FORCE AND MOTION

Physics is a study of motion, including acceleration.

Physics is also a study of what can cause an object to accelerate.

That cause is a force (push/pull on the object)

"A force from something on another thing"

NEWTONIAN MECHANICS

Relation Between Force & Acceleration (Isaac Newton 1642–1727)

3 primary Laws of Motion

Not always Valid → high speeds : Einstein's Special Theory of Relativity

too small : Quantum Mechanics

NEWTON'S FIRST LAW

Before, it was Believed that some influence, a "force" was needed to keep a Body moving at constant velocity. Similarly a Body was thought to Be in its "natural state" when it was at Rest. For a body to move with constant velocity, it must have had to be propelled in some way by a push/pull or otherwise it would "naturally" stop moving.

Thought experiment: a puck → wooden table : stops

ice : moves further Before stopping.

---> in the Limit - extremely slippery surface (frictionless surface)

→ A body will keep moving with constant velocity if no force acts on it.

⟹ $\boxed{\text{NEWTON'S } 1^{st} \text{ LAW: If no force acts on a body, the body's velocity cannot change; that is the body cannot accelerate.}}$

(if at rest → stays at Rest; if moving, moves with the same velocity)

same magnitude, same direction

FORCES

Defined in terms of acceleration a force gives to a standard reference body (1kg)

We pull it until we reach an acceleration of $1\,m/s^2$

⟹ We are exerting 1N magnitude of force.

Force is a vector Quantity.

We can add them: Principle of superposition of forces.

$\vec{F}$, $\vec{F}_{net}$

⇒ Newton's 1^{st} Law Revisited: If no <u>net</u> force acts on a body ($\vec{F}_{net}=0$) the body's velocity cannot change.

INERTIAL REFERENCE FRAMES

Newton's 1^{st} Law is not true in all reference frames (e.g., inside an elevator), but we can always find reference frames in which it is true. Such special frames are called inertial Reference frames (or simply "inertial frames").

For example, we can assume that the ground is an inertial frame, provided we can neglect Earth's astronomical motions.

Ex: puck & short strip of ice ✓

puck & long strip of ice extending from the North pole

If we view it from space:

Space   ground ⟶ ground is a non-inertial frame.

MASS

Kick two objects in the same way.
(bowling & soccer ball)

The soccer ball receives larger acceleration, due to its mass.

$m_0 = 1\,kg$, $a_0 = 1\,m/s^2 \longrightarrow F = 1\,N$

$m = m_x$, $a_x = 0.25\,m/s^2$ $(F = 1\,N) \longrightarrow$ heavier mass, less acceleration

$$\Rightarrow \frac{m_x}{m_0} = \frac{a_0}{a_x}, \quad m_x = m_0 \frac{a_0}{a_x} = 1\,kg \, \frac{1\,m/s^2}{0.25\,m/s^2} = 4\,kg$$

$$\left.\begin{array}{l} F = 8N \xrightarrow{m_0 = 1kg} a_0 = 8\,m/s^2 \\ F = 8N \xrightarrow{m_x} a_x = 2\,m/s^2 \end{array}\right\} \longrightarrow m_x = m_0 \frac{a_0}{a_x} = 4\,kg$$

⇒ Mass is an intrinsic characteristic (automatically comes with the existence)

mass ⟶ scalar

The mass of a body is the characteristic that relates a force to the resulting acceleration ⟶ $\boxed{\text{only when there is an acceleration!}}$

Newton's 2nd Law

The net force on a body is equal to the product of the body's mass and its acceleration

$\boxed{\vec{F}_{net} = m.a}$ Newton's 2nd Law

Only forces that act on <u>that</u> body are to be included.

$$F_{net,x} = m.a_x \; ; \; F_{net,y} = m\,a_y \; ; \; F_{net,z} = m.a_z$$

→ The acceleration components along a given axis is caused only by the sum of the force components along that same axis, and not by force components along any other axis.

$$\text{if } \vec{F}_{net} = 0 \longrightarrow \vec{a} = 0$$

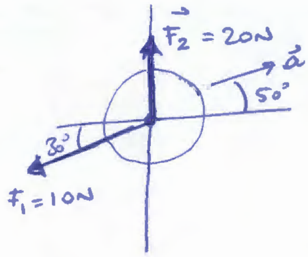
$$1\,N = (1kg)(1m/s^2) = 1\,kgm/s^2$$

	F	m	a
SI	newton (N)	kg	m/s^2
CGS	dyne	g	cm/s^2

* To solve problems using Newton's 2nd Law, we often draw "free-body" diagram

A system consisting of one or more bodies, and any force on the bodies inside the system, from bodies outside is called "external force".

Ex:



$m = 2kg$, $\vec{F}_3 = ?$

$$\vec{F}_{Net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 = m\vec{a}$$

$$\vec{F}_3 = m\vec{a} - \vec{F}_1 - \vec{F}_2$$

x - components:

$$F_{3,x} = ma_x - F_{1,x} - F_{2,x}$$

$$= m(a \cos 50^\circ) - F_1 \cos(-150^\circ) - F_2 \cos 90^\circ$$

$$= 2kg \cdot 3\,m/s^2 \cos 50^\circ - 10N \cdot \cos 150^\circ - 20N \cos 90^\circ$$

$$= 12.5N$$

Y - components:

$$F_{3,y} = ma_y - F_{1,y} - F_{2,y}$$

$$= m(a \sin 50^\circ) - F_1 \sin(-150^\circ) - F_2 \sin 90^\circ$$

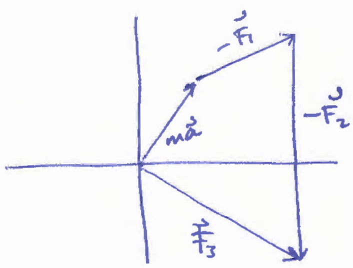
$$= 2kg\ 3\,m/s^2\ \sin 50^\circ - 10N \cdot \sin(-150^\circ) - 20N \cdot \sin 90^\circ$$

$$= -10.4N$$

$$\Rightarrow \vec{F}_3 = F_{3,x}\hat{i} + F_{3,y}\hat{j} = (12.5N)\hat{i} - (10.4N)\hat{j}$$

$$\simeq 13N\hat{i} - 10N\hat{j} \Rightarrow F_3 = 16N$$

$$\theta = \tan^{-1}\frac{F_{3,y}}{F_{3,x}} = -40^\circ$$



Ex: 1- and 2-D forces

$m = 0.20\,kg$

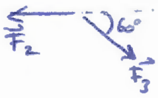
$F_1 = 4N$, $F_2 = 2N$, $F_3 = 1N$ $\rightarrow a = ?$

A) 

$F_1 = a_x\, m \rightarrow a_x = \frac{F_1}{m} = \frac{4N}{0.2kg} = 20\, m/s^2$

B) 

$F_1 - F_2 = m\, a_x \rightarrow a_x = \frac{4N - 2N}{0.2kg} = 10\, m/s^2$

C) 

$\rightarrow$ only the horizontal component of $\vec{F_3}$ competes with $\vec{F_2}$

$$F_{3,x} - F_2 = m\, a_x$$

$$a_x = \frac{F_{3,x} - F_2}{m} = \frac{F_3 . \cos\theta - F_2}{m} = \frac{1N . 1/2 - 2N}{0.2\,kg} = -7.5\, m/s^2$$

$$a_y = \frac{F_{3y}}{m} = \frac{F_3 . \sin\theta}{m} = \frac{1N . \sqrt{3}/2}{0.2kg} = 2.5\sqrt{3}\, m/s^2$$

Some particular forces

* The Gravitational Force

mass of m, free-fall acceleration with a magnitude of g.

If we neglect the effects of the air, the only force acting will be the gravitational force $\vec{F_g}$.

Newton's 2^{nd} Law: $\vec{F} = m\vec{a}$

$$F_{net,y} = m . a_y$$

$$-F_g = m(-g)$$

$$\rightarrow \boxed{F_g = mg}$$

This same gravitational force, with the same magnitude still acts on the body even when the body is not in free-fall but at rest on a table or moving across a table.

$$\vec{F_g} = -F_g\,\hat{j} = -mg\,\hat{j} = m\vec{g}$$

WEIGHT: The weight of a body is the magnitude of the net force required to prevent the body from falling freely, as measured by someone on the ground.

Suppose that, for a ball, 2N is necessary to prevent it from falling – we say that the ball weighs 2N (or the ball weighing 2N).

Heaviness, defined → Another ball with 3N weight is heavier than the first ball.

$$F_{net,y} = m a_y$$

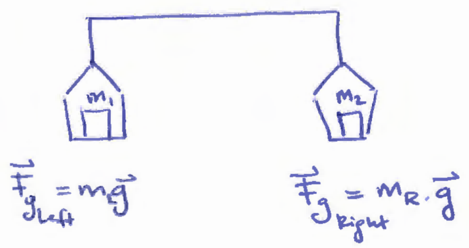
$W - F_g = m.(0) \longrightarrow W = F_g$ (weight, with ground as an inertial frame)

→ The weight W of a body is equal to the magnitude F_g of the gravitational force on the body.

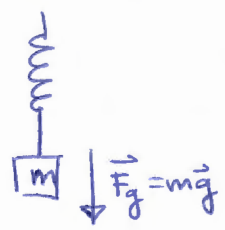
$$mg = F_g \longrightarrow \boxed{W = mg} \quad \text{(Weight)}$$

Measuring Weight

i) Equal Arm Balance:



ii) Spring Scale:



If the scale is marked in mass units, it is accurate only where the value of g is the same as where the scale is calibrated.

The weight of a Body must be measured when the Body is not accelerating vertically relative to the ground. For example, you can measure your weight on a scale in your bathroom or on a fast train. However, if you Repeat it in an accelerating Elevator, the reading differs. Such a measurement is called an "apparent Weight".

<u>Caution:</u> A body's mass is not its mass.

The weight of a bowling ball with a mass of 7.2kg:

71 N on earth

but 12 N on moon.

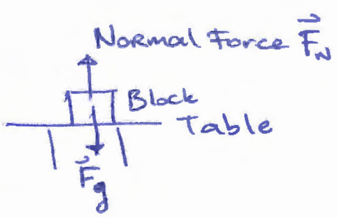
Mass is same but free-fall acceleration on moon is $1.6 \, m/s^2$

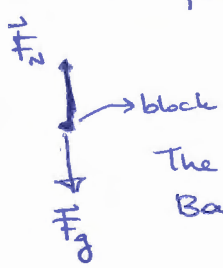
THE NORMAL FORCE

If you stand on a bed, Earth pulls you downward but you Remain stationary. The Reason is the mattress — it Deforms to push you up. Even a seemingly rigid concrete floor does this.

The push on you from the bed or floor is a <u>normal</u> force $\vec{F}_N$.

→ perpendicular





The Forces Balance.

$$F_N - F_g = m a_y$$

$$F_N - mg = m a_y$$

$$F_N = mg + m a_y = m\underbrace{(g + a_y)}$$

tables block
they might be in an elevator

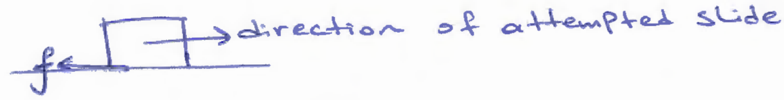
if $a_y = 0$

$\longrightarrow F_N = mg$

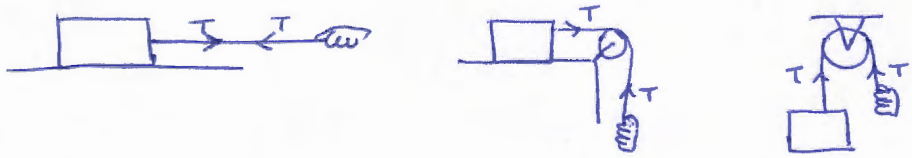
FRICTION: If we either slide or attempt to slide a body over a surface, the motion is resisted by a bonding between the body and the surface.

This resistance is considered a single force, $\vec{f}$ and called frictional force / friction

It's directed along the surface, direction is opposite of the intended motion.



TENSION: When a cord/rope is attached to a body and pulled, the cord pulls on the body with a force $\vec{T}$ directed away from the body & along the cord.



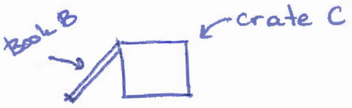
The force is often called a tension force because the cord is said to be under tension, which means that it's being pulled.

The tension in the cord is the magnitude T of the force on the body.

A cord is often said to be massless and unstretchable.

Newton's 3rd Law

Two bodies are said to interact when they push or pull each other — that is, when a force acts on each body due to the other body.

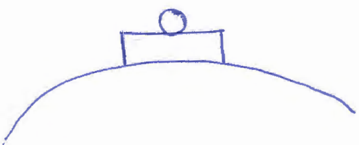


$\Rightarrow$ When two bodies interact, the forces on the bodies from each other are always equal in magnitude and opposite in direction.

$\longrightarrow F_{BC} = F_{CB}$

$\vec{F}_{BC} = -\vec{F}_{CB}$: A third law force-pair

Ex:



F_{BT} : Force on the ball from the table

F_{BE} : " " " " " the earth

$\longrightarrow$ These are not a third-law force pair.

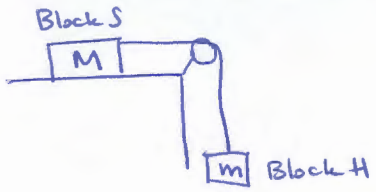
$\vec{F}_{EB}$ (Ball pulls the Earth)

$\vec{F}_{BE}$ (gravitational)

$$\vec{F}_{EB} = -\vec{F}_{BE}$$

$$\vec{F}_{BT} = -\vec{F}_{TB}$$

APPLYING NEWTON'S LAWS

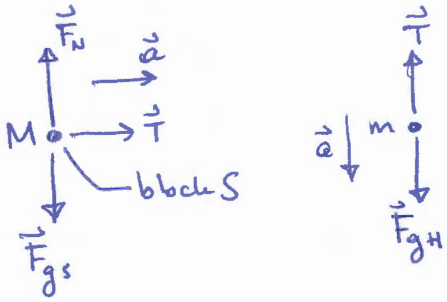


$M = 3.3\,kg$

$m = 2.1\,kg$

frictionless

1) $a_S = a_H$ they Both move the same amount in a given time



$F_{net,x} = M a_x$ $\qquad F_{net,y} = M a_y$

$F_{net,z} = M a_z$

$$F_{net,y} = M a_y^{\swarrow 0}$$

$$F_N - F_{gS} = 0 \longrightarrow F_N = F_{gS}$$

$$F_{net,x} = M a_x \longrightarrow \underbrace{T = Ma}$$

$$F_{net,y} = m a_y$$

$$\longrightarrow T - F_{gH} = m a_y \Rightarrow T - mg = -ma$$

$$\downarrow$$

$$Ma - mg = -ma$$

$$\rightarrow a = \frac{m}{M+m} g$$

$$T = \frac{Mm}{M+m} g$$

$$a = \frac{m}{M+m} g = \frac{2.1\,kg}{3.3\,kg + 2.1\,kg} 9.8\,m/s^2 = 3.8\,m/s^2$$

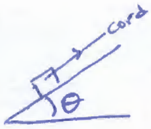
$$T = \frac{Mm}{M+m} g = \frac{(3.3\,kg)(2.1\,kg)}{3.3\,kg + 2.1\,kg} 9.8\,m/s^2 = 13\,N$$

Check: let's take $g = 0 \rightarrow$ <u>space</u> $\rightarrow$ no movement, no tension.

$M = 0 \rightarrow ?$

$M \rightarrow \infty \rightarrow ?$

Ex:

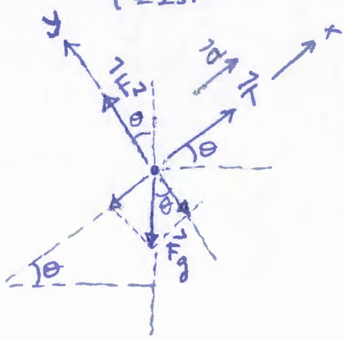


$m = 5kg$

$\theta = 30°$

$T = 25N$

a along the plane?



$$\boxed{\begin{aligned} T - mg\sin\theta &= ma \\ a &= 0.1\, m/s^2 \end{aligned}}$$

$$\boxed{\vec{F}_N = mg\cos\theta}$$

Ex: A passanger, $m = 72.2\,kg$ stands on a scale in an elevator.

a) Find a general solution for the scale Reading.

$$\vec{F}_{net} = m\vec{a} \longrightarrow F_N - F_g = ma$$

$$F_N = F_g + ma$$

$$F_N = m(g + a)$$

b) Stationary / moving upward with a constant velocity of 0.5 m/s

$$a = 0 \longrightarrow F_N = (72.2\,kg)(9.8\, m/s^2 + 0)$$

$$= 708\,N$$

c) Upward / downward with $|\vec{a}| = 3.2\, m/s^2$

Upward: $a = 3.2\, m/s^2 \longrightarrow F_N = (72.2\,kg)(9.8\, m/s^2 + 3.2\, m/s^2)$

$$= 939\,N$$

Downward: $a = -3.2\, m/s^2 \longrightarrow F_N = (72.2\,kg)(9.8\, m/s^2 - 3.2\, m/s^2)$

$$= 477\,N$$

d) During upward acceleration,

*) What is the magnitube of F_{Net} on the passanger?

*) What is the magnitude $a_{p,cab}$ of his acceleration as measured in the frame of the cab?

F_g is independent of the motion of the person.

$\longrightarrow 708\,N\ (b)$

$$F_{Net} = F_N - F_g = 939\,N - 708\,N = 231\,N$$

However, his acceleration $a_{p,cab}$ relative to the frame of the cab is zero.

Thus, in non-inertial frame of the cab, F_{net} is not Equal to $m.a_{p,cab}$! Newton's 2nd Law does not HolD.