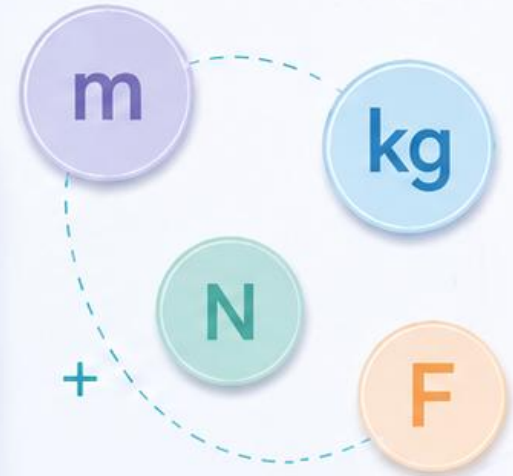
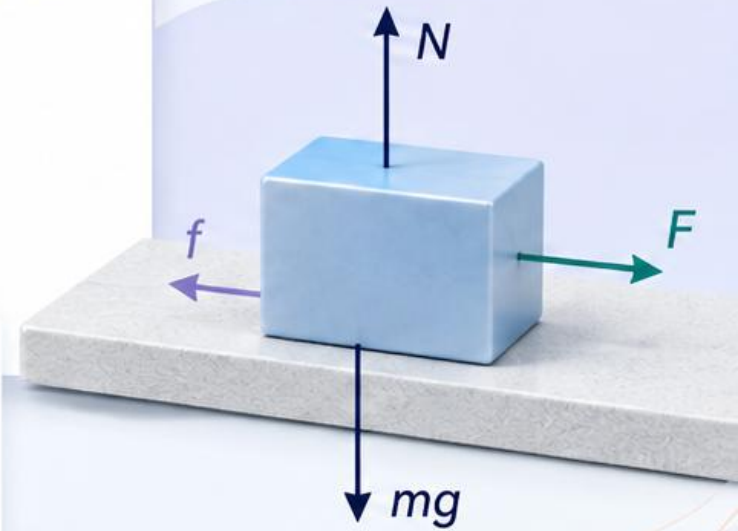
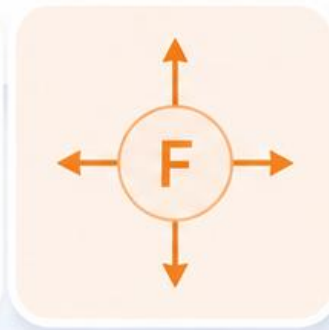
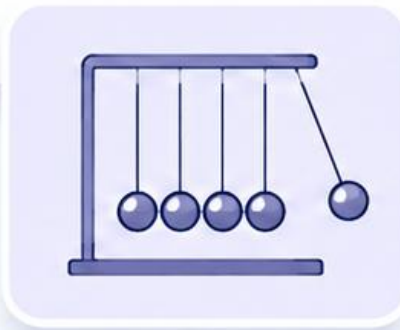
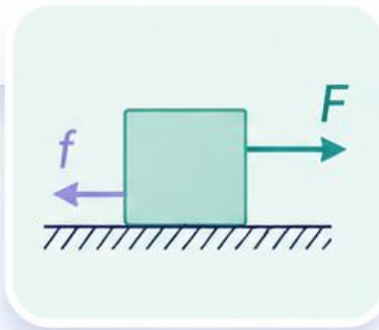
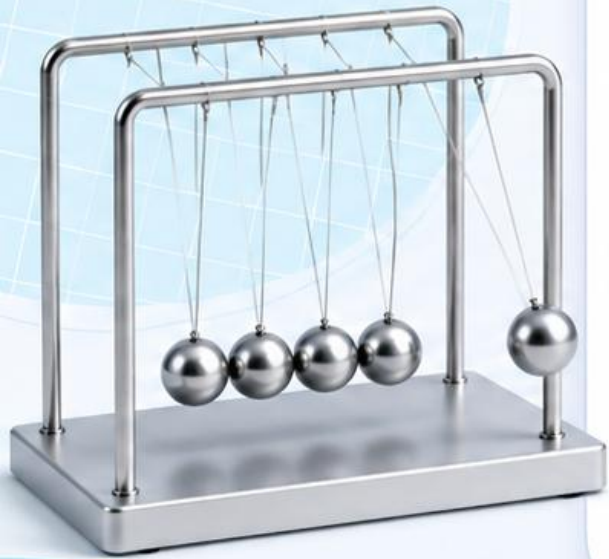


Chapter 4

Laws of Motion

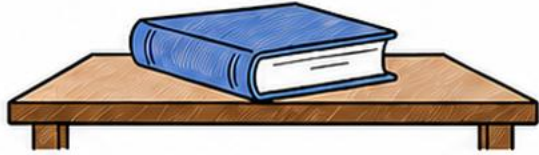
Force • Newton's Laws • Friction



LAWS OF MOTION

Motion changes only when interactions produce a non-zero net external force.

① INERTIA



Book at rest on a table

$$\sum \vec{F}_{\text{ext}} = \vec{0} \rightarrow \vec{a} = \vec{0} \rightarrow \vec{v} = \text{constant}$$

② SECOND LAW

$$\sum \vec{F}_{\text{ext}} = \frac{d\vec{p}}{dt}$$

For constant mass,

$$\sum \vec{F}_{\text{ext}} = m\vec{a}$$

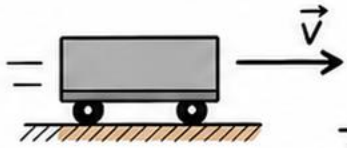
③ THIRD LAW



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

Forces act on different bodies.

④ MOMENTUM & IMPULSE

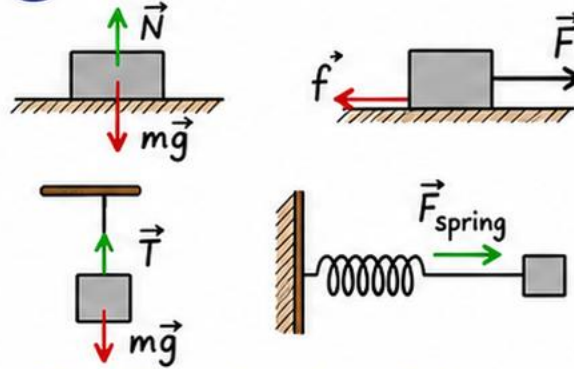


$$\vec{p} = m\vec{v}$$

$$\vec{J} = \int_{t_1}^{t_2} \vec{F} dt = \Delta \vec{p}$$

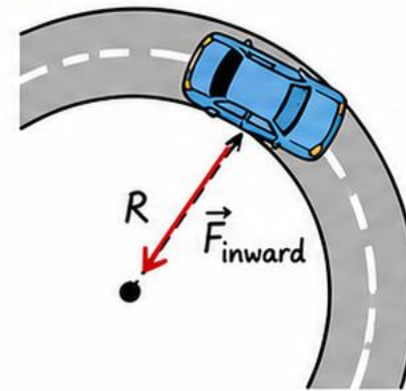
Impulse equals change in momentum.

⑤ CONTACT FORCES



Gravity acts at a distance.

⑥ CIRCULAR MOTION



An inward (toward center) real force provides the centripetal force.

$$F_{\text{inward}} = \frac{mv^2}{R}$$

CHOOSE SYSTEM → DRAW FBD → RESOLVE FORCES → APPLY NEWTON'S LAWS → CHECK SIGNS & UNITS

FORCE, INTERACTIONS & NET FORCE

1. WHAT IS FORCE?

- Force is a vector quantity that arises due to interaction between two objects.
- It is a push or pull exerted by one object on another.
- Force is not something a moving object stores. A force exists only while the interaction exists.
- A force can change the momentum, speed or direction of an object.

$$\text{Unit: } 1 \text{ N} = 1 \text{ kg m s}^{-2}$$

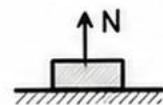
Examples:

- A hand pushes a door.
- The Earth attracts a stone.
- A magnet pulls an iron nail.
- A string pulls a bucket.

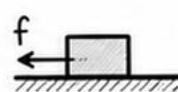
2. CONTACT & DISTANCE FORCES

Forces can be contact or non-contact (distance) forces.

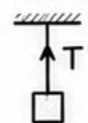
Contact forces (require physical contact):



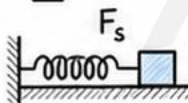
Normal force (N): Exerted by a surface perpendicular to the surface.



Friction (f): Acts along the surface at the contact, opposing relative motion.



Tension (T): Pull exerted by a string or rope along its length.



Spring force (F_s): Opposite to the displacement from the equilibrium position.



Fluid drag (F_d): Acts opposite to the relative motion of the body through the fluid.

Non-contact (distance) forces:



Gravitational force: Weight of a body near the Earth is $F_g = mg$ acting towards the Earth's centre.



Electric force: Between charges.

Magnetic force: Between currents or moving charges and magnets.

3. NET EXTERNAL FORCE

The net external force on a system is the vector sum of all external forces acting on it.

$$\sum \vec{F}_{\text{ext}} = \vec{F}_1 + \vec{F}_2 + \dots + \vec{F}_n$$

$$\bullet \text{ If } \sum \vec{F}_{\text{ext}} = \vec{0} \Rightarrow \vec{a} = \vec{0}$$

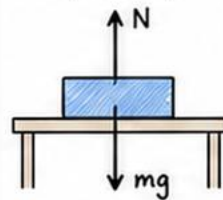
The velocity of the system remains constant (can be zero or non-zero).

$$\bullet \text{ If } \sum \vec{F}_{\text{ext}} \neq \vec{0}$$

The momentum of the system changes in the direction of $\sum \vec{F}_{\text{ext}}$.

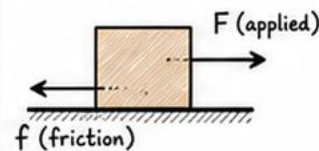
Illustrations:

(i) Book on a table (at rest)



N upward, mg downward
 $\Rightarrow \sum \vec{F}_{\text{ext}} = \vec{0}$

(ii) Box pulled on a rough surface



If $F > f \Rightarrow$ net force to the right.

(iii) Freely falling stone (neglect drag)



Only mg acts downward
 $\Rightarrow \sum \vec{F}_{\text{ext}} = mg$ downward

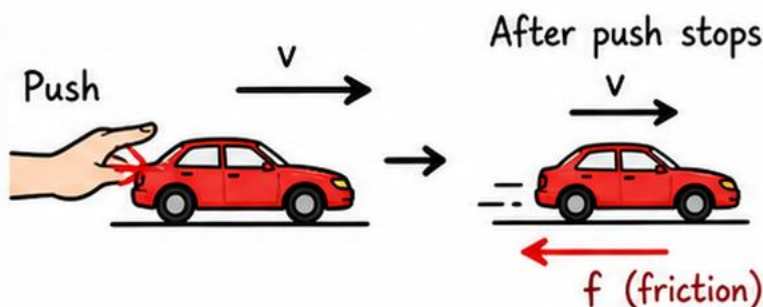
Note: Internal forces (forces between parts of the chosen system) occur in equal and opposite pairs and cancel out. They are not included in $\sum \vec{F}_{\text{ext}}$. Only external forces are considered.

ARISTOTLE'S FALLACY & THE ROLE OF FRICTION

Aristotle believed that a body requires a continuous force to keep moving.
This is a misconception caused by ignoring friction.

ARISTOTLE'S CLAIM (WRONG)

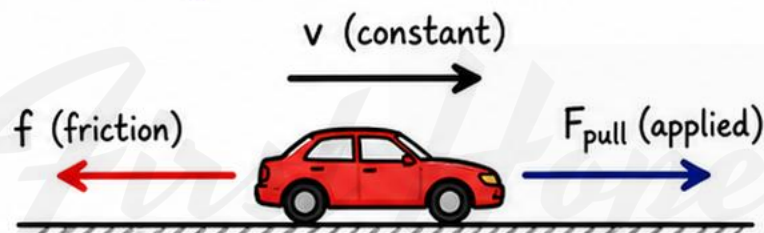
A continuous force is needed to keep a body moving.



- When the push stops, the car slows down and eventually stops.
- Aristotle concluded that motion needs a continuous force.

WHAT REALLY HAPPENS

When the car moves at constant speed on a rough surface.



- Applied pull to the right balances friction to the left.
- Net force is zero $\rightarrow$ no acceleration.

$$\Sigma F_x = F_{\text{pull}} - f = 0$$

$a = 0$

(Velocity is constant.)

IDEAL FRICTIONLESS LIMIT

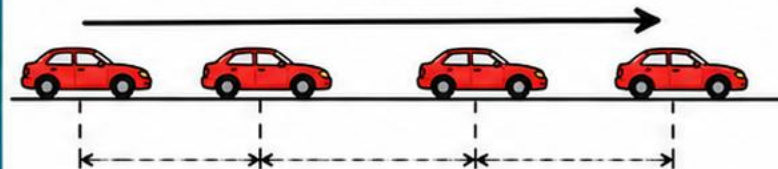
In the absence of friction.

After the push ends:

$$F_{\text{pull}} = 0, f = 0$$

$$\Sigma F_{\text{ext}} = 0 \rightarrow a = 0$$

v (constant)



Equal distances in equal time intervals.

- The car continues with the same velocity in a straight line forever.
- No force is needed to sustain uniform motion when friction is absent.

KEY IDEA: Force is needed in practice to overcome friction – not to sustain uniform velocity.

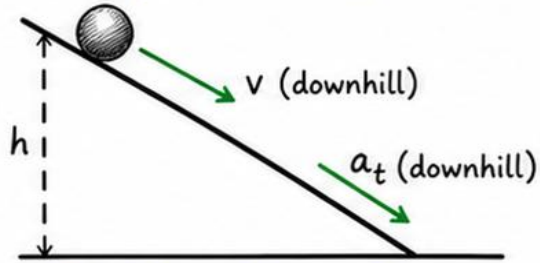
Net force determines acceleration, not velocity.

$$\Sigma F_{\text{ext}} = ma \quad (1^{\text{st}} \text{ law: if } \Sigma F_{\text{ext}} = 0, \text{ then } a = 0)$$

GALILEO & THE LAW OF INERTIA

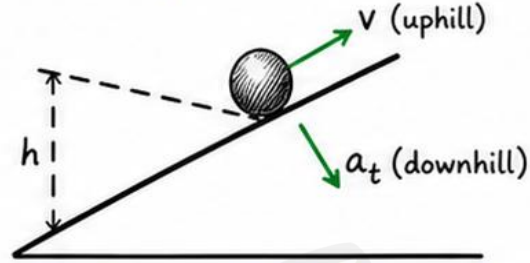
A ball on a smooth incline (negligible rolling resistance and air drag)

① Rolling DOWN
Speed increases



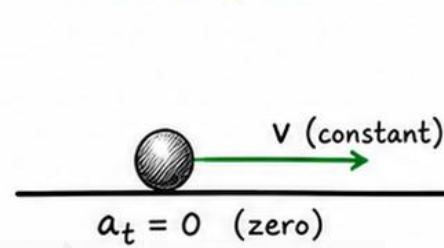
Velocity and tangential acceleration are downhill.

② Rolling UP
Speed decreases



Velocity is uphill but tangential acceleration is downhill.

③ Horizontal limit ($\theta \rightarrow 0^\circ$)
Constant speed

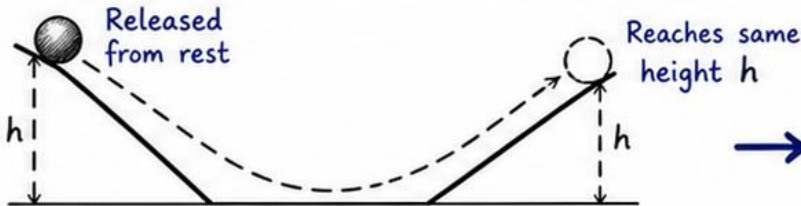


No tangential acceleration.
Velocity remains constant.

INERTIA

- An object at rest remains at rest.
- An object in uniform straight-line motion remains in uniform straight-line motion.
- Rest and uniform straight-line motion are equivalent zero-net-force states.
- Inertia is the property by virtue of which a body resists any change in its state of motion (change of velocity).

Galileo's double-incline thought experiment (smooth, frictionless)



Ball released from height h on the left climbs to the same height h on the right.



If the right incline is less steep, the ball travels a longer distance.



In the limiting case (horizontal), the ball never rises and keeps moving with constant velocity indefinitely (no reason to stop on a smooth surface).

A parallel idea in ancient India

The concept of **vega** (वेग) in classical Indian thought described the natural tendency of a body to move straight and continue moving, opposed by contact resistance or air resistance acting from outside.

Ideal assumptions

- Surface is smooth (no friction)
- Negligible rolling resistance
- Negligible air drag

Key takeaway

Without external forces, there is no reason for the state of motion to change.

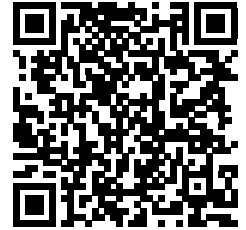


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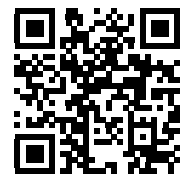


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