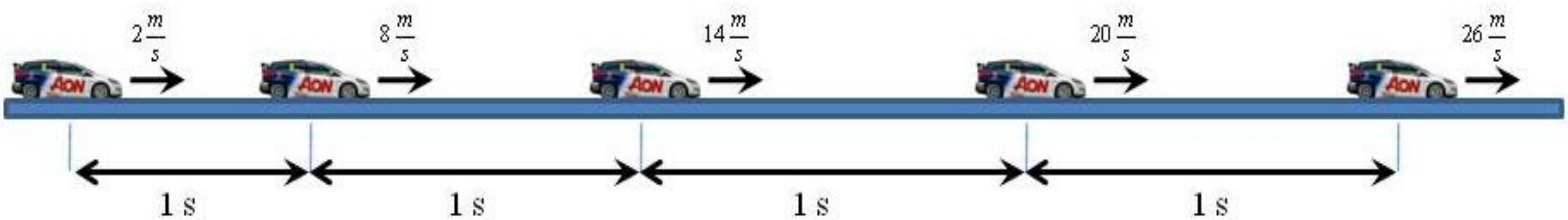
Velocity is the rate at which distance changes with time; acceleration is the rate at which velocity changes with time.

Notes on Acceleration

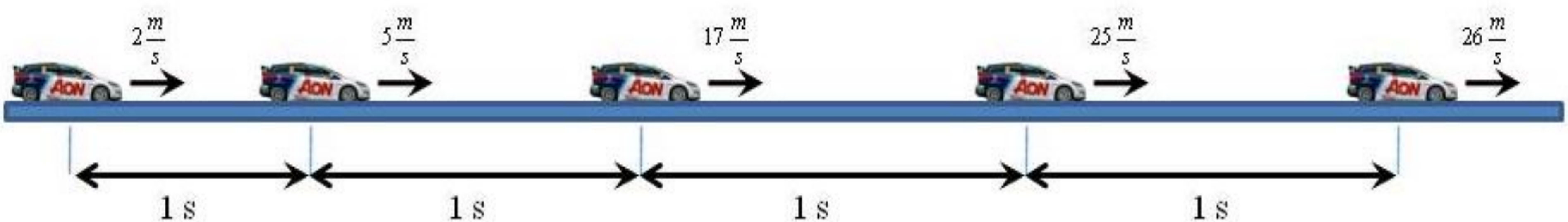
- Notes
  - Constant velocity means no acceleration (= zero acceleration).
  - Unit of acceleration is (units of velocity)/(units of time) = m/s^2.
  - Acceleration is the change in velocity not the change in speed, so even the change in direction only is considered to be acceleration. For example, when a car makes a turn at a constant speed it is still accelerating.
  - **Positive acceleration (with positive velocity) means increasing speed (speeding up) and negative acceleration (with positive velocity) means decreasing speed (slowing down).**
  - When something slows down, we often call this deceleration.
  - Constant acceleration means that the same increase in velocity takes place in equal time intervals.

Constant acceleration

- Constant acceleration: constant change in velocity at similar time intervals



Constant acceleration



Variable acceleration

Exercises

Exercise: If the speed of a certain car at a certain moment is 12 m/s and its acceleration is 3 m/s^2, what will be the speed of the car 8 seconds later? (Ans. 36 m/s)

Exercise: A train slows down from a speed of 126 km/h to a speed of 54 km/h in 8 seconds.

a) What is the acceleration of the train? (note: mind the units!) (126 km/h = 35 m/s, 54 km/h = 15 m/s).

(Ans. -2.5 m/s^2; what does the negative sign mean?)

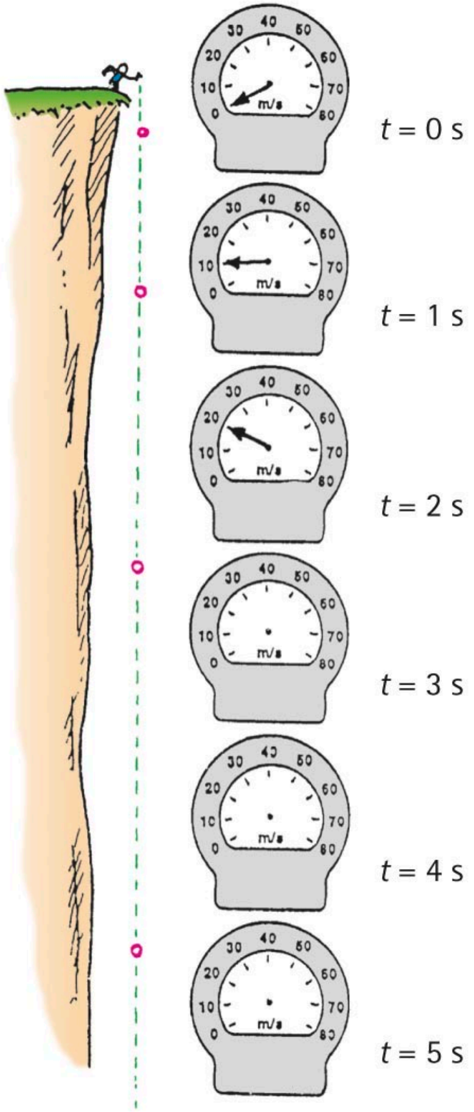
b) If it continues to decelerate at the same rate, how long will it take it to stop from its initial speed?

Acceleration

- Free fall:

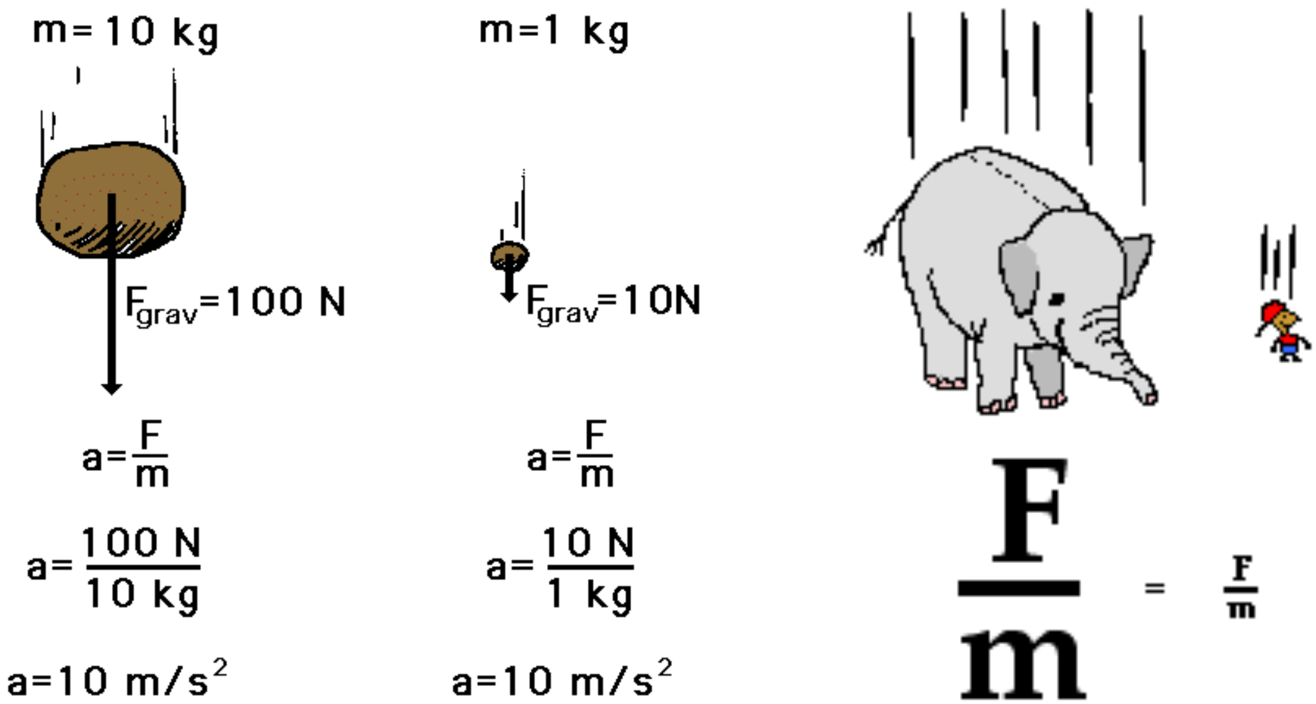
  When **the only force acting on a falling object is gravity** (the weight), **with negligible air resistance**, the object is in a state of **free fall**.

  - An upward moving object under these conditions is also in free-fall!



Free Fall Acceleration

- Acceleration of free fall **does not** depend on mass. It is **constant**.



Free Fall Acceleration

- Neglecting air resistance, all objects in free fall in the earth's gravitational field have a constant acceleration of magnitude:

$$g \cong 9.81\ m/s^2 \approx 10\ m/s^2$$

Direction of *g* is **always downwards** (towards earth's center).

- In other words, **the speed of an object increases by 10 m/s each second while falling down, and decreases by 10 m/s each second while moving up.**

- The distance travelled by a freely falling object released from rest is directly proportional to the square of the time of fall, In equation form:

$$d = \frac{1}{2} g t^2$$

Acceleration
CHECK YOUR NEIGHBOR

If a falling object gains 10 m/s each second it falls, its acceleration is

A. 10 m/s.

B. 10 m/s per second.

C. Both of the above.

D. Neither of the above.

Acceleration
CHECK YOUR ANSWER

If a falling object gains 10 m/s each second it falls, its acceleration is

A. 10 m/s.

B. 10 m/s per second.

C. Both of the above.

D. Neither of the above.

Explanation:

It is common to express 10 m/s per second as 10 m/s/s, or 10 m/s^2.

Acceleration
CHECK YOUR NEIGHBOR

A free-falling object has a speed of 30 m/s at one instant. Exactly one second later its speed will be

A. the same.

B. 35 m/s.

C. more than 35 m/s.

D. 60 m/s.

Acceleration
CHECK YOUR ANSWER

A free-falling object has a speed of 30 m/s at one instant. Exactly one second later its speed will be

A. the same.

B. 35 m/s.

C. more than 35 m/s.

D. 60 m/s.

Explanation:

One second later its speed will be 40 m/s, which is more than 35 m/s.

Acceleration
CHECK YOUR NEIGHBOR

The distance fallen by a free-falling body

A. remains constant each second of fall.
B. increases each second when falling.
C. decreases each second when falling.
D. None of the above.

Acceleration
CHECK YOUR ANSWER

The distance fallen by a free-falling body

A. remains constant each second of fall.

B. increases each second when falling.

C. decreases each second when falling.

D. None of the above.

Explanation:

See Table 1.2 for verification of this. Falling distance ~ time squared.

Exercises

Exercise: (1st exam, term 111) A 7-kg ball is thrown at 10 m/s straight upward. Neglecting air resistance, the net force that acts on the ball when it is half way to the top of its path is about

a) 10 N b) 5 N c) 35 N d) 70 N e) None of the above.

Exercise: (1st exam, term 111) An object is in a downward free-fall. At one instant, it travels at a speed of 37 m/s. Exactly 2 s later, its speed is about:

a) 37 m/s b) 10 m/s c) 57 m/s d) 17 m/s e) 20 m/s

Exercise: (1st exam, term 111) A rock is thrown vertically into the air. At the top of its path, its acceleration in m/s^2 is about:

a) 10 b) Zero c) Between 0 and 10 d) Greater than 10

e) None of the above

Exercises

Exercise: A ball is thrown at a speed of 90 m/s directly upward from ground.

a) What is the speed of the ball 7 seconds later?

b) What is the time needed for the ball to reach the top point?

c) What is the speed of the ball 4 seconds after reaching the top point?

e) What is the ball’s flight time?

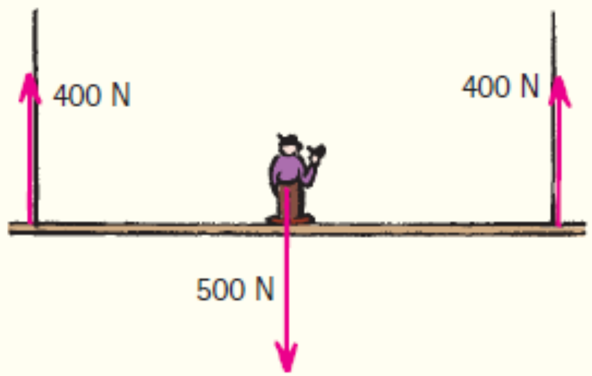
Exercises

Exercise: A stone is dropped from rest from a large height. What is the distance traveled in the seventh second?

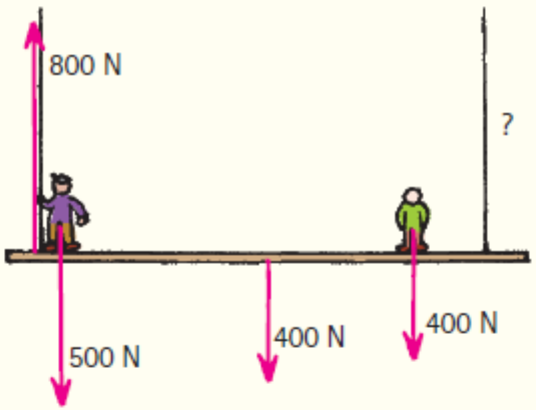
Exercise: A ball thrown vertically upward from the ground is caught again by the thrower 12 seconds later. What is the maximum height reached by the ball?

Problems

43. The sketch shows a painter's scaffold in mechanical equilibrium. The person in the middle weighs 500 N, and the tension in each rope is 400 N. What is the weight of the scaffold?



44. A different scaffold that weighs 400 N supports two painters, one 500 N and the other 400 N. The reading in the left scale is 800 N. What is the reading in the right-hand scale?



Problems

45. A horizontal force of 120 N is required to push a bookcase across a floor at a constant velocity.
(a) What is the net force acting on the bookcase?
(b) How much is the friction force that acts on the sliding bookcase?
(c) How much friction acts on the bookcase when it is at rest on a horizontal surface without being pushed?

55. A ball is thrown straight up with enough speed so that it is in the air for several seconds.
(a) What is the velocity of the ball when it reaches its highest point?
(b) What is its velocity 1 s before it reaches its highest point?
(c) What is the change in its velocity, Δv, during this 1-s interval?
(d) What is its velocity 1 s after it reaches its highest point?
(e) What is the change in velocity, Δv, during this 1-s interval?
(f) What is the change in velocity, Δv, during the 2-s interval from 1 s before the highest point to 1 s after the highest point? (Caution: We are talking about velocity, not speed.)
(g) What is the acceleration of the ball during any of these time intervals and at the moment the ball has zero velocity?

57. An airplane starting from rest at one end of a runway accelerates uniformly at 4.0 m/s^2 for 15 s before takeoff.
(a) What is its speed of takeoff?
(b) Show that the plane travels along the runway a distance of 450 m before takeoff.