Phys 100: The Physical World
Chapters 4 & 5

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Textbook Sections

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- 2.5 The Equilibrium Rule
- 2.6 Support Force
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Newton's Second Law

The acceleration of an object is proportional to the net force acting on it and inversely proportional to its mass.

(i) Acceleration is a change in velocity over time. Forces can make objects speed up, slow down, and change direction.

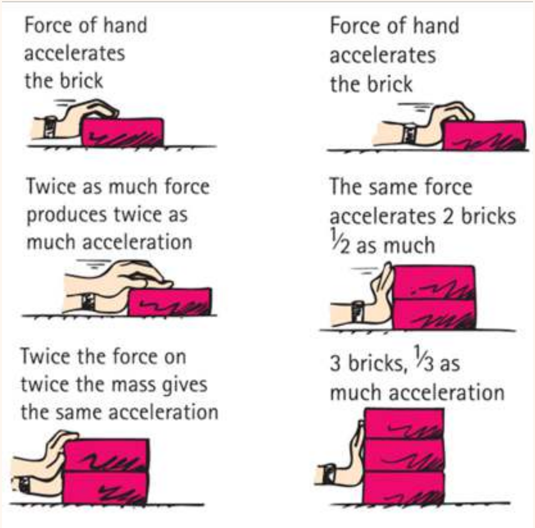
(ii) The acceleration is in the same direction as the net force.

(iii) Objects with more mass are harder to accelerate.

$$\text{Acceleration} = \frac{\text{Net Force}}{\text{Mass}}$$

For example, if the net force is doubled on an object, the acceleration will be doubled. If the mass of an object is doubled, the acceleration will instead be halved.

Newton's Second Law



Mass and Force

A force is a push or a pull that changes an object's motion.

Inertial mass measures an object's resistance to applied forces.

In order to measure a force, we need to observe the change in motion that occurs for a known mass. However, to measure a mass, we need to observe the change in motion that occurs under the action of a known force. It appears that we're stuck in a logical loop-de-loop! This is not a logical error, but rather a limitation of foundational definitions.

To see what I mean, try defining the terms "point" or "object." These are familiar terms, meaning we clearly understand what we mean by them, but do they have air-tight definitions? What other terms can we use to define them that don't beg for definitions themselves?

Axiomatic Systems

Concepts like "mass" and "force" ultimately derive meaning from the role they play in Newton's laws. We treat them as primitives, meaning they have no formal definitions and we can only describe how they behave. Think of them like building blocks from which we can build a theory, define other terms, and ultimately derive testable predictions.

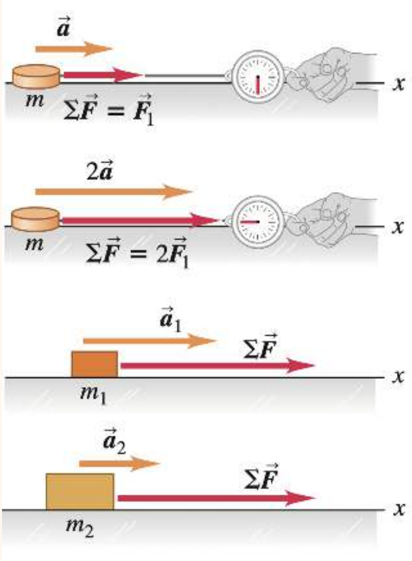
One goal for this class is to learn that science is not only a collection of facts, but also a creative endeavor to understand the world. Newton's laws are like a well-designed game: we make up a few rules and see how the pieces move. The rules aren't sacred—they're invented. But they're incredibly good at matching what happens in the real world. The more evidence we have in support of the theory, the more confident we are that it portrays an accurate picture of the physical world.

Operational Definitions

We can use the framework of Newton's laws to describe procedures for measuring forces and masses. One way to operationally define a force would be to take an object and pull on it with a stiff spring. We notice that when the extension of the spring is constant, the object accelerates uniformly. If we pull harder until the extension of the spring doubles, the object accelerates twice as much. Hence, the force from the spring is proportional to its extension.

On the other hand, if we fix the extension of the spring and measure the accelerations of two different objects attached to the end, then the ratio of their masses will be equal to the inverse ratio of their accelerations. This procedure is a bit awkward in practice, so we'll learn how ordinary weight scales work later.

Operational Definitions



Units of Mass and Force

The kilogram (kg) is the fundamental unit of mass in the International System of Units (SI), also known as the metric system. Before 2019, it was defined as the mass of the International Prototype of the Kilogram, a specific platinum-iridium cylinder stored at the International Bureau of Weights and Measures in France. The kilogram is now defined in terms of more advanced concepts that we may discuss later in the course.

One newton (N) is the amount of net external force that gives an acceleration of 1 meter per second squared to an object with a mass of 1 kilogram. The force of gravity on a 100-gram apple is about 1 newton.

The Kilogram

Click here to watch video. (5:57)

Conceptual Question 1

The net force on a cart on a level track is doubled. If the acceleration does not change, what is a possible explanation?

(a) The mass of the cart doubled when the force doubled.

(b) The mass of the cart halved when the force doubled.

(c) Newton's laws became modified.

(d) Friction reversed direction.

Weight

Weight is a measure of the gravitational force acting on an object. Weight is therefore measured in newtons while mass is measured in kilograms. Mass and weight are not the same thing! To find the weight of an object, simply take its mass and multiply by the acceleration due to gravity:

$$W = mg$$

Mass is a fundamental concept, while weight depends on the circumstances. A 1-kg object weighs roughly 10 N on Earth's surface, but for reasons we'll discuss later, the same 1-kg object weighs less than 2 N on the Moon.

Mass and Weight

Click here to watch video (2:21)

Conceptual Question 2

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

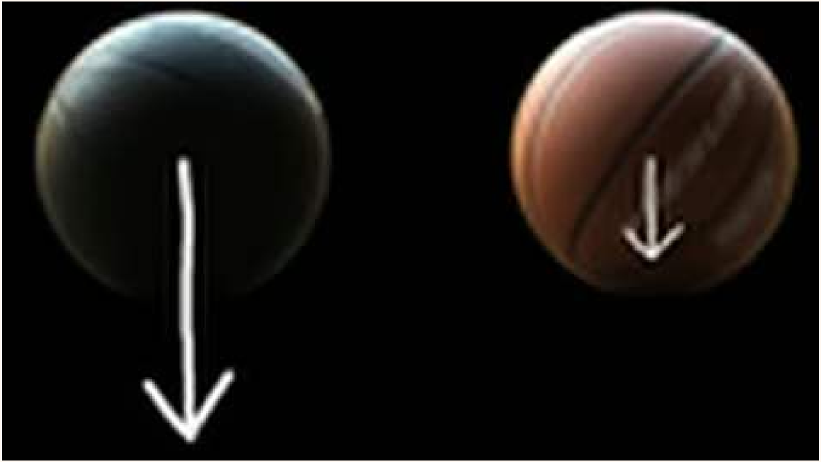
(a) less.

(b) the same.

(c) more.

(d) undetermined.

Misconceptions About Falling Objects



Click here to watch video (3:22)

Surface Gravity and Free Fall

Galileo discovered that the acceleration due to gravity near the Earth's surface was the same for all *freely falling* objects. Newton figured out why! According to Newton's law of gravity, the force on a freely falling object near the Earth should be proportional to the product of its mass and a constant acceleration that depends on the mass and overall size of the Earth itself.

In free fall, the only force acting on an object is the gravitational force (it's weight). According to Newton's second law,

$$W = mg = ma \rightarrow a = g$$

An object with a larger gravitational force will also have more inertia. The two effects "cancel each other out" in a sense.

Conceptual Question 3

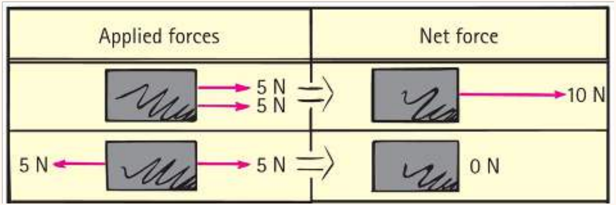
While my wife isn't looking, I like to toss baby Lucas playfully into the air and then catch him. He loves it! Ignoring air resistance, at the tip top of his vertical path, Lucas has an acceleration that is

(a) at a minimum.
(b) for an instant, zero.
(c) the same as halfway down.
(d) actually, undefined.

Net Force

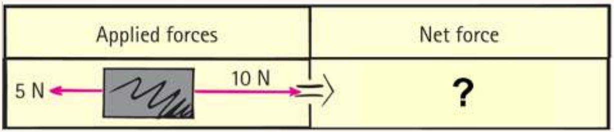
A net force is the combination of all forces that act on an object. Since individual forces can act in different directions, we need the tools of geometry to determine the net force.

How do we combine forces in different directions? We use vectors! A vector is a quantity with magnitude and direction that obeys a geometric rule of addition. For example,



Example 1

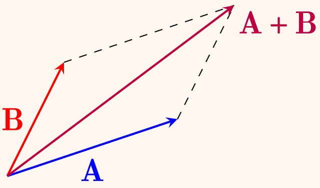
A cart is pulled to the right with a force of 10 N while being pulled to the left with a force of 5 N. What is the net force on the cart?

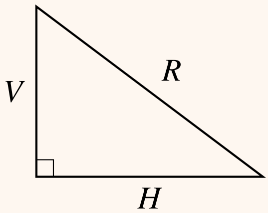


Vector Addition and the Resultant

A resultant is the sum of two or more vectors. Here are the rules of vector addition (more on this later):

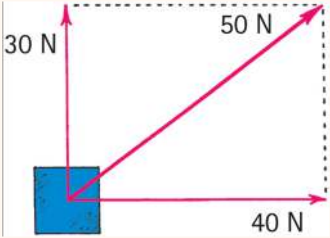
1. For vectors in the same direction, add arithmetically.
2. For vectors in opposite directions, subtract arithmetically.
3. For two vectors that don't act in the same or opposite directions, use the parallelogram rule.
4. For two vectors at right angles to each other, use the Pythagorean Theorem: $R^2 = H^2 + V^2$





Vector Components

It will often be useful to consider vector components. Any vector can be treated as the resultant of two vectors that are perpendicular to one another. In the figure below, the 30-N vector and the 40-N vector are the components of the 50-N vector.



The Equilibrium Rule

Newton's second law implies that when the vector sum of forces acting on an object is zero (they cancel each other out), then the object will not accelerate.

(i) If the object is at rest, it will remain at rest.

(ii) If the object is moving with constant velocity, it will continue to move with constant velocity.

There is a conceptual difference between the equilibrium rule and Newton's first law. Newton's first law applies in the absence of forces, while the equilibrium rule, derived from Newton's second law, involves a cancellation of possibly many forces.

Air Resistance

When an object falls downward through the air, it experiences a force of gravity pulling it downward and a force of air drag acting upward. Air resistance is proportional to frontal area and increases with increasing speed.

When the object is moving fast enough so that air resistance builds up to balance the force of gravity, there will be no net force, no acceleration, and the velocity will be constant.

Terminal speed occurs when acceleration terminates (when air resistance balances weight, so that net force is zero).

Terminal velocity refers to terminal speed along with the direction of motion, which is downward.

Conceptual Question 4

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

Conceptual Question 5

If a 50-N person falls at terminal speed, the air resistance is

(a) less than 50 N.

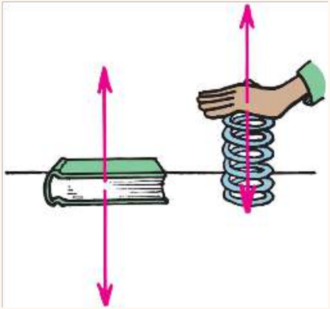
(b) 50 N.

(c) more than 50 N.

(d) None of the above.

Support Force

Support force (normal force) is an upward force on an object that is opposite to the force of gravity. For example, a book on a table compresses the table, and the compressed table produces the support force.



Conceptual Question 6

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

(a) your weight.

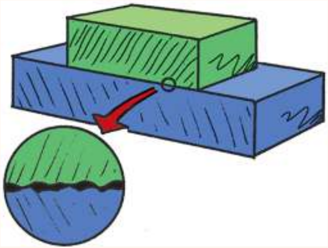
(b) half your weight.

(c) zero.

(d) more than your weight.

Friction

The force of friction depends on the kinds of material and how much they are pressed together. It is due to tiny surface bumps and to "stickiness" of the atoms on a material's surface.



Conceptual Question 7

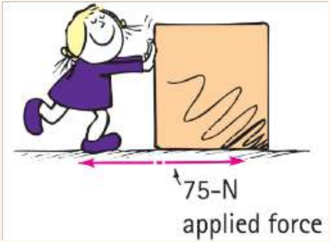
You push a crate at a steady speed in a straight line. If the friction force is 75 N, how much force must you apply?

(a) More than 75 N.

(b) Less than 75 N.

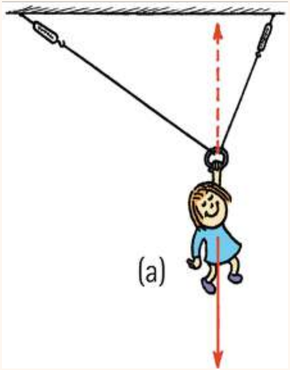
(c) Equal to 75 N.

(d) Not enough information.

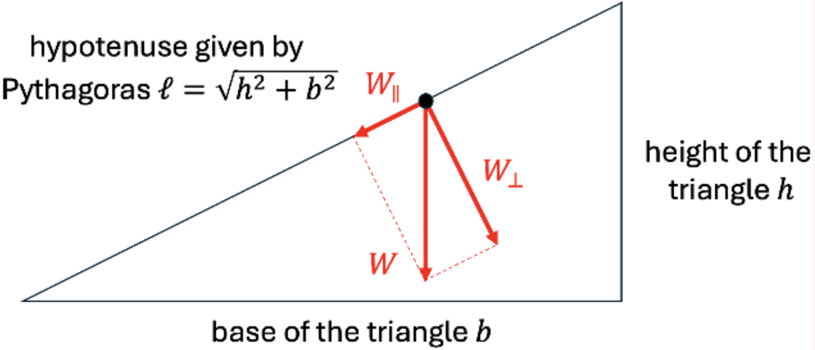


Conceptual Question 8

Nellie Newton hangs from a rope as shown. Which side has the greater tension? There are three forces acting on Nellie: her weight, W, a tension in the left-hand side of the rope, and a tension in the right-hand side.



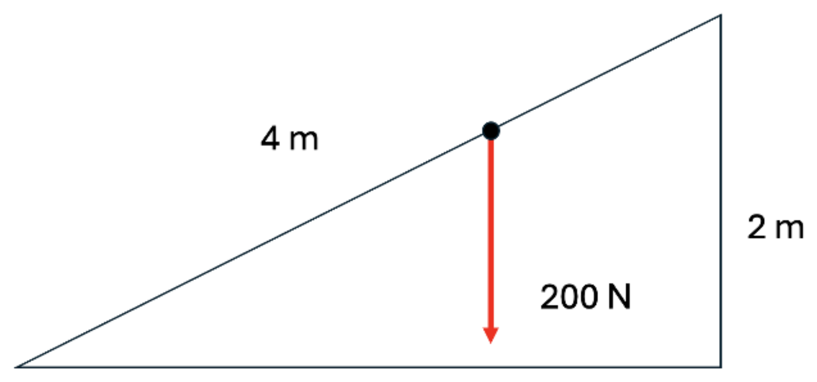
Inclined Planes



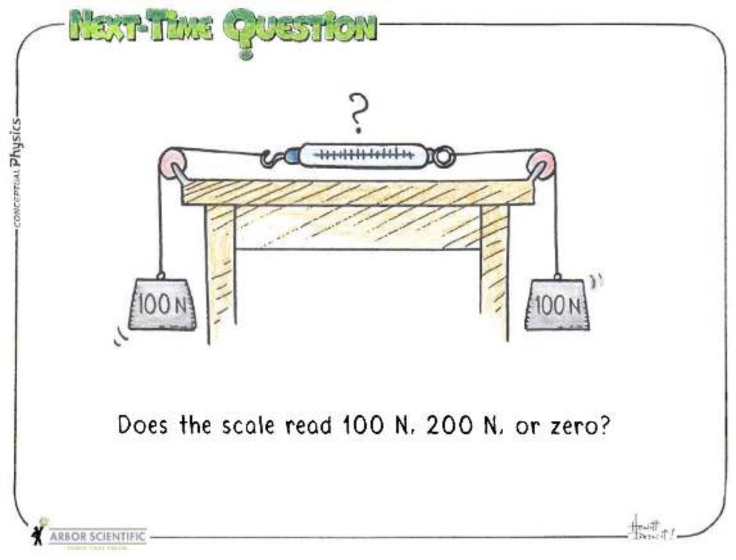
$$\frac{W_{\parallel}}{W} = \frac{h}{\ell} \rightarrow \boxed{W_{\parallel} = W \times \frac{h}{\ell}} \qquad \frac{W_{\perp}}{W} = \frac{b}{\ell} \rightarrow \boxed{W_{\perp} = W \times \frac{b}{\ell}}$$

Example 2

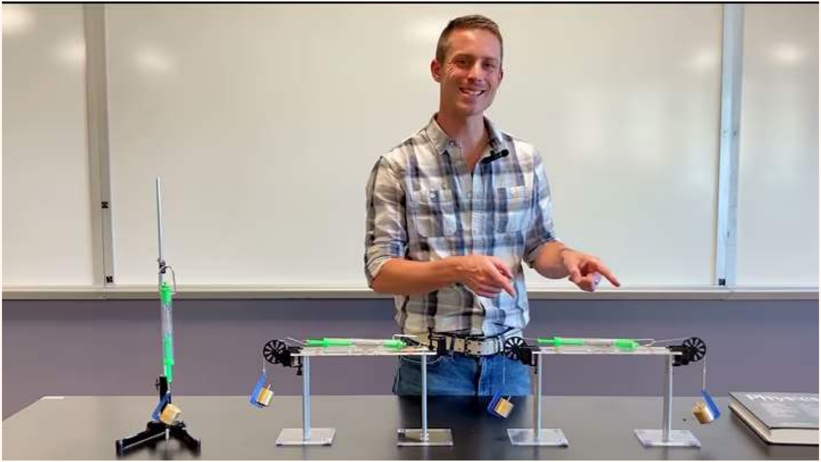
Consider a 200-N object sitting at rest on the inclined plane below. First find the friction force from the incline and then find the normal force (support force). Draw them in the diagram.



Conceptual Question 9



Paradox of Forces



Click here to watch video. (2:34)

Conceptual Question 10

Nellie is suspended by a rope inside an elevator. Two forces act on her: rope tension T and the force due to gravity mg. When the elevator accelerates upward

(a) $T > mg$

(b) $T = mg$

(c) $T < mg$

(d) Not enough information.

If somehow the outer cable supporting the elevator snaps, the net force on Nellie would be

(e) zero

(f) mg

(g) Not enough information.

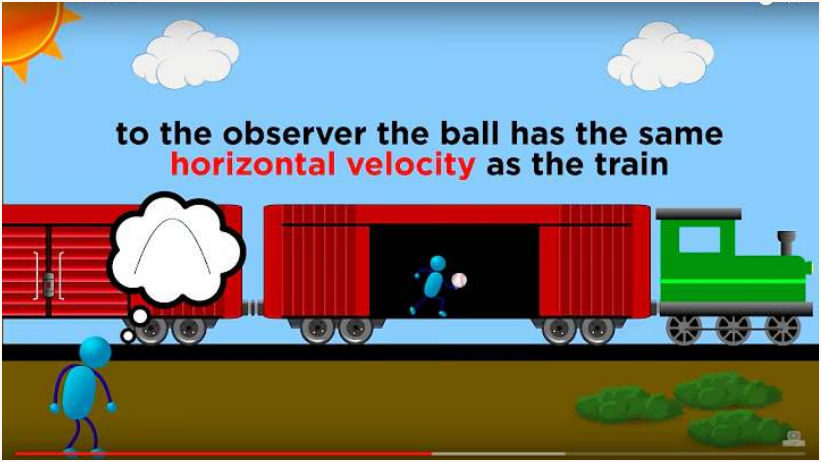
Non-inertial Reference Frames

A non-inertial reference frame is one in which Newton's laws are violated: an object can accelerate in the absence of forces and even stay at rest when forces are acting on it!

Newton's laws are simply not valid in non-inertial frames of reference. This restriction is crucial for understanding and identifying real forces, which result from physical interactions between objects, as opposed to fictitious or inertial forces, which arise due to the acceleration of the reference frame itself.

A rock falls because the Earth pulls on it. Your car comes to a stop because friction slowed it down. Ultimately, the restriction to inertial frames of reference allows us to speak with some confidence about cause and effect relationships. You don't have to worry about suddenly accelerating into the atmosphere!

Relative Motion and Inertial Frames



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Newton's Third Law

For each force acting on an object, there is an equal and opposite force acting on some other object.

(i) Each interaction is composed of two forces acting on two different objects: there is an action force on the object of interest and a reaction force on its interaction partner.

(ii) Action and reaction forces are always equal in magnitude and opposite in direction.

Action: Tires push road backward   Reaction: Road pushes tires forward

Conceptual Question 11

When you step off a curb, Earth pulls you downward. If the action force is the force of gravity pulling you down, the reaction force is

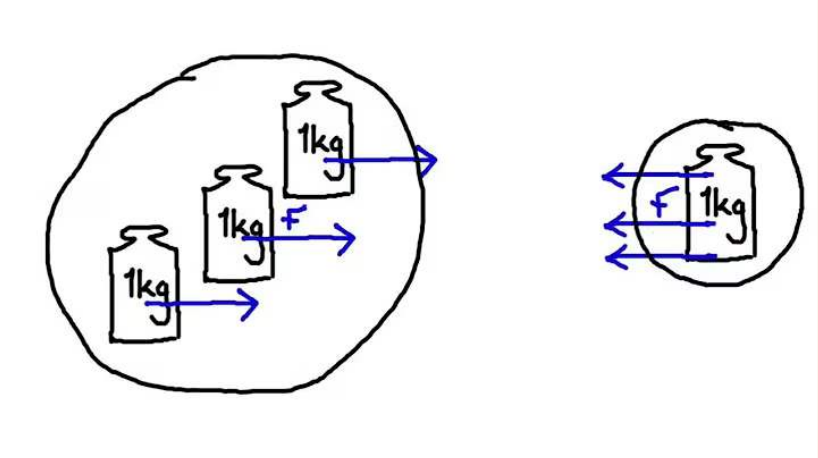
(a) a slight air resistance.

(b) nonexistent in this case.

(c) you pulling Earth upward.

(d) None of the above.

Misconceptions about Newton's Third Law



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Conceptual Question 12

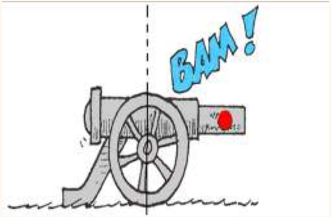
When a cannon is fired, the accelerations of the cannon and cannonball are different because the

(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.



Conceptual Question 13

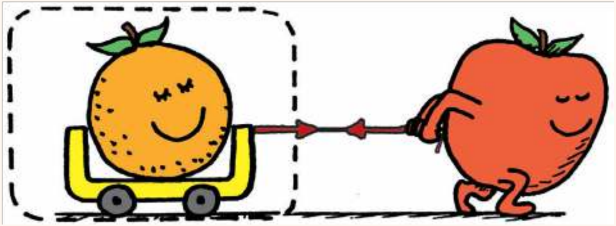
When participants in the tug-of-war pull on the rope with equal and opposite 500-N forces, the scale reading is

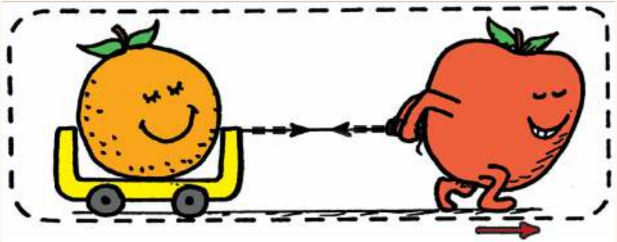
A. 0 N. B. 500 N. C. 1000 N. D. None of these.

The person to win in the tug of war is the one who

E. pulls harder on the rope than the other.
F. exerts a yanking force.
G. Both of these.
H. None of these.

Defining a System





Conceptual Question 14

Boxes A and B are in contact on a horizontal, frictionless surface. You push on box A with a horizontal 100 N force. Box A weighs 150 N, and box B weighs 50 N. The force that box A exerts on box B is

(a) equal to 100 N

(b) greater than 100 N

(c) less than 100 N

(d) Impossible to determine

Summary of Newton's Laws

1. **The law of inertia:** in the absence of forces, an object at rest tends to remain at rest, and an object in motion tends to remain in motion at constant speed along a straight-line path.

2. **The law of acceleration:** when a net force acts on an object, the object will accelerate in the same direction as the net force. The acceleration is directly proportional to the net force and inversely proportional to the mass.

3. **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.