Forces and laws of motion

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2025 W37[1]

[1] Phys 20.01 Mod 2. All figures are from Urone (2022), Hewitt (2024), Young and Freedman (2019) unless noted.

Agenda

Forces 🔥

Newton’s laws of motion ⚖️

Quiz time 🕐

Forces 🔥

The why

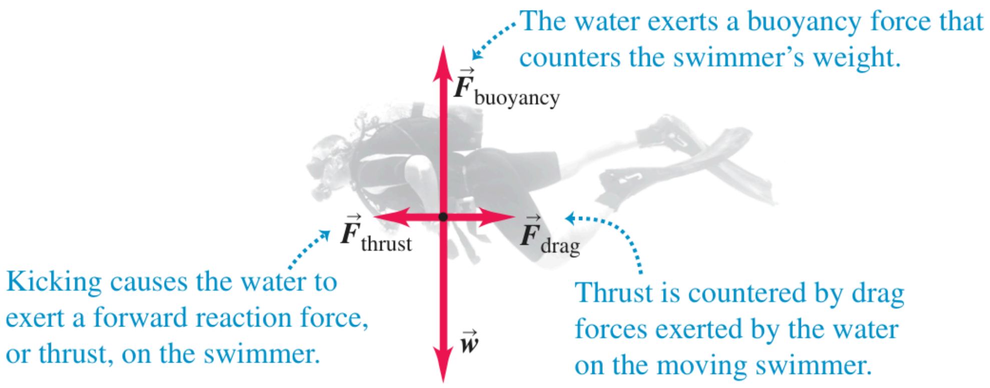
- We've seen how kinematics is used to describe motion
- But what causes objects to move the way that they do?
  - eg. Why does a dropped feather fall more slowly than a dropped baseball?

The why

-
  - eg. Why don't we sink straight to the bottom when we swim?
  - eg. Why do you feel pushed backward in a car that accelerates forward?

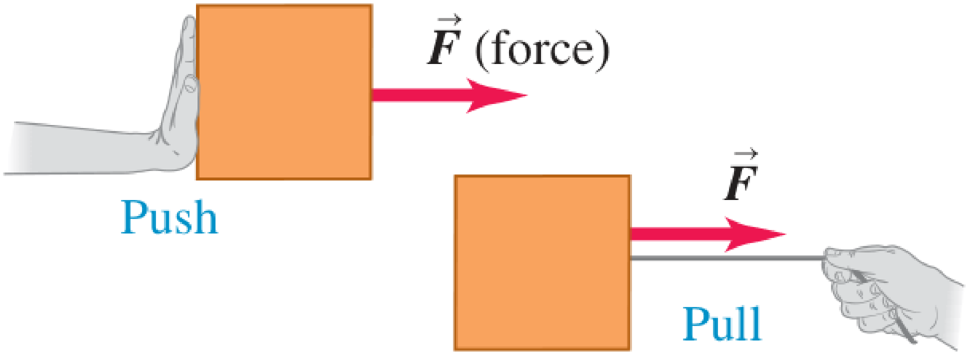
The why = forces

- Answers take us into the subject of **dynamics**, the study of the relationship of motion to the **forces** that cause it



Force

- **Force** is a push or a pull
- More precisely, it is an interaction between two objects or between an object and its environment
  - That's why we always refer to the force that one object exerts on another object



Force

- Its SI unit is newton (N), where $1\ \mathrm{N} = 1\ \mathrm{kg\ m/s^2}$
- A force involving direct contact is **contact force**, eg. 🐕 leash
- A force acting even when separated by empty space is **long-range force**, eg. force of gravity

(a) **Normal force $\vec{n}$:** When an object rests or pushes on a surface, the surface exerts a push on it that is directed perpendicular to the surface.

(b) **Friction force $\vec{f}$:** In addition to the normal force, a surface may exert a friction force on an object, directed parallel to the surface.

(c) **Tension force $\vec{T}$:** A pulling force exerted on an object by a rope, cord, etc.

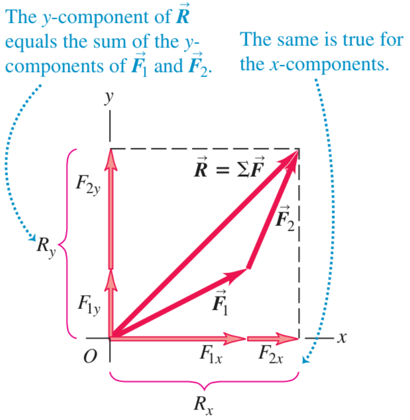
(d) **Weight $\vec{w}$:** The pull of gravity on an object is a long-range force (a force that acts over a distance).

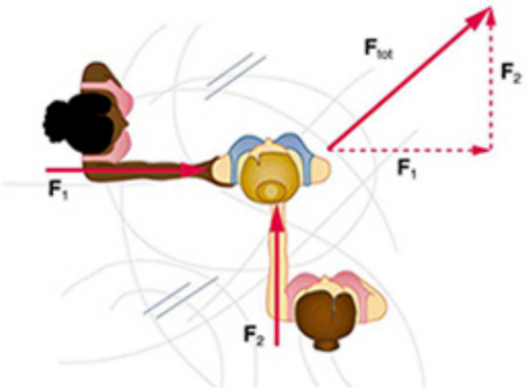
Force as a vector

- Force is a vector having both magnitude and direction
- When several external forces act on an object, the effect on its motion is same as if a single force, equal to vector sum of forces, acts on the object. This is called **superposition of forces**

$$\vec{R} = \sum \vec{F} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots$$

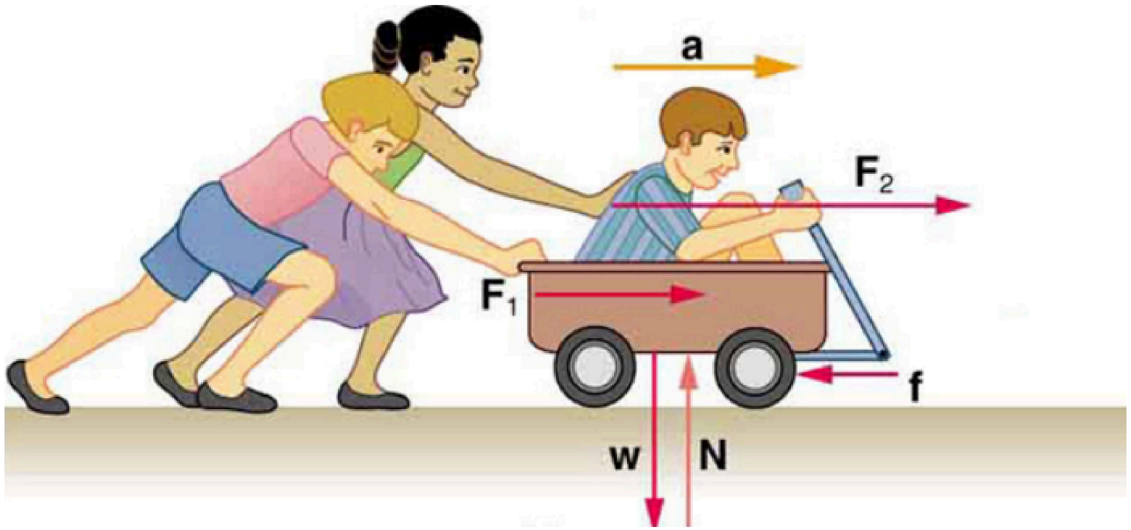
$$\vec{R} = \sqrt{R_x^2 + R_y^2} \quad \text{via Py. thm.}$$





External forces

- **External forces** are any outside forces that act on a body
- An external force is one acting on a system from outside the system, as opposed to **internal forces** which act between components within the system
- Here, **system** is defined by the boundaries of an object or collection of objects being observed



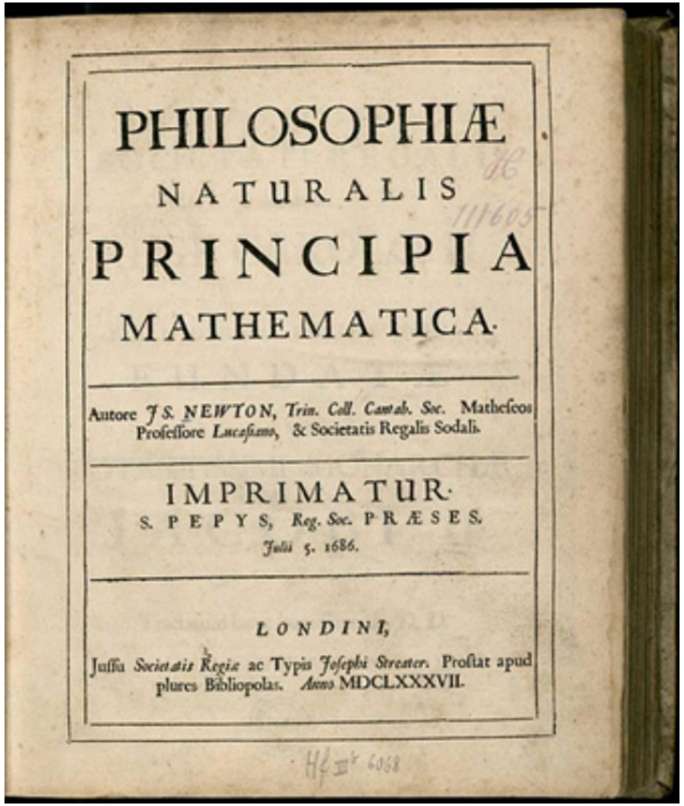
- eg. The system of interest is the wagon plus the child in it
  - The two forces exerted by other children are external forces
  - The force the child in the wagon exerts to hang onto the wagon is an internal force between elements of the system

Questions? 😲

Newton’s laws of motion ⚖️

Newton’s laws

- Newton’s laws of motion are the foundation of dynamics
- They provide an example of how physics can be broadly encompassing yet simplistic in describing nature



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Newton's laws

- These laws are also universal
  - Applicable to similar situations on earth and in space
  - Given some modifications, also applicable to cases involving extremely high speeds (near speed of light ⚡) or very small sizes (within atom ⚛️)
- Btw, Newton did not derive the laws of motion, but rather deduced them from a multitude of experiments performed by other scientists, especially Galileo Galilei who died the year Newton was born. Imagine them meeting tho!

First law ⚓

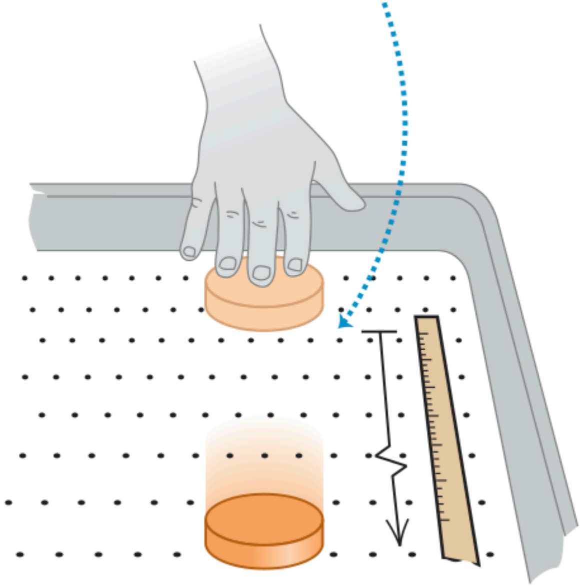
- **First law** states that a body at rest remains at rest, or if in motion remains in motion at a constant velocity, unless acted on by a net external force. This is also known as **law of inertia**

First law ⚓

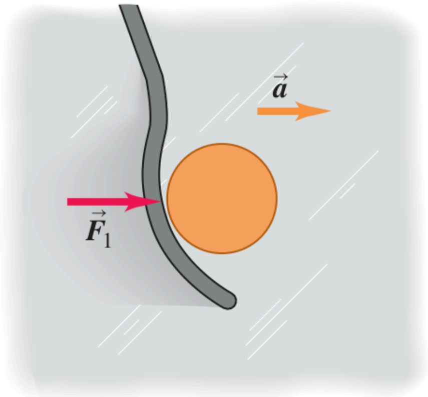
- Why does the downward motion and sudden stop of the hammer tighten the hammerhead?
- Why does slow continuous increase in downward force breaks string above the ball, but sudden increase breaks lower string?

- Why will the coin drop into glass when a force accelerates card?

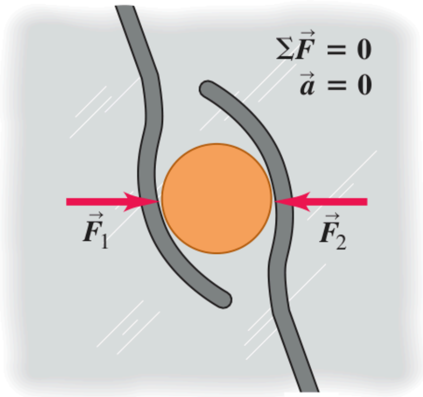
- **Inertia** is the tendency of an object to remain at rest or in motion, and is related to an object’s mass
  - It isn’t a kind of force
  - It’s a property of all matter to resist changes in motion



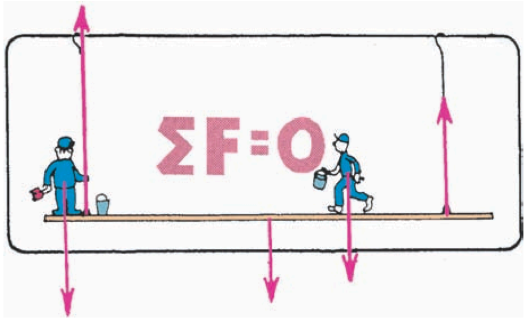
(a) A puck on a frictionless surface accelerates when acted on by a single horizontal force.

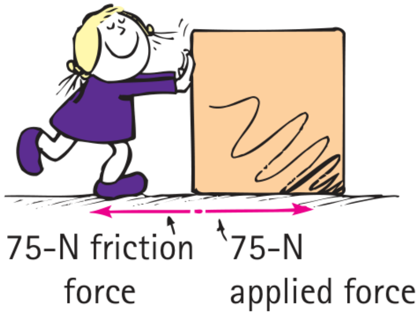


(b) This puck is acted on by two horizontal forces whose vector sum is zero. The puck behaves as though no external forces act on it.



- When an object is either at rest or moving with constant velocity (in a straight line), we say the object is in **equilibrium**



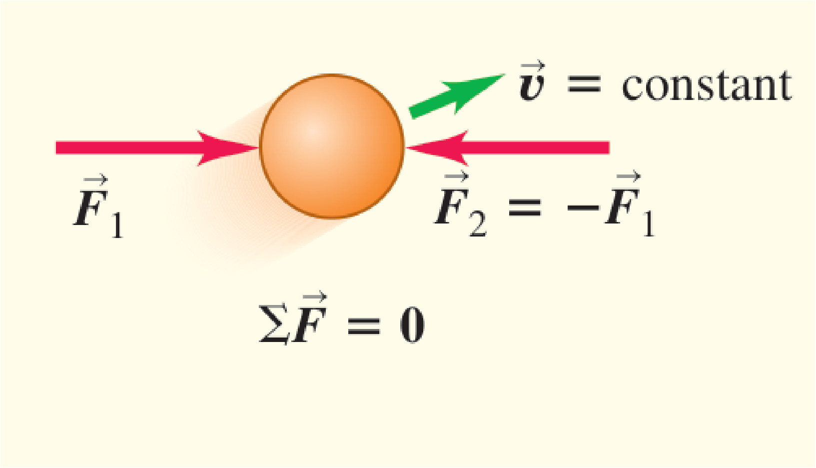


- eg. The sum of upward forces equals the sum of downward forces, making the scaffold be in (**static**) equilibrium at rest
- eg. When the push on crate is as great as force of friction that floor exerts on crate, the net force on crate is zero and it slides at unchanging speed. It is in (**dynamic**) equilibrium in motion

Net external force and the first law

- More formally, the first law states that when the vector sum of all external forces acting on a object (the net external force) is zero, the object is in equilibrium and has zero acceleration

$$\sum \vec{F} = \vec{0}$$



First law ⚓

Example. In the classic 1950 sci-fi film "Rocketship X-M", a spaceship is moving in the vacuum of outer space, far from any star or planet, when its engine dies. As a result, the spaceship slows down and stops. What does first law say about this scene?

First law ⚓

Example. In the classic 1950 sci-fi film "Rocketship X-M", a spaceship is moving in the vacuum of outer space, far from any star or planet, when its engine dies. As a result, the spaceship slows down and stops. What does first law say about this scene?

No external forces act on the spaceship after the engine dies, so according to the first law it will not stop but will continue to move in a straight line with constant speed 🚀

First law ⚓

Example. You are driving a Porsche 918 Spyder on a straight testing track at a constant speed of 250 km/h. You pass a 1971 Volkswagen Beetle doing a constant 75 km/h. On which car is the net external force greater?

First law ⚓

Example. You are driving a Porsche 918 Spyder on a straight testing track at a constant speed of 250 km/h. You pass a 1971 Volkswagen Beetle doing a constant 75 km/h. On which car is the net external force greater?

The key word in this question is "net." Both cars are in equilibrium because their velocities are constant. Newton's first law therefore says that the net external force on each car is zero.

Questions? 😀

Checkpoint. How does the law of inertia account for removing snow from one's shoes by stamping on the floor, or removing dust from a coat by shaking it?

👞 🧥

Stamping or shaking suddenly stops the shoe or coat, Stamping or shaking suddenly stops the shoe or coat, but the snow or dust

Stamping or shaking suddenly stops the shoe or coat, but the snow or dust continues in its original motion due to inertia, Stamping or shaking suddenly stops the shoe or coat, but the snow or dust continues in its original motion due to inertia, thus separating from shoe or coat

🕺

Checkpoint. Would it be correct to say that inertia is the reason a moving object continues in motion when no force acts?

Checkpoint. Would it be correct to say that inertia is the reason a moving object continues in motion when no force acts?

No.

Checkpoint. Would it be correct to say that inertia is the reason a moving object continues in motion when no force acts?

No. We don't know why objects persist in their motion when no forces act on them.

We refer to the property of an object to behave in this predictable way as **inertia**

Second law 💨

- **Second law** states that the acceleration $\vec{a}$ of a system is directly proportional to and in the same direction as the net external force $\sum \vec{F}$ acting on the system, and is inversely prop. to its mass m

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

Second law 💨

- Or equivalently, the more familiar

$$\sum \vec{F} = m\vec{a}$$

- Recall that acceleration $\vec{a}$ is the rate of change in velocity $\vec{v}$
  - This means that a change in the latter's magnitude or direction or both causes the former

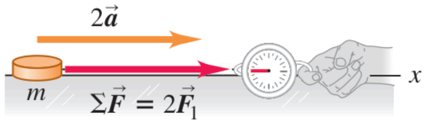
Mass and force

- The ratio of the magnitude $\left|\sum \vec{F}\right|$ of the net external force to the magnitude $a = |\vec{a}|$ of the acceleration is constant, regardless of the magnitude of the net external force
  - We call this ratio the **inertial mass**, or simply **mass**, of the object and denote it by m. That is

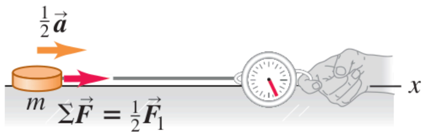
$$m = \frac{\left|\sum \vec{F}\right|}{a} \qquad \text{or} \qquad \left|\sum \vec{F}\right| = ma \qquad \text{or} \qquad a = \frac{\left|\sum \vec{F}\right|}{m}$$

(a) A constant net external force $\Sigma\vec{F}$ causes a constant acceleration $\vec{a}$.

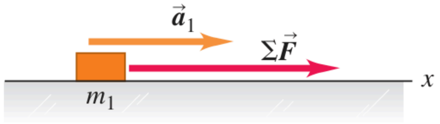
(b) Doubling the net external force doubles the acceleration.



(c) Halving the net external force halves the acceleration.



(a) A known net external force $\Sigma\vec{F}$ causes an object with mass m_1 to have an acceleration $\vec{a}_1$.



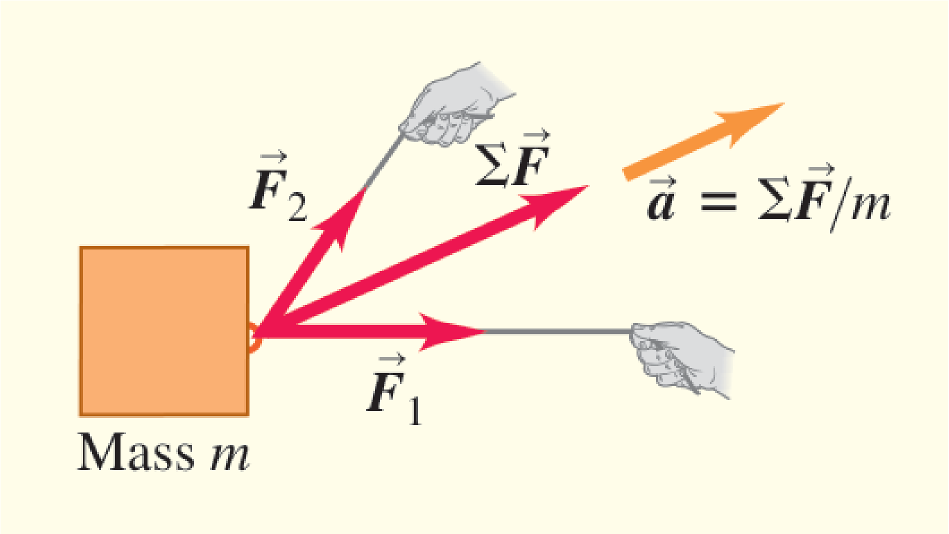
(b) Applying the same net external force $\Sigma\vec{F}$ to a second object and noting the acceleration allow us to measure the mass.

(c) When the two objects are fastened together, the same method shows that their composite mass is the sum of their individual masses.

$$\uparrow \vec{a} = \frac{\uparrow \sum \vec{F}}{\downarrow m}$$

Mass, acceleration, and the second law

- More formally, the second law states that an object's acceleration under action of a given set of external forces is directly proportional to the vector sum of forces (net force) and inversely prop. to the mass of the object



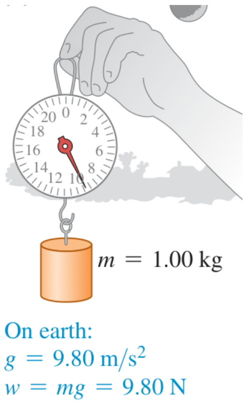
- $\sum \vec{F} = m\vec{a}$
- $\sum F_x = ma_x, \quad \sum F_y = ma_y$

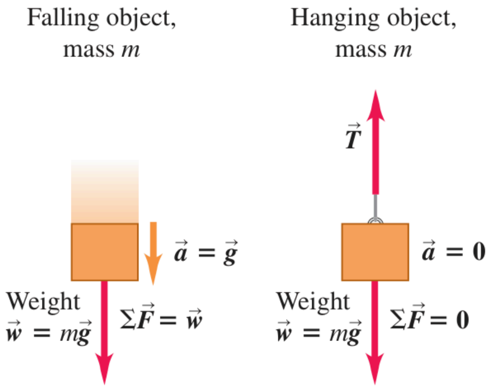
Weight

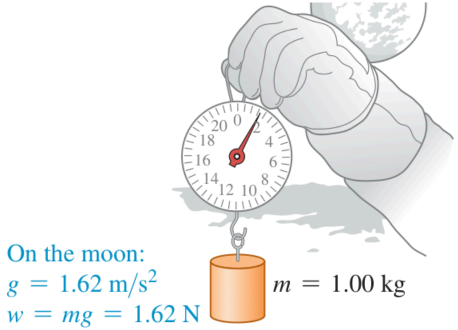
- The weight $\vec{w}$ of an object is gravitational force exerted on it by the earth. In symbols,

$$\vec{w} = m\vec{g}$$

- It is a vector quantity
- The weight of an object depends on its location, its mass does not







Second law 💨

Example. A worker applies a constant horizontal force with magnitude 20 N to a box with mass 40 kg resting on a level, freshly waxed floor with negligible friction. What is $\vec{a}_{\text{box}}$?

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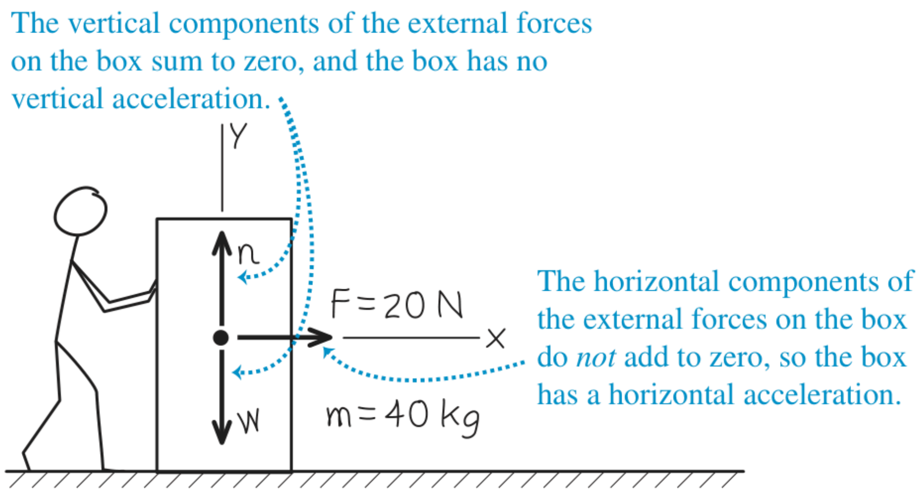

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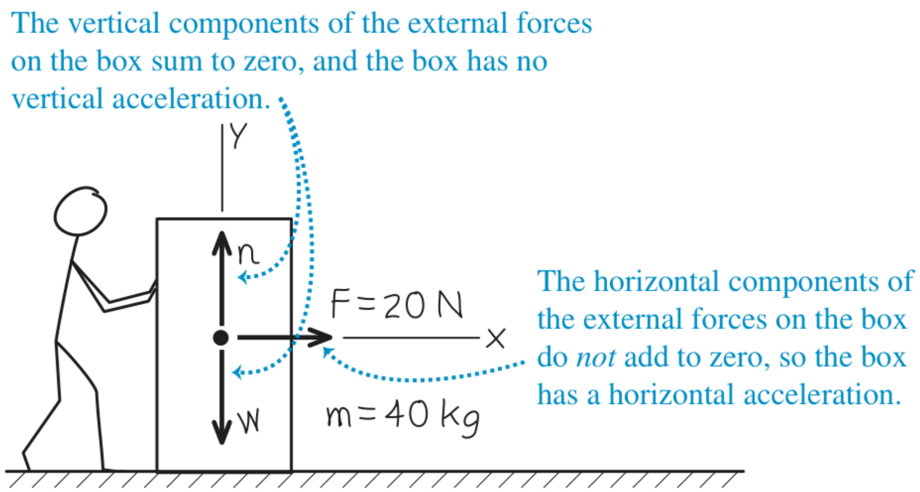

$$\sum F_x = F + 0 + 0 = 20\text{ N} = ma_x$$

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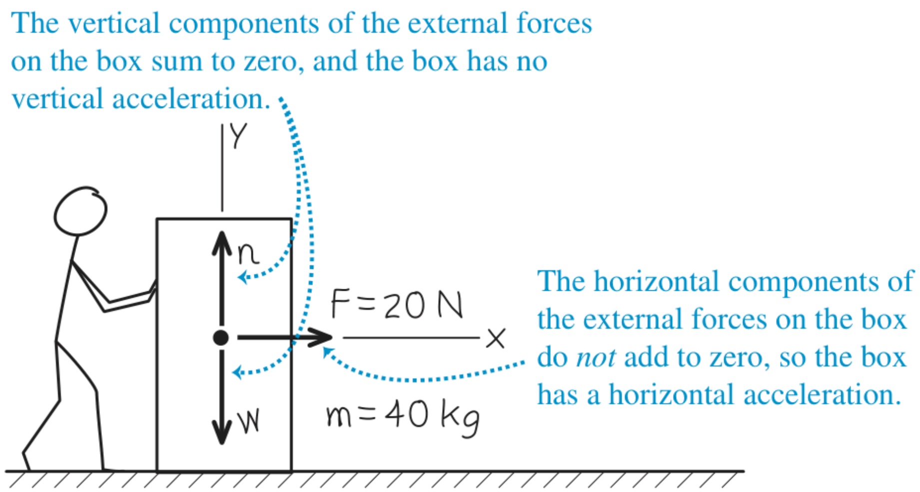

$$\sum F_x = F + 0 + 0 = 20\ \text{N} = ma_x$$
$$\sum F_y = 0 + n - w = ma_y = 0$$

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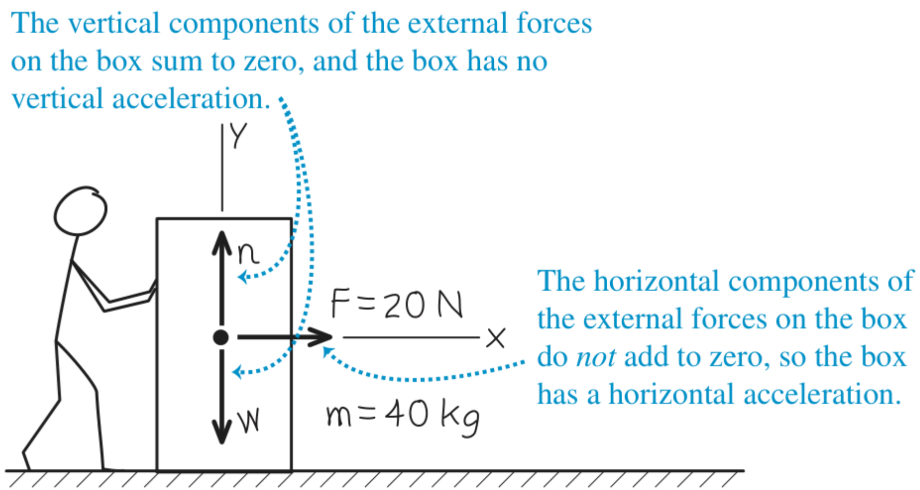


$$\sum F_x = F + 0 + 0 = 20\text{ N} = ma_x$$

$$\sum F_y = 0 + n - w = ma_y = 0$$

$$a_x = \frac{\sum F_x}{m} = \frac{20\text{ N}}{40\text{ kg}} = \frac{20\text{ kg m/s}^2}{40\text{ kg}}$$

$$= 0.50\text{ m/s}^2$$

Weight vs mass

- Don't confuse mass and weight. The SI units for mass and weight are often misused in everyday life
  - eg. It's incorrect to say "This box weighs 6 kg." What this really means is that the mass of the box, probably determined indirectly by weighing, is 6 kg
- In SI units, weight (a force) is measured in newtons, while mass is measured in kilograms

Weight vs mass

Example. A 2.45×10^4 N truck traveling in the $+x$-direction makes an emergency stop. The x-component of the net external force acting on it is -1.83×10^4 N. What is its acceleration?

Weight vs mass

Example. A 2.45×10^4 N truck traveling in the $+x$-direction makes an emergency stop. The x-component of the net external force acting on it is -1.83×10^4 N. What is its acceleration?

- $$m = \frac{w}{g} = \frac{2.45 \times 10^4 \text{ N}}{9.80 \text{ m/s}^2} = \frac{2.45 \times 10^4 \text{ kg m/s}^2}{9.80 \text{ m/s}^2} = 2540 \text{ kg}$$
- Then $\sum F_x = ma_x$ gives

$$a_x = \frac{\sum F_x}{m} = \frac{-1.83 \times 10^4 \text{ N}}{2540 \text{ kg}} = \frac{-1.83 \times 10^4 \text{ kg m/s}^2}{2540 \text{ kg}} = -7.20 \text{ m/s}^2$$

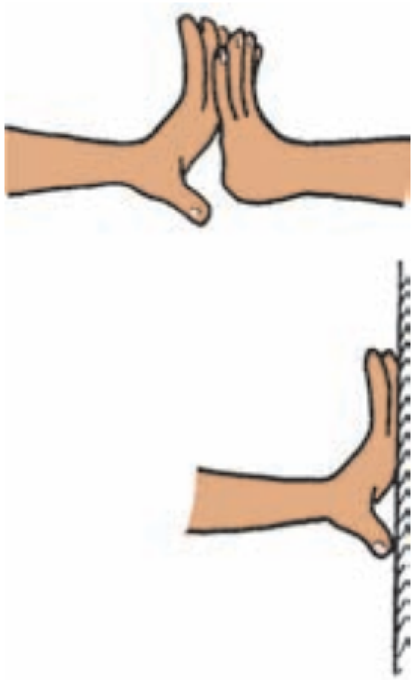
Questions? 😪

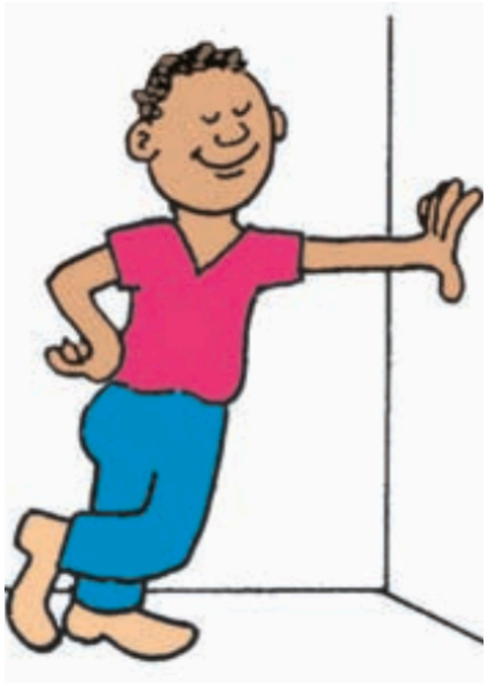
Brain break! 🧠 💤

Push mo 'yan

Have a friend push ur hand 🙏

Now, walk over to the wall and show that the inanimate wall does the same as you push against the wall





Push mo ‘yan

You can feel your fingers being pushed by your friend’s fingers.

Push mo ‘yan

You can feel your fingers being pushed by your friend’s fingers. You also feel the same amount of force when you push on a wall and it pushes back on you.

Push mo 'yan

You can feel your fingers being pushed by your friend's fingers. You also feel the same amount of force when you push on a wall and it pushes back on you. As a point of fact, you can't push on the wall unless it pushes back on you.

Push mo 'yan

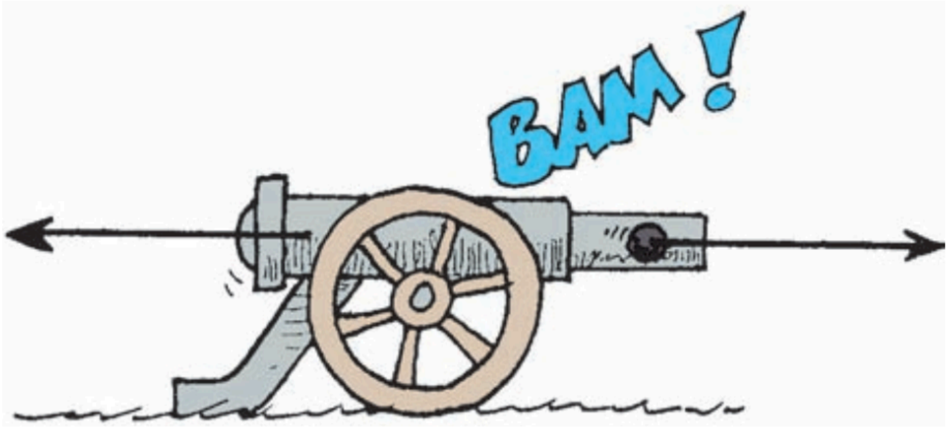
You can feel your fingers being pushed by your friend's fingers. You also feel the same amount of force when you push on a wall and it pushes back on you. As a point of fact, you can't push on the wall unless it pushes back on you. This is the third law in action! 🫳

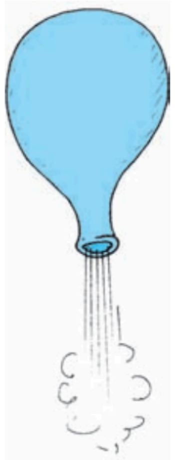
Third law 🪞

- **Third law** states that whenever one body exerts a force on a second body, the first body experiences a force that is equal in magnitude and opposite in direction to the force that the first body exerts

Third law 🪞

- A **thrust** is a reaction force that pushes a body forward in response to a backward force, eg. rockets, planes and cars are pushed forward by thrust

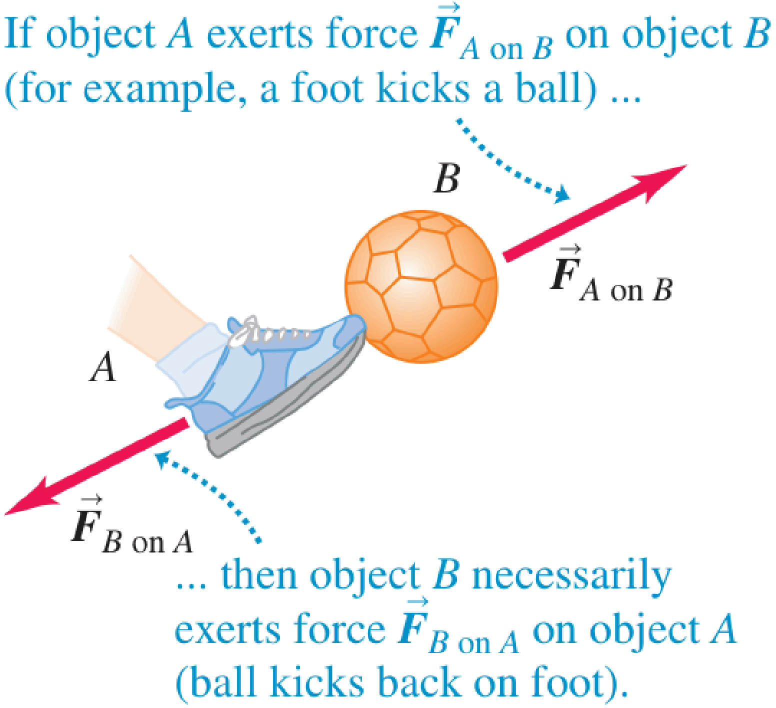




Action-reaction pairs and the third law

- More formally, the third law states that when two objects interact, they exert forces on each other that are equal in magnitude and opposite in direction

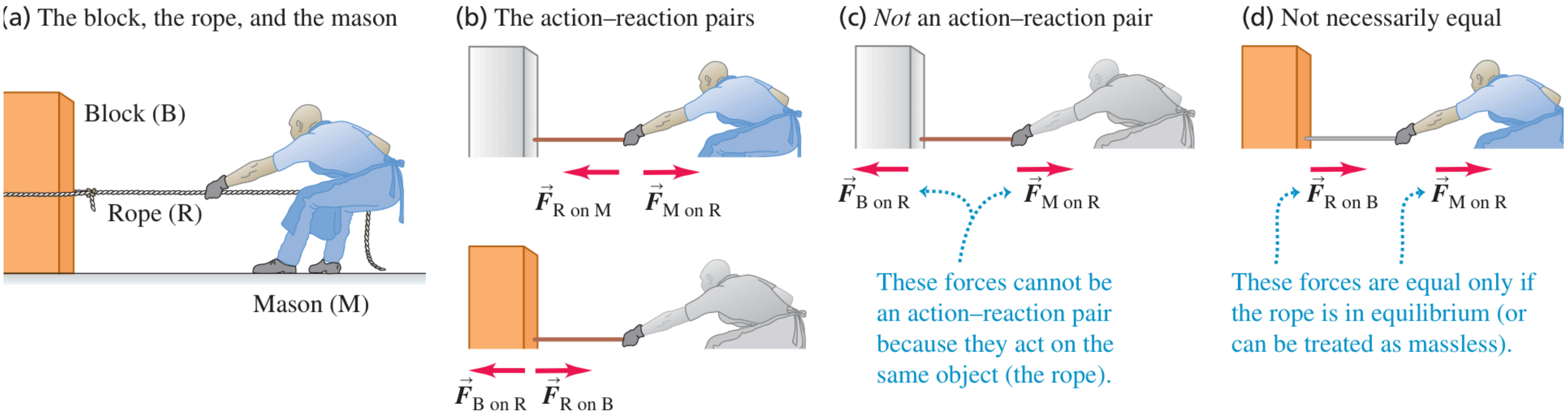
$$\vec{F}_{A \text{ on } B} = -\vec{F}_{B \text{ on } A}$$



Action-reaction pairs and the third law

- These forces are called **action** and **reaction** forces
  - This is not meant to imply any cause-and-effect relationship
  - We can consider either force as action and other as reaction
  - We often say simply that the forces are equal and opposite, meaning that they have equal magnitudes and opposite directions
- Each of these two forces acts on only one of the two objects. They never act on the same object

Example. A stonemason drags a marble block across a floor by pulling on a rope attached to the block. The block isn't necessarily in equilibrium. What are the forces that correspond to interactions between block, rope, mason? What are the action-reaction pairs?



Checkpoint. A car accelerates along a road. Identify force that moves the car.

🚗

It is the road that pushes the car along.

It is the road that pushes the car along. Only the road provides horizontal force to move car forward.

It is the road that pushes the car along. Only the road provides horizontal force to move car forward. How does it do this?

It is the road that pushes the car along. Only the road provides horizontal force to move car forward. How does it do this?

The rotating tires of car push back on the road (action). The road simultaneously pushes forward on the tires (reaction).

Quiz time 🕐

Dear grandma 🧓

Write a letter to Grandma, telling her what you've learned from Newton. Introduce the concepts of acceleration and inertia, and explain to her how he saw the connection between forces, mass, and acceleration. In this letter, feel free to use an equation or two, but make sure to clarify for Grandma that an equation is simply a shorthand notation for the ideas you've already explained.