Force and Motion

AS Level Physics 9702

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By the end of this topic I can. . .

- state and apply Newton's three laws of motion
- draw free-body diagrams and find the resultant force
- describe weight, drag, upthrust, normal contact and friction, and explain terminal velocity
- solve problems on slopes and for connected bodies

Newton’s first law

First law

An object stays at **rest** or moves at **constant velocity** unless acted on by a **resultant force**.

- inertia: resistance to changes in motion
- no resultant force: equilibrium

Newton's second law

Second law

Acceleration is **proportional to the resultant force** and **inversely proportional to the mass**, in the direction of the force.

- 1 N: the force giving 1 kg an acceleration of 1 m s^{-2}
- mass: a measure of inertia

$$F_{\text{net}} = ma$$

Example: pushing a box

Example: pushing a box

$$F_{\text{net}} = F - f = ma \quad \Rightarrow \quad a = \frac{F - f}{m} = \frac{30 - 21}{6.0} = 1.5 \text{ m s}^{-2}$$

Example: braking

Example: braking

Using Newton's second law and noticing braking force acts opposite to direction of motion:

$$F_{\text{net}} = ma \quad \Rightarrow \quad -2000 = 800 \times a \quad \Rightarrow \quad a = -2.5 \text{ m s}^{-2}$$

$$2as = v^2 - u^2 \quad \Rightarrow \quad s = \frac{v^2 - u^2}{2a} = \frac{0^2 - 20^2}{2 \times (-2.5)} = 80 \text{ m}$$

Newton’s third law

Third law

The forces between two bodies are **equal in size**, **opposite in direction**, of the **same type**, and act on **different bodies**.

Example: action and reaction pairs

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(a) The person exerts downward force on scale, scale exerts an upward reaction on the person.
(b) The rotors of helicopter push air downwards, air exerts an upward force on helicopter.
(c) The Sun pulls the earth through gravitational attraction, the Earth also attracts the sun in return.

Free-body diagrams

- draw the FBD for the object
- resolve and find the resultant force
- apply Newton's second law
- solve for *a*, then use the equations of motion

Weight and free fall

$$W = mg$$

$$a = g$$

- weight is a vector (N); mass is a scalar (kg)
- free-fall acceleration is independent of mass

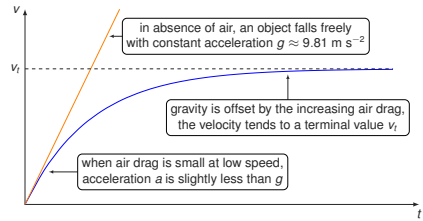
Example: weight on Mars

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Mass of astronaut: $m = \frac{W_M}{g_M} = \frac{300}{3.7} \approx 81.1$ kg
Weight on earth: $W_E = mg_E = 81.1 \times 9.81 \approx 795$ N

Drag and terminal velocity

- drag opposes motion; grows with speed, area, fluid density
- $a = g$ at the start; a decreases as drag grows
- terminal velocity: $f = mg$, $a = 0$



Example: terminal velocity

Example: terminal velocity

equilibrium between weight and air drag when falling at terminal speed, so

$$mg = bv_t \quad \Rightarrow \quad b = \frac{mg}{v_t} = \frac{5.0 \times 9.81}{70} \approx 0.70 \text{ kg s}^{-1}$$

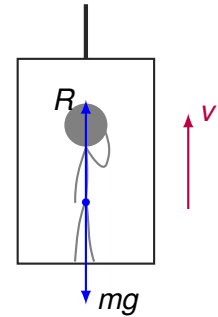
at any instant, equation of motion is: $F_{\text{net}} = ma = mg - bv$
at 30 m s^{-1}, acceleration is: $a = \frac{mg-bv}{m} = \frac{5.0\times9.81-0.70\times30}{5.0} \approx 5.6 \text{ m s}^{-2}$

Example: a lift

A man of 80 kg stands in a lift. Find his apparent weight, i.e., the contact force, when the lift is (a) moving upwards at steady speed of 2.0 m s^{-1}, (b) accelerating upwards at 2.0 m s^{-2}, (c) moving upwards but slowing down at a deceleration of 1.5 m s^{-2}.

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The forces acting on man are weight and normal contact, for either case, equation of motion for the man reads:

$$F_{\text{net}} = ma = R - mg$$

so normal contact force: $R = mg + ma$

when rising at steady speed, man is in equilibrium ($a = 0$), so: $R = mg = 80 \times 9.81 \approx 785$ N

when accelerating upwards ($a = +2.0$ m s^{-2}):

$R = 80 \times 9.81 + 80 \times 2.0 \approx 945$ N

Example: pulling a sleigh

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No vertical acceleration, so the vertical forces balance; the horizontal resultant gives the acceleration.

(a) $R = mg = 15 \times 9.81 \approx 147$ N, $a = \dfrac{P}{m} = \dfrac{75}{15} = 5.0$ m s^{-2}

(b) $\tan\alpha = \frac{3}{4}$ gives $\sin\alpha = \frac{3}{5}$, $\cos\alpha = \frac{4}{5}$.

Vertical: $R + P\sin\alpha = mg \quad \Rightarrow \quad R = 147 - 75 \times \frac{3}{5} \approx 102$ N. Horizontal:

$$P\cos\alpha = ma \quad \Rightarrow \quad a = \frac{75 \times \frac{4}{5}}{15} = 4.0 \text{ m s}^{-2}$$

Friction

Friction

The component of the contact force **parallel** to the surfaces; it opposes sliding.

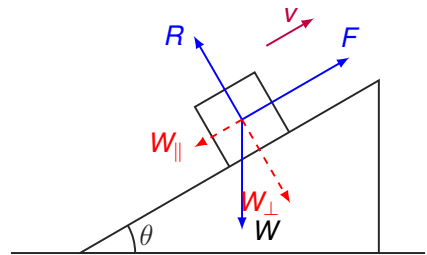
- **static**: adjusts to match the applied force, up to a maximum
- **kinetic**: acts when surfaces are already sliding

Slopes

Resolve parallel and perpendicular to the slope:

$$W_{\parallel} = mg \sin\theta$$

$$W_{\perp} = mg \cos\theta$$

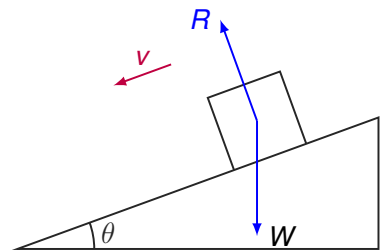


Example: block sliding down a smooth slope

A block of mass m slides down a *smooth* slope. The angle of the slope to the horizontal is θ. Find the acceleration of the block.

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only force acting along the slope is component of weight down the slope, so:

$$F_{\text{net}} = ma = mg\sin\theta \quad \Rightarrow \quad a = g\sin\theta$$

as $\theta \to 0$, $a \to 0$, this shows if plane becomes horizontal, the block simply stays put

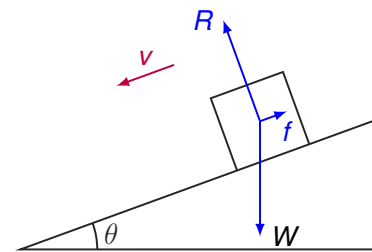
as $\theta \to 90^\circ$, slope becomes vertical, block would undergo free fall, so naturally $a \to g$

Example: block on a rough slope

A block of mass 2.0 kg slides down a rough slope from rest. The slope is inclined at angle $\theta = 20^\circ$ to the horizontal, and the block experiences a constant friction of 5.0 N. (a) What is the block's acceleration? (b) What is the distance travelled in 2.5 seconds?

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Resolving along slope:

$$F_{\text{net}} = mg\sin\theta - f = ma$$

$$a = \frac{2.0\times 9.81\times \sin 20^\circ - 5.0}{2.0} \approx 0.855 \text{ m s}^{-2}$$

Distance travelled:

$$s = \cancel{ut}^{0} + \frac{1}{2}at^2 = \frac{1}{2}\times 0.855 \times 2.5^2 \approx 2.67 \text{ m}$$

Example: block sliding up a slope

A block of mass 3.0 kg is travelling up an inclined slope at an initial speed of 2.8 m s^{-1}. The slope makes an angle of 18° with the horizontal. A constant friction of 7.5 N acts on the block.

(a) What is the block's deceleration?

(b) How far does the block travel along the slope before its speed decreases to zero?

(c) Suggest whether the block could stay on the slope.

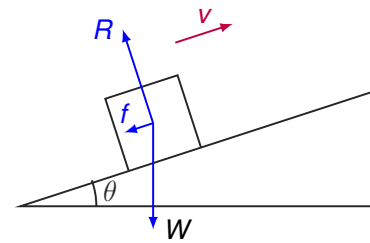
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Resolving along slope (take direction of initial velocity as positive direction):

$$F_{\text{net}} = -mg\sin\theta - f = ma \quad \Rightarrow \quad a = \frac{-mg\sin\theta - f}{m} = \frac{-3.0\times 9.81\times\sin 18^\circ - 7.5}{3.0} \approx -5.53 \text{ m s}^{-2}$$

$$v^2 - u^2 = 2as \quad \Rightarrow \quad s = \frac{v^2-u^2}{2a} = \frac{0^2-2.8^2}{2\times(-5.5.3)} \approx 0.709 \text{ m}$$

Note that component of weight down the slope is:

Example: two boxes pushed together

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For A: $F - R = M_A a$. For B: $R = M_B a$. For the system: $F = (M_A + M_B)a$.
$a = \dfrac{F}{M_A + M_B}$ and the contact force $R = M_B a = \dfrac{M_B}{M_A + M_B} F$.

Example: towing a trailer

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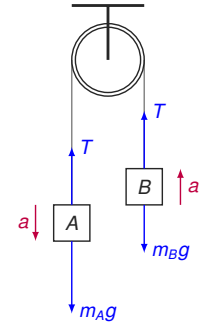
Whole system: $F_{\text{net}} = 9600 - 3600 - 1800 = 4200$ N, $m = 2000$ kg, so $a = \dfrac{4200}{2000} = 2.1 \text{ m s}^{-2}$.
Trailer: $T - 1800 = 500 \times 2.1 \quad \Rightarrow \quad T = 2850$ N.

Example: two masses over a pulley

Two blocks of mass m_A and m_B ($m_A > m_B$) are joined together by a light inextensible string. The string passes over a smooth pulley as shown. The two blocks are suddenly released from rest. Find the acceleration of each block and the tension in the string.

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Apply Newton's second law to each block:

$$\begin{cases} \text{for } A: & m_Ag - T &= m_Aa \\ \text{for } B: & T - m_Bg &= m_Ba \end{cases}$$

adding the two, one obtains equation of motion for whole system:

$$m_Ag - m_Bg = (m_A + m_B)a$$

solving these equations, we find

$$a = \frac{m_A - m_B}{m_A + m_B}g \qquad T = \frac{2m_Am_Bg}{m_A + m_B}$$

Question: the firefighter

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(a) $s = \frac{1}{2}at^2 \quad \Rightarrow \quad a = \dfrac{2 \times 6.0}{2.0^2} = 3.0 \text{ m s}^{-2}$

(b) $mg - f = ma \quad \Rightarrow \quad f = 85 \times (9.81 - 3.0) \approx 5.8 \times 10^2 \text{ N}.$

Key equations

second law	$F_{\text{net}} = ma$	along slope	$W_{\parallel} = mg\sin\theta$
weight	$W = mg$	normal to slope	$W_{\perp} = mg\cos\theta$