Name: ____

HONORS PHYSICS
UNIT 2: FORCES AND DYNAMICS

PHYSICS 9-12
Georgia Standards of Excellence

SP2. Obtain, evaluate, and communicate information about how forces affect the motion of objects.

a. Construct an explanation based on evidence using Newton's Laws of how forces affect the acceleration of a body.
   - Explain and predict the motion of a body in absence of a force and when forces are applied using Newton's 1st Law (principle of inertia).
   - Calculate the acceleration for an object using Newton's 2nd Law, including situations where multiple forces act together.
   - Identify the pair of equal and opposite forces between two interacting bodies and relate their magnitudes and directions using Newton's 3rd Law.

b. Develop and use a model of a Free Body Diagram to represent the forces acting on an object (both equilibrium and non-equilibrium).

c. Use mathematical representations to calculate magnitudes and vector components for typical forces including gravitational force, normal force, friction forces, tension forces, and spring forces.

Equations

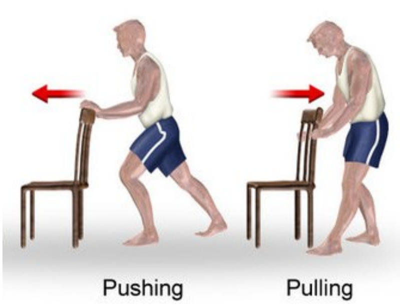
Force	$F_{Net} = m \cdot a$	F = force (N) (net force) m = mass (kg) a = acceleration (m/s^2)
Acceleration	$\vec{a} = \dfrac{\vec{v}_f - \vec{v}_0}{t}$	a = acceleration (m/s^2) v_f = final velocity (m/s) v_0 = initial velocity (m/s) t = time (s)
Gravity force (weight)	$F_{Grav} = w = m \cdot g$	w = weight (N) g = acceleration due to gravity (9.8 m/s^2) m = mass (kg)

Normal force (support force, push-back force by surface)	$F_{Norm} = F_{Grav} \cdot \cos\phi$	F_{Grav} = weight (N) ϕ = slope angle of surface (degrees)
Friction force	$F_{Frict} = F_{Norm} \cdot \mu$	F_{Norm} = normal force (N) μ = friction coefficient (values 0 to 1.0)
Applied parallel force (Action force, unassisted)	$F_{Appl} = F_{Grav} \cdot \sin\phi$	F_{Grav} = weight (N) ϕ = slope angle of surface (degrees)
Friction coefficient	$\mu \approx \tan\phi_r$ $\phi^r \approx \mu^{-\tan}$	μ = friction coefficient (values 0 to 1.0) ϕ^r = angle of repose (degrees)
Parallel or Action Force (pulling or pushing at an angle) Horizontal component force	$F_x = F' \cdot \cos\theta$	F_x = parallel force (N) F' = effort force at an angle (N) θ = push or pull angle (degrees)
Vertical force component (pulling or pushing at an angle)	$F_y = F' \cdot \sin\theta$	Fy = vertical force component (N) F' = effort force at an angle (N) θ = push or pull angle (degrees)

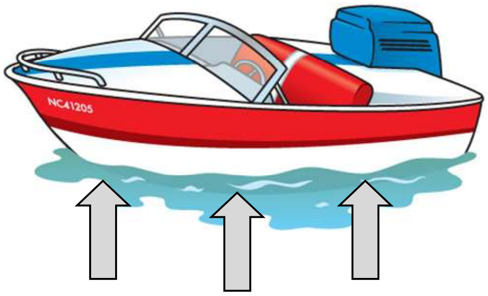
FORCES AND CALCULATING FORCES

What Are Forces?

Forces are push or pull actions that occur when one object interacts with another object. ***Forces cause objects to accelerate***—forces make objects speed up, slow down, or change direction. Remember, ***acceleration is the change in velocity***: a change in rate of motion (getting faster or slower with time) or a change in direction. Forces are **vectors** just like velocity and acceleration, and must have both a magnitude (how strong, how big) and a direction. Forces may be positive or negative depending on the direction of influence or action. If the acceleration is positive, the force causing the acceleration is positive. If the acceleration is negative, the force causing the acceleration is negative.

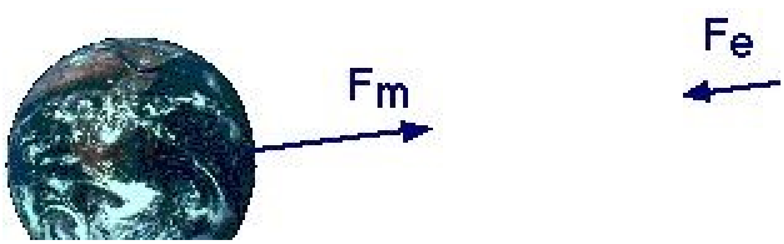


Some forces are ***contact forces***—objects need to touch, or have physical contact with each other for one to exert a force upon the other. Examples of contact forces include friction, air resistance, buoyancy, tension, and impacts.



Example: Buoyancy is a contact force. The water in the lake is touching the bottom and sides of the boat. The force of buoyancy pushes upward onto the boat keeping the boat afloat in the water.

Some forces are ***action-at-a-distance forces*** or ***non-contact forces***—objects do not need to touch each other for one to exert a force upon the other. The forces pass through space, air, liquids, and solids. Action-at-a-distance forces include electric fields, magnetic fields, and gravity. Magnets, for example, do not need to touch for them to attract or repel each other.



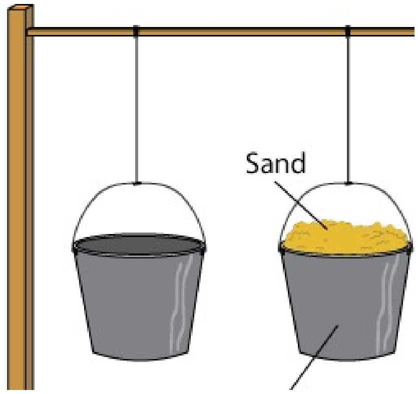
Example: Gravitational attraction force is an action-at-a-distance or non-contact force. Earth's moon and the Earth are pulling on each other with equal and opposite forces despite not touching each other. The pull force of gravity between Earth and moon keeps Earth's moon in orbit around the Earth.

Mass and Inertia

Mass is defined as the quantity of matter contained within an object. Mass tells us "how much stuff" is inside objects. ***Mass is a conserved property of matter***, meaning that mass is constant regardless of the forces acting upon the object or the motion of the object. In other words, mass never changes.

The property called ***inertia*** is proportional to the mass of the object. ***Inertia*** is an object's resistance to changing its state of motion; the object's resistance to accelerate. Bigger objects require more force to be accelerated because they have more inertia due to their larger mass. Conversely, smaller objects require lesser force to be accelerated because they have less inertia due to their smaller mass.

Example: The empty bucket has less mass, therefore has less inertia. As a result, the empty bucket can be easily pushed or pulled by a weak force—less mass means less resistance to accelerating by a force. In contrast, the bucket filled with sand has a very large mass. As a result, a stronger force is needed to push or pull the sand-filled bucket—greater mass means more resistance to accelerating by a force.



Calculating Forces

Force is calculated as the product of mass (kg) times acceleration (m/s^2). The force equation may be rearranged to solve for acceleration or mass.

Force = Mass x Acceleration

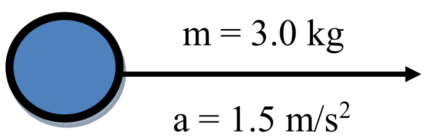
$$F_{net} = m \cdot a \qquad a = \frac{F_{net}}{m} \qquad m = \frac{F_{net}}{a}$$

F = force (N) [Net force acting upon object]
a = acceleration (m/s^2)
m = mass (kg)
N = newtons (unit of force, $N = kg\frac{m}{s^2}$)

Forces are reported in units of **Newtons** (N), named after Sir Isaac Newton. Note that the ***mass must always be in kg*** and ***acceleration must always be in m/s²***.

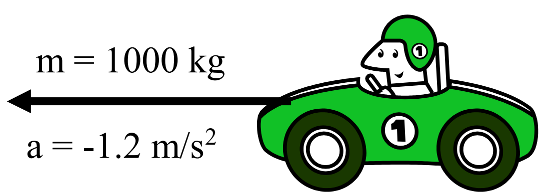
Example: A 3.0 kg ball is accelerated at 1.5 m/s^2. Calculate the applied force acting upon the ball.

$$F = m \cdot a = 3.0\,\text{kg} \cdot 1.5\,{}^{\text{m}}\!/_{\text{s}^2} = 4.5\,\text{N}$$



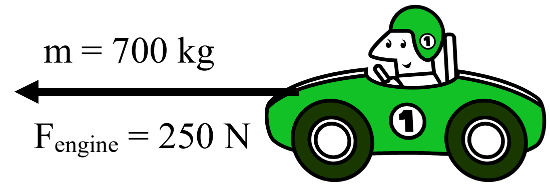
Example: A car's engine accelerates the car by -1.2 m/s^2. The mass of the car is 1000 kg. Calculate the force of the engine accelerating the car.

$$F = m \cdot a = 1000\,\text{kg} \cdot -1.2\,{}^{\text{m}}\!/_{\text{s}^2} = -1200\,\text{N}$$



Example: A car's engine uses a force of 250 N to move accelerate the car. Calculate the acceleration.

$$a = \frac{F}{m} = \frac{250N}{700kg} = 0.357 \, {}^{m}\!/_{s^2}$$



NEWTON'S LAWS OF MOTION

Natural laws describe how matter and energy behave in our universe. The processes that are described by natural laws always occur regardless of physical state, place, time, or motion. ***Newton's Laws of Motion*** are natural laws that describe how forces affect the motion of objects in our universe.

Newton's 1ST Law of Motion

Newton's 1st Law of Motion: "Law of Inertia", an object will maintain its original state of motion unless acted upon by an external unbalanced force. An object will maintain a constant velocity (straight-line, uniform rate of motion) unless acted upon by an external unbalanced force.

Newton's 1st Law describes what happens to objects' motions because of balanced and unbalanced forces. Balanced forces (net force = 0) will not change the motion of objects (no acceleration). Unbalanced forces acting upon an object (net force > 0) will change the motion of that object (cause acceleration).

What really happens to the motion of objects because of Newton's 1st Law?

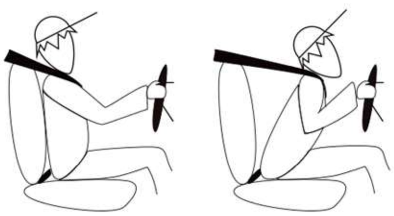
- All objects at rest (motionless, v = 0 m/s) will remain at rest until disturbed by an unbalance force to get it moving.
- All objects in motion will move in a straight-line direction at the same velocity forever unless a force (a push or pull by another object) causes the object to speed up, slow down, or change direction.

Inertia is the property of matter where an object resists acceleration and wants to retain its original state of motion. ***Inertia is proportional to mass***: the more massive the object, the more inertia and more resistance to acceleration. Conversely, the less massive the object, the less inertia and less resistance to acceleration. An object with a mass of 10 kg has 2-times the inertia as an object with a mass of 5 kg—the 10 kg object is resisting "twice as much" to be moved by a force compared to the 5 kg object. It will take a stronger force to accelerate the 10 kg mass and weaker force to accelerate the 5 kg mass.

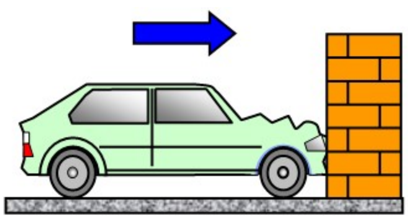
Small mass = small inertia

Big mass = Big inertia

Example: The tennis ball has a very small mass, thus it weakly resists acceleration. The small impact force of the tennis racket will change its velocity. In contrast, th elephang has a huge mass and huge inertia. It will resist moving unless the force is very, very large.



Example: Most people have experienced the effect of inertia while riding in an automobile. When the automobile is moving at a constant velocity, the driver and passengers' bodies remain upright—there is no acceleration. When the automobile brakes or slows, however, the driver and passengers' bodies lean forward. Their bodies resist accelerating, in this case resisting to the slowing down. Their bodies continue forward at the car's original velocity before braking occurred even though the car beneath them had slowed or stopped. *Object in motion wants to remain in motion*.



Example: A car moving at a constant velocity strikes an immovable object like a wall. The car's front end crumples because the car's mass tries to continue forward at its original velocity before the collision occurred. *Object in motion wants to remain in motion*—the impact with the wall is the external force stopping the car.

Newton's 2ND Law of Motion

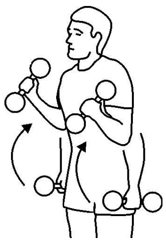
Newton's 2nd Law of Motion: $a = \frac{F}{m}$ The acceleration experienced by an object is proportional to the magnitude of the force (F) causing the acceleration and inversely proportional to the mass of the object being accelerated.

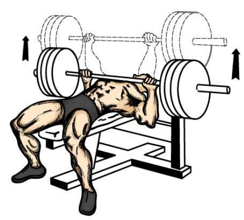
Newton's 2nd Law describes what happens to objects of different masses when forces cause acceleration. A more massive object requires more force to change its state of motion (accelerate it). Conversely, a less massive object requires lesser force to change its state of motion.

Lesser mass requires less force to accelerate it

Greater mass requires more force to accelerate it.

The empty shopping car will be easier to push and to turn because it has less mass—less force is needed to push it forward and turn it. The full shopping car will be more difficult to push and to turn because it has more mass—more force is needed to push it forward and turn it.

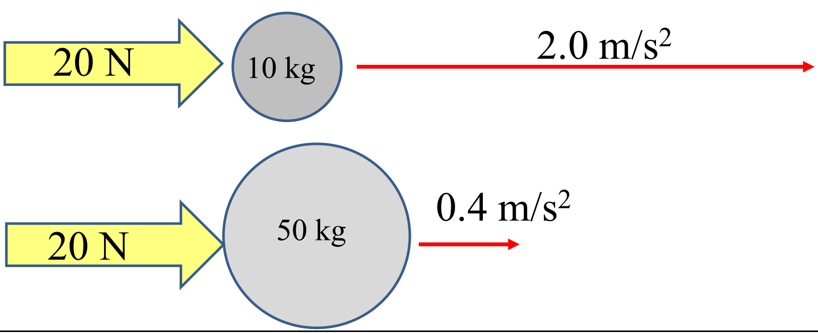




The man will exert less force to lift the 5 kg dumbbells because they have less mass. The man will exert more force to push the 50 kg barbell because it has more mass.

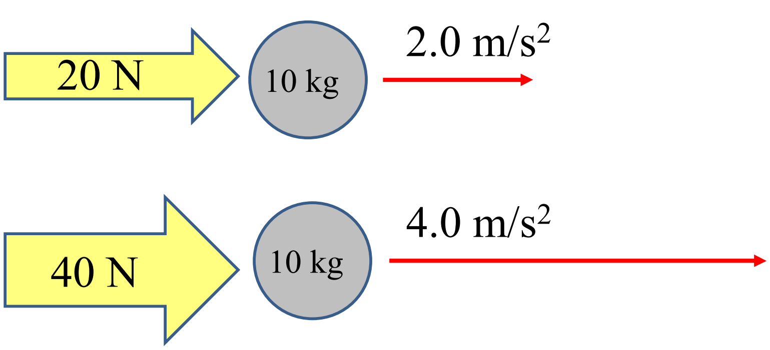
What really happens to the motion of objects because of Newton's 2nd Law?

- A stronger force will cause a greater acceleration; a weaker force will cause a lesser acceleration.
- The greater the mass of the object, the greater the force required to accelerate the object.
- The lesser the mass of the object, the lesser the force required to accelerate the object.
- If two objects of unequal mass (one greater, one lesser) are affected by the same force, the object with the greater mass experiences a lesser acceleration, the object with the lesser mass experiences the greater acceleration.



Two objects of unequal mass are pushed by equal forces.

The object with the smaller mass has the greater acceleration. The object with the greater mass has the lesser acceleration.

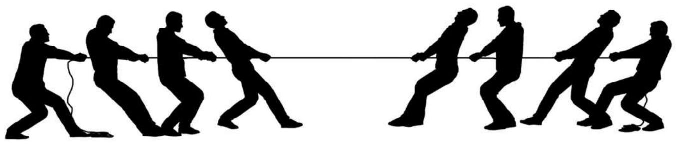


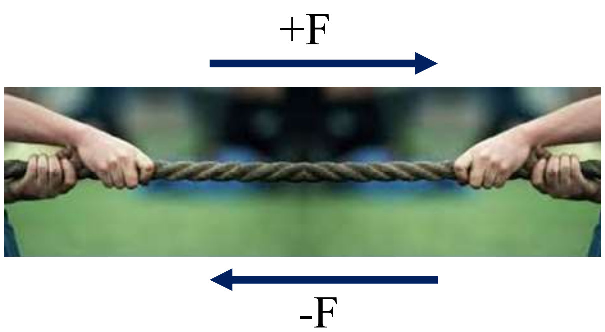
Two objects of equal masses are pushed by forces of different magnitude.

The object pushed by the weaker force has the lesser acceleration. The object pushed by the stronger force has the greater acceleration.

Newton's 3rd Law of Motion

Newton's 3rd Law: "Law of paired forces", when two objects interact, the force exerted by one object is equal in magnitude and opposite in direction to the force exerted by the other object.



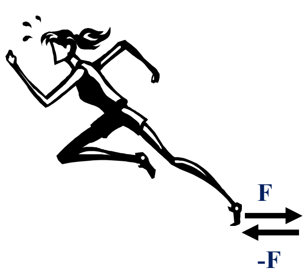


Not to be confused with balanced forces, Newton's 3rd Law describes that all interactions between objects through forces have are equal and opposite. When an object pushes on another object, that object pushes back with a force with the same magnitude, but opposite in direction. Newton's 3rd law applies to the point of the interaction between the two interfering objects. Objects may still be under balanced or unbalanced force conditions.

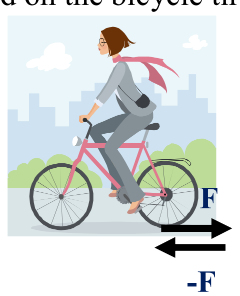
What really happens to the motion of objects because of Newton's 3rd Law?

- Object 1 pushes or pulls with the same force upon object 2 as object 2 pushes or pulls upon object 1, but in opposite directions.
- If you push on an object, the object pushes back with equal force in opposite direction.
- If you pull on an object, the object pulls back with equal force in opposite direction.

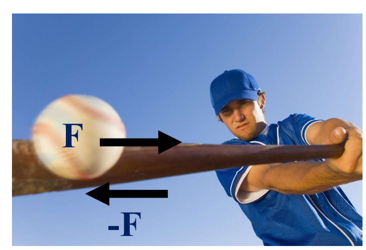
The runner's shoe pushes with a force backward against the pavement. The pavement pushes with an equal & opposite force forward on the runner's shoe.



The force of the bicycle tire pushing backward on the road surface is equal & opposite the force of the road surface pushing forward on the bicycle tire.



The force of the baseball striking the bat is equal and opposite the force of the bat striking the baseball.



BALANCED AND UNBALANCED FORCES

If two objects interact, there may be cases when the forces are balanced and when the forces are unbalanced. If you recall about ***Newton's 1st Law of Motion***, an object will maintain its original state of motion unless acted upon by an external unbalanced force. An object will maintain a constant velocity (straight-line, uniform rate of motion) ***unless acted upon by an external unbalanced force***. Unbalanced forces cause objects to accelerate and change their states of motion.

A state of ***balanced forces*** occurs when the forces that act upon an object are equal in magnitude and opposite in direction. The ***net force*** acting upon both objects is zero—the forces cancel each other out. When forces are balanced, *the object retains its original state of motion*. ***Static equilibrium*** (static = still, equilibrium = balance) is a specific case in which an object is affected by balanced forces that cause the object to remain motionless when it is originally motionless.

The two teams pull on the rope with equal force and in opposite directions: +300 N (to the right) and -300 N (to the left. The pull forces cancel each other out creating a net force of zero. Neither team will accelerate.

When forces acting upon an object are **balanced** (equal in magnitude and opposite in direction)

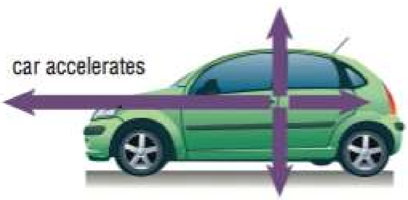
- Net force = 0 Newtons (all of the forces cancel each other out, no net force remains)
- If the object is initially motionless, the object will remain motionless (static equilibrium)
- If the object is initially moving, the object will remain moving at its original velocity (the same rate of motion and direction).

Unbalanced forces occur when the forces of two interacting objects that act upon each other are not equal in magnitude and/or are not in opposite directions. The net force acting upon the object or objects will not be zero. Unbalanced forces cause objects to change their states of motion—objects will move faster with time, will move slower with time, or will change direction. The change of motion is always *in the direction of the net force*.

The two teams pull on the rope with unequal forces: +300 N (to the right) and -400 N (to the left. The pull forces do not cancel each other out. The net force acting upon both teams is -100 N. The teams will accelerate to the left.

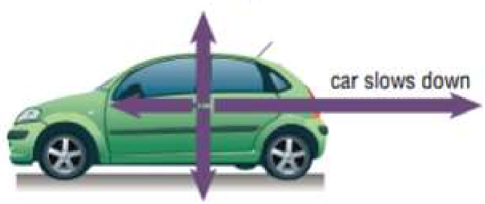
When forces acting upon an object are **unbalanced** (at least one force is greater than the other forces, forces do not cancel out)

- Net force is > 0 N. Forces acting upon an the object are NOT equal and opposite.
- If an object is initially motionless, it will start to move in the direction of the greater force.
- If an object is initially in motion, its state of motion will change (get faster, get slower, or change direction) in the direction of the greater force.



Unbalanced forces. The force of the car's motor is greater than the force of friction. As a result, the car will get faster with time (accelerate in direction of motion).

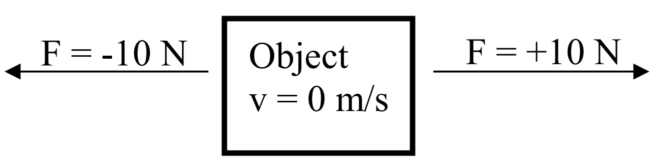
Balanced forces. The force of the car's motor is equal and opposite the force of friction. As result, the car will move at constant velocity (same rate, will not get faster or slower)



Unbalanced forces. The force of friction is greater than the force of the car's motor. As a result, the car will get slower with time (accelerate in the direction opposite of motion).

Illustrative example of Balanced Forces

An object is initially motionless. Two forces objects are pulling on the object in opposite direction with equal magnitude of force: -10 N (left) and +10 N (right). Thus the net force acting upon the object is zero.

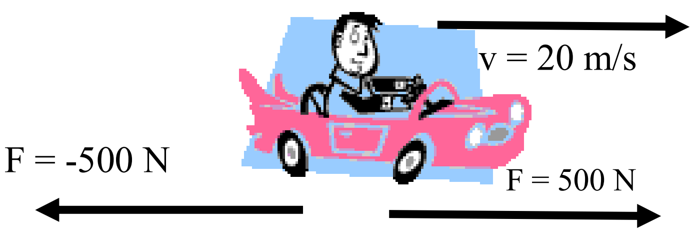


Because the net force is zero (balanced), the object maintains its original state of motion. It will remain motionless. This condition is called ***static equilibrium*** because balanced forces are keeping an object that was initially motionless still.

Net force: $F_{Net} = -10N + 10N = 0$

Illustrative example of Balanced Forces

A car is in motion and moving at a constant velocity of +20 m/s (right). The force of the motor pulling the car forward is equal in magnitude and opposite in direction to the force of friction: +500 N (right) and -500 N (left).

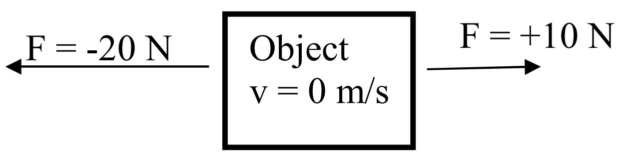


Because the force exerted by the motor and the friction force are equal in magnitude but opposite, the net force acting upon the car is zero. The forces are balanced, thus the car will move at +20 m/s and maintain its original state of motion—the car will neither speed up nor slow down (zero acceleration).

Net force: $F_{Net} = -500N + 500N = 0$

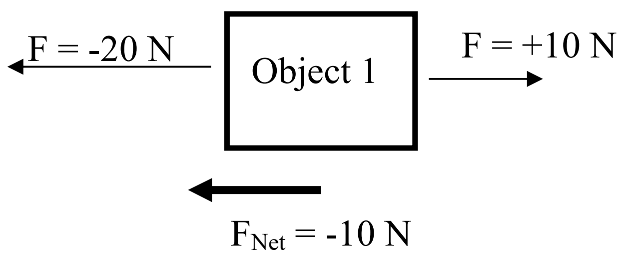
Illustrative example of Unbalanced Forces

An object is initially motionless. Two opposing and unequal forces pull on the object in opposite directions. Force 1 is greater in magnitude than force 2: -20 N (left) and +10 N (right).



Because the net force acting upon the object is a value other than zero, the will accelerate in the direction of the net force. Net force: -10 N. The object will move in the direction of the net force. The object will accelerate to the left.

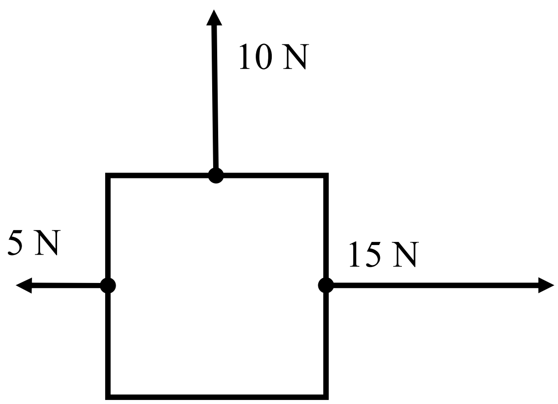
Net force acting upon object: $F_{Net} = -20N + 10N = -10N$



2-DIMENSIONAL FREEBODY DIAGRAMS

Drawing free body diagrams

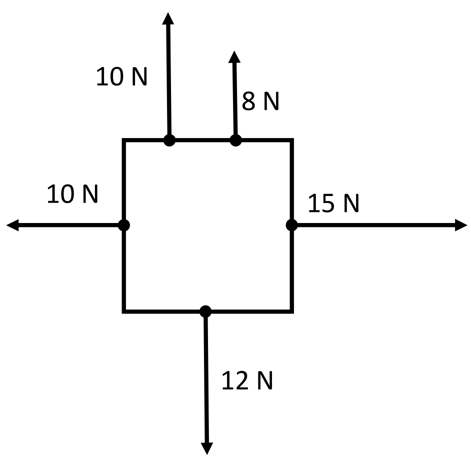
Free body diagrams are diagrams or drawings that show all of the forces that simultaneously act upon bodies or objects. All forces on the free body diagram are represented by vector arrows. The point of the arrow indicates the direction of the forces' influences and the lengths of the arrows indicate the forces' magnitudes. The values of the forces' magnitudes are often written next to their respective arrows.



The free body diagram to the left shows an object (represented by a square) that is simultaneously affected by four different forces.

- 10 N north (+10 N)
- 15 N east (+15 N)
- 5 N west (-5 N)
- 0 N south (not shown)

Note that the lengths of the vector arrows are proportional to the forces' magnitudes. Stronger force = longer arrow.



The free body diagram to the left shows an object (represented by a square) that is simultaneously affected by five different forces.

- 10 N north (+10 N)
- 8 N north (+8)
- 15 N east (+15 N)
- 10 N west (-10 N)
- 12 N south (-12 N)

Note that the lengths of the vector arrows are proportional to the forces' magnitudes. Stronger force = longer arrow.

Calculating Net Force

The **net force** (or **resultant force**) is the overall single force acting upon an object. The net force is the single force (magnitude and direction) that remains when all forces are added together. If all of the forces when added together cancel out, and the net force is determined to be 0 N, then forces are balanced. Under balanced force conditions, the object will not accelerate—the object will maintain its original state of motion. If all of the forces when added together yield one remaining net force > 0 N, then forces are unbalanced. The object will accelerate in the direction of the net force. The magnitude of the acceleration is proportional to the net force—the greater the net force, the greater the acceleration.

How to calculate the net force

Step 1: Identify all of the forces that act upon the body. List the forces.

- Group North and South forces together
- Group East and West forces together.

Step 2. Determine the net force in the N-S transect and the net force in the E-W transect.

- Calculate the net force acting upon the object in the North and South direction. North is (+) and South is (-)

$$F_{N-S} = F_{(North)} + F_{(South)}$$

- Calculate the net force acting upon the object in the East and West direction. East is (+) and West is (-)

$$F_{E-W} = F_{(East)} + F_{(West)}$$

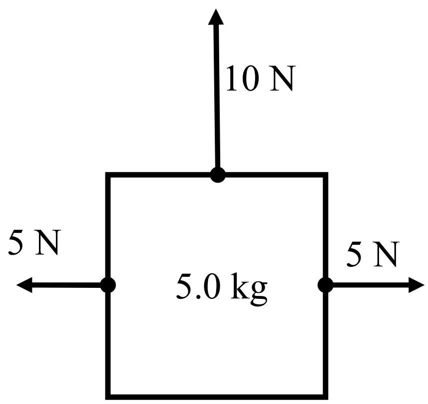
Step 3. Redraw the free body diagram using only the net forces that remain in the N-S transect and the E-W transect.

Step 4. Determine the overall net force acting upon the object. Use the Pythagorean Theorem only if transect net forces in two directions remain and a right triangle can be formed.

Step 5. Calculate the acceleration of the object by using the object's mass and the net force.

$$a = \frac{F}{m}$$

Example of Determining the Net Force

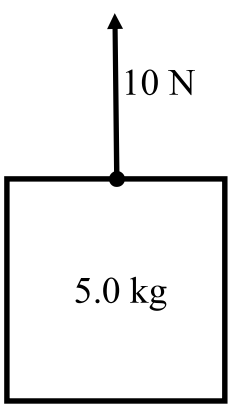


- Step 1: List the forces (there are three forces)
  10 N north; 0 N south
  5 N east; 5 N west

- Step 2: Calculate the net force in the N-S transect (add together the forces in the north and south directions).
  $F_{N-S} = 10N + 0N = 10N$
  Net force = 10 N north

- Step 2: Calculate the net force in the E-W transect (add together the forces in the east and west directions).
  $F_{E-W} = 5N + -5N = 0N$
  Net force = 0 N

Redrawn with only remaining forces



- Step 3: Redraw the free body diagram using only the net forces in the N-S and E-W transects.

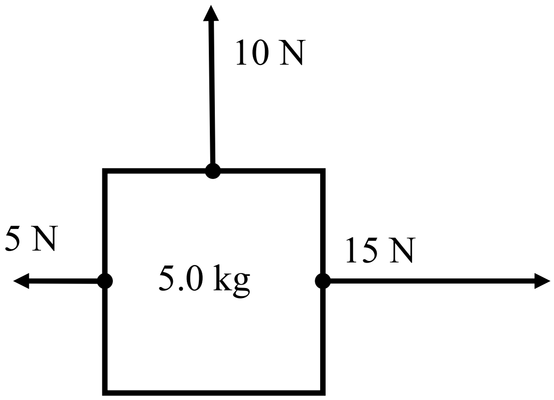
- Step 4: Determine the overall net force affecting the object.
  The only remaining force is the 10 N north.

- Step 5: Calculate the acceleration affecting the object

$$a = \frac{F}{m} = \frac{10N}{5.0kg} = 2.0\, {}^{m}\!/_{s^2}\ @\ N$$

Answer: The net force affecting the object is 10 N north. The object will accelerate north at 2.0 m/s^2.

Example of Determining the Net Force

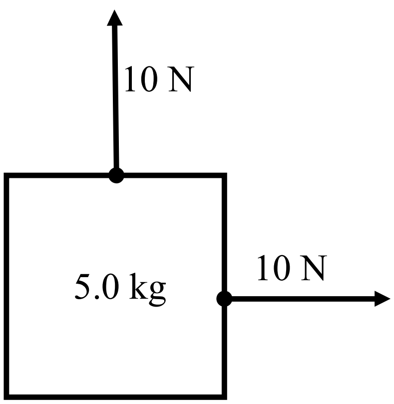


- Step 1: List the forces (there are three forces)
  10 N north; 0 N south
  15 N east; 5 N west

- Step 2: Calculate the net force in the N-S transect (add together the forces in the north and south directions).
  $$F_{N-S} = 10N + 0N = 10N$$
  Net force = 10 N north

- Step 2: Calculate the net force in the E-W transect (add together the forces in the east and west directions).
  $$F_{E-W} = 15N + -5N = 10N$$
  Net force = 10 N east

Redrawn with only remaining forces

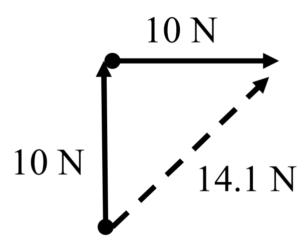


- Step 3: Redraw the free body diagram using only the net forces in the N-S and E-W transects.

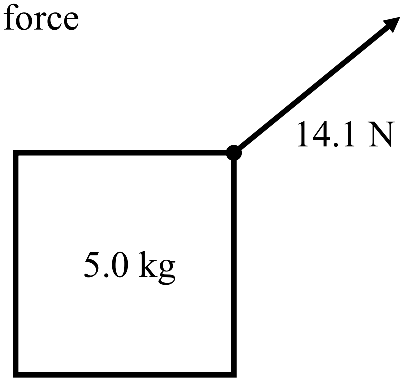
- Step 4: Determine the overall net force affecting the object.
  The net forces are 10 N north and 10 N east.

  Use the Pythagorean Theorem to solve for the net force

  $$C = \sqrt{(10N)^2 + (10N)^2} = 14.1\,N \text{ @ NE}$$



Redrawn with only the net force



- Step 5: Calculate the acceleration affecting the object
  $$a = \frac{F}{m} = \frac{14.1N}{5.0kg} = 2.82\,{}^{m}\!/_{s^2} \text{ @ } NE$$

Answer: The net force affecting the object is 14.1 N @ NE. The object will accelerate NE at 2.82 m/s^2.