

3.1.1 Newton's laws, resultant force and $F = ma$

Name: _____ Class: _____ Date: _____

Total: 38 marks

KEY WORDS resultant force 合力 • normal contact force 支持力 • tension 张力 • mass 质量
• weight 重力

Objective

Build the skills to answer exam questions that use **Newton's laws of motion** 牛顿运动定律 when several forces act: finding the **resultant force** 合力, using $F = ma$, the forces in a lift and between joined objects, **third-law pairs** 作用力与反作用力, and the force from a stream of water or air. This sheet covers syllabus 3.1, learning outcomes 1 to 6.

You must be able to:

- explain that **mass** 质量 is the property of an object that resists change in motion, and use weight $W = mg$
- draw the forces on one object and add them to find the resultant force
- use $F = ma$ to solve problems, knowing that the acceleration and the resultant force are always in the same direction
- state and apply each of Newton's laws, including to an object moving at constant velocity
- find the normal contact force on a person in a lift
- find the acceleration of two joined objects, then the force between them
- name the other force in a Newton's third-law pair
- define and use **linear momentum** 动量 as the product of mass and velocity, and use force as the **rate of change of momentum** 动量变化率 for a stream of water or air

1 Worked examples

Study these first. Each one shows a **method** that a question later on this sheet needs.

■ Mass and weight

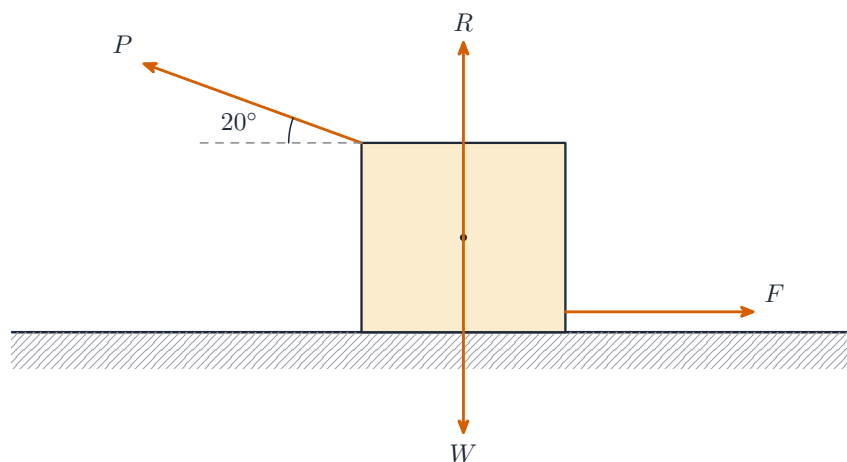
- **Mass** is the property of an object that resists a change in its motion. It is measured in kg, and it is the **same everywhere**.
- **Weight** is the effect of a **gravitational field** 重力场 on a mass. It is the product of the mass and the **acceleration of free fall** 自由落体加速度: $W = mg$.
- Near the Earth's surface $g = 9.81 \text{ N kg}^{-1}$, the **gravitational field strength** 重

力场强度, which is the same as 9.81 m s^{-2} .

- A 2.0 kg bag weighs $2.0 \times 9.81 = 19.6 \text{ N}$ on the Earth. On Mars, where $g = 3.7 \text{ N kg}^{-1}$, it weighs $2.0 \times 3.7 = 7.4 \text{ N}$, but its mass is still 2.0 kg.

■ Finding the resultant force

A box of mass 6.0 kg is pulled to the left along a rough floor. The rope pulls with a force $P = 40 \text{ N}$ at 20° above the horizontal, and the **friction** 摩擦力 force is $F = 15 \text{ N}$.



1. Draw a **free-body diagram** 受力图: every force on the box, and only the forces on the box.
2. Resolve the force at an angle (Topic 1). The horizontal component of the pull is $40 \cos 20^\circ = 37.6 \text{ N}$ and the vertical component is $40 \sin 20^\circ = 13.7 \text{ N}$.
3. Add the forces along the direction of motion, giving each direction a sign:

$$F_{\text{resultant}} = 37.6 \text{ N} - 15 \text{ N} = 22.6 \text{ N}$$

4. Use $F = ma$. The acceleration is in the direction of the resultant force, to the left:

$$a = \frac{22.6 \text{ N}}{6.0 \text{ kg}} = 3.8 \text{ m s}^{-2}$$

5. The box does not move up or down, so the vertical forces balance: $R + 13.7 \text{ N} = W = 58.9 \text{ N}$, so $R = 45 \text{ N}$.

■ Constant velocity, speeding up and slowing down

- **Newton's first law:** if the resultant force is zero, an object stays at rest or keeps moving at **constant velocity**. A lorry moving at a steady speed has a driving force **equal** to the total resistive force, for example 3200 N each.
- If the driving force rises to 4000 N, the resultant force is 800 N forwards, and the lorry of mass 16 000 kg speeds up: $a = 800/16\,000 = 0.050 \text{ m s}^{-2}$.
- When a car brakes, the resultant force points **backwards**, so the acceleration points backwards too, even though the car still moves forwards. For a 1200 kg car

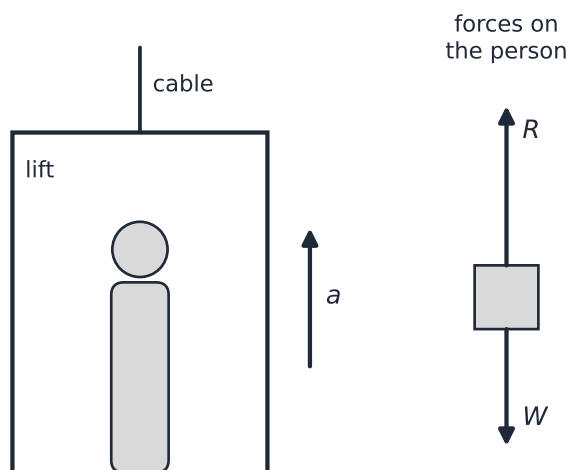
with a braking force of 6000 N and air resistance of 600 N:

$$a = \frac{-(6000 + 600) \text{ N}}{1200 \text{ kg}} = -5.5 \text{ m s}^{-2}$$

- From 20 m s^{-1} the car then stops in $s = \frac{0 - 20^2}{2(-5.5)} = 36 \text{ m}$ (Topic 2).

■ The normal contact force in a lift

A person of mass 60 kg stands in a lift. Two forces act on the person: the weight $W = 60 \times 9.81 = 589 \text{ N}$ downwards, and the **normal contact force** 支持力 R from the floor upwards. Take up as positive, so $R - W = ma$ and $R = m(g + a)$.

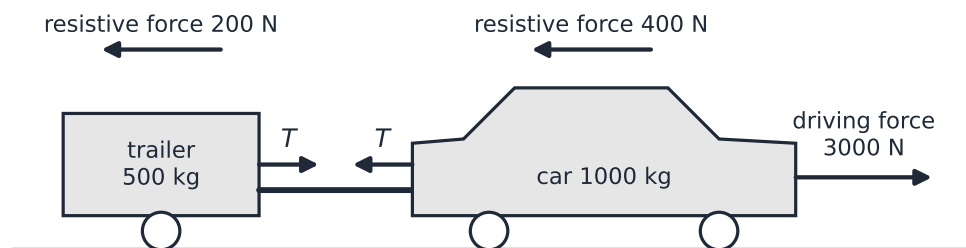


motion of the lift	acceleration	$R = m(g + a)$
going up and speeding up	$+1.5 \text{ m s}^{-2}$	$60(9.81 + 1.5) = 680 \text{ N}$
steady speed, up or down	0	589 N
going up and slowing down	-1.5 m s^{-2}	$60(9.81 - 1.5) = 500 \text{ N}$

- A lift going **down** and speeding up also has an acceleration of -1.5 m s^{-2} , so again $R = 500 \text{ N}$ and the person feels lighter.
- Bathroom scales in the lift read R , not the weight.

■ Two objects joined together

A car of mass 1000 kg tows a trailer of mass 500 kg. The driving force is 3000 N. The resistive forces are 400 N on the car and 200 N on the trailer.



1. **Treat both as one object** to find the acceleration. The **tension** 张力 in the tow bar is inside this object, so it cancels:

$$a = \frac{(3000 - 400 - 200) \text{ N}}{(1000 + 500) \text{ kg}} = 1.6 \text{ m s}^{-2}$$

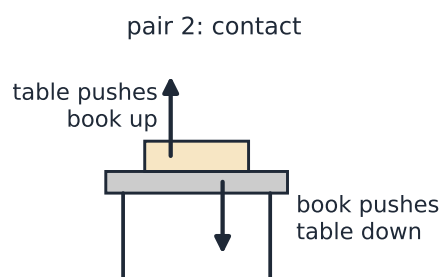
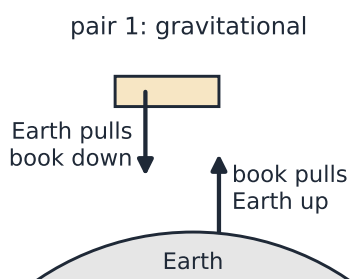
2. **Then take one object on its own** to find the force between them. On the trailer, T pulls forwards and 200 N acts backwards:

$$T - 200 \text{ N} = 500 \text{ kg} \times 1.6 \text{ m s}^{-2} \Rightarrow T = 1000 \text{ N}$$

3. Check with the car: $3000 - 400 - 1000 = 1600 \text{ N}$, and $1000 \text{ kg} \times 1.6 \text{ m s}^{-2} = 1600 \text{ N}$.

■ Newton's third-law pairs

Newton's third law: if object A exerts a force on object B, then B exerts a force on A that is **equal in size, opposite in direction and of the same type**. The two forces act on **different** objects.

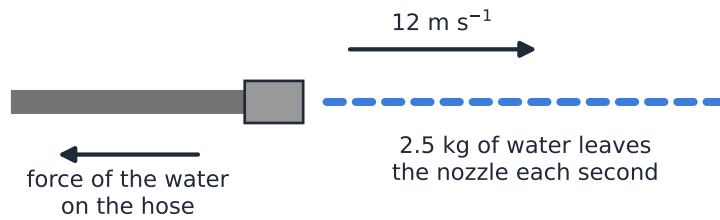


- To find the partner of a force, **swap the two objects** in its description: “the Earth pulls the book” becomes “the book pulls the Earth”.
- The weight of the book and the push of the table are equal in size, but they are **not** a pair. Both act on the book, and they are different types of force. They are equal because the book is in equilibrium (first law), not because of the third law.

■ A force from a stream of water or air

Linear momentum is the product of mass and velocity, $p = mv$, measured in kg m s^{-1} . Newton's second law says that the resultant force is the rate of change of momentum. For a stream, find the momentum given to the fluid **each second**:

$$F = \frac{\Delta p}{\Delta t} = \frac{\Delta m}{\Delta t} \times \Delta v$$



- Each second, 2.5 kg of water speeds up from rest to 12 m s^{-1} at the **nozzle** 喷嘴:
 $F = 2.5 \text{ kg s}^{-1} \times 12 \text{ m s}^{-1} = 30 \text{ N}$ on the water, forwards.
- By the third law, the water pushes the hose with 30 N **backwards**, so the person holding the hose must push forwards with 30 N.

2 Practice

Now use the methods above.

2.1 A rock sample has a weight of 12 N on a planet where $g = 4.0 \text{ N kg}^{-1}$.

- (a) Calculate the mass of the rock. [1]

- (b) Calculate the weight of the rock on the Earth. [1]

2.2 A sledge of mass 12 kg is pulled across flat snow by a rope at 25° above the horizontal. The tension in the rope is 50 N, and the friction force on the sledge is 20 N.

- (a) Calculate the horizontal component of the tension. [1]

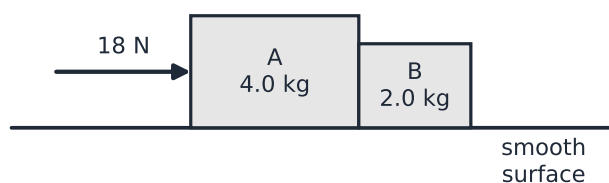
- (b) Calculate the acceleration of the sledge. [2]

2.3 A lift and its passengers have a total mass of 800 kg. The lift is pulled up by a cable. Calculate the tension in the cable when the lift is:

- (a) accelerating upwards at 0.60 m s^{-2} [2]

- (b) moving upwards at a constant speed. [1]

2.4 Two blocks, A and B, are pushed along a smooth horizontal surface by a force of 18 N, as shown.



- (a) Calculate the acceleration of the blocks. [1]

- (b) Calculate the force that block A exerts on block B. [2]

2.5 A leaf blower takes in still air and blows out 0.30 kg of air each second at 40 m s^{-1} .

- (a) Calculate the force on the air. [1]

- (b) State the size and the direction of the force of the air on the leaf blower. [1]

3 Exam-style questions

3.1 A lift is moving upwards and slowing down. T is the tension in the cable and W is the weight of the lift. Which statement is correct? [1]

A	B
C	D

A T is greater than W .

B T is equal to W .

C T is less than W .

D T is zero.

3.2 A horse pulls a cart forwards along a level road. Which force forms a Newton's third-law pair with the force of the horse on the cart? [1]

A	B
C	D

A the force of the road on the cart

B the force of the cart on the horse

C the weight of the cart

D the force of the road on the horse

3.3 Two forces act on an object of mass 2.5 kg: 6.0 N to the east and 8.0 N to the north. No other forces act. What is the magnitude of the acceleration of the object? [1]

A	B
C	D

A 0.80 m s⁻²

B 2.4 m s⁻²

C 4.0 m s⁻²

D 5.6 m s⁻²

3.4 A water jet pack lifts a rider above a lake. The total mass of the rider and the pack is 90 kg. Water that starts from rest leaves the pack vertically downwards at 20 m s^{-1} .

(a) **Explain** how sending water downwards gives an upward force on the pack. [2]

(b) The rider stays at the same height. Calculate the mass of water that leaves the pack each second. [2]

(c) The rider now accelerates upwards at 1.5 m s^{-2} , and the water still leaves at 20 m s^{-1} . Calculate the mass of water that must leave the pack each second. [2]

3.5 A car of mass 1100 kg tows a caravan of mass 900 kg along a straight, level road. The driving force on the car is 2600 N. The resistive force is 350 N on the car and 450 N on the caravan.

(a) State Newton's second law of motion. [1]

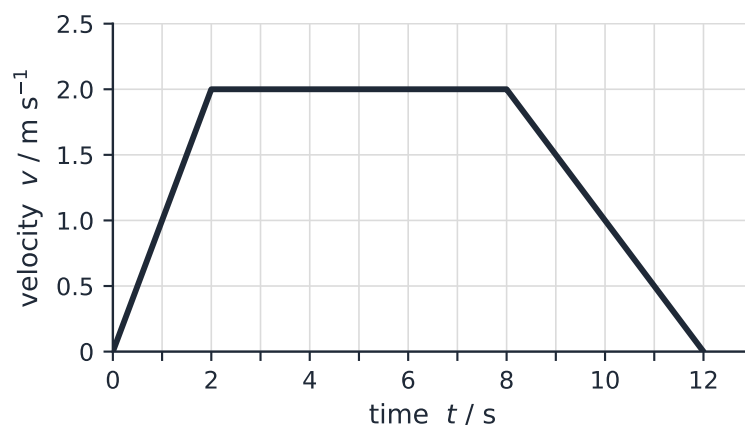
(b) Calculate the acceleration of the car and caravan. [2]

(c) **Show that** the force of the tow bar on the caravan is about 1300 N. [2]

(d) State the size and the direction of the force of the caravan on the tow bar, and name the law you used. [2]

(e) Later the car and caravan move at a constant speed, with the same resistive forces. State the driving force. [1]

3.6 A student of mass 55 kg stands on bathroom scales in a lift. The graph shows how the velocity of the lift changes as it moves upwards from rest.



(a) **Determine** the acceleration of the lift between $t = 0$ and $t = 2.0$ s. [1]

(b) Calculate the reading of the scales, in newtons:

(i) between $t = 0$ and $t = 2.0$ s [2]

(ii) between $t = 2.0$ s and $t = 8.0$ s [1]

(iii) between $t = 8.0$ s and $t = 12.0$ s. [2]

(c) **Explain**, using Newton's laws, why the reading between $t = 8.0$ s and $t = 12.0$ s is less than the weight of the student. [2]

Solutions

Each answer shows the steps, then the **result**.

2.1

(a) $m = W/g = 12 \text{ N}/4.0 \text{ N kg}^{-1} = \mathbf{3.0 \text{ kg}}$

(b) the mass does not change, so $W = mg = 3.0 \text{ kg} \times 9.81 \text{ N kg}^{-1} = \mathbf{29 \text{ N}}$

2.2

(a) $T_H = 50 \text{ N} \times \cos 25^\circ = \mathbf{45 \text{ N}}$

(b) resultant force $= 45.3 \text{ N} - 20 \text{ N} = 25.3 \text{ N}$, so $a = 25.3 \text{ N}/12 \text{ kg} = \mathbf{2.1 \text{ m s}^{-2}}$

2.3

(a) up positive: $T - mg = ma$

$$T = 800 \text{ kg} \times (9.81 + 0.60) \text{ m s}^{-2} = \mathbf{8330 \text{ N}}$$

(b) constant speed, so the resultant force is zero: $T = mg = 800 \text{ kg} \times 9.81 \text{ m s}^{-2} = \mathbf{7850 \text{ N}}$

2.4

(a) both blocks together: $a = \frac{18 \text{ N}}{(4.0 + 2.0) \text{ kg}} = \mathbf{3.0 \text{ m s}^{-2}}$

(b) the only horizontal force on B is the push of A: $F = 2.0 \text{ kg} \times 3.0 \text{ m s}^{-2} = \mathbf{6.0 \text{ N}}$

2.5

(a) $F = \frac{\Delta m}{\Delta t} \Delta v = 0.30 \text{ kg s}^{-1} \times 40 \text{ m s}^{-1} = \mathbf{12 \text{ N}}$

(b) **12 N**, **opposite** to the direction in which the air leaves the blower (Newton's third law)

3.1 C

- the lift slows down while it moves up, so its acceleration and the resultant force are **downwards**: $W > T$
- A** is a lift speeding up on the way up, **B** a lift at constant velocity, and **D** a lift in free fall

3.2 B

- swap the two objects: the horse pulls the cart, so the partner is the cart pulling the horse
- A**, **C** and **D** involve other objects or other types of force

3.3 C

- the forces are at right angles: resultant $= \sqrt{6.0^2 + 8.0^2} = 10 \text{ N}$, so $a = 10 \text{ N}/2.5 \text{ kg} = 4.0 \text{ m s}^{-2}$
- D** adds the forces as plain numbers, **B** uses only the 6.0 N force, and **A** subtracts them

3.4

(a) the pack pushes the water downwards, changing the momentum of the water

- by Newton's third law, the water pushes the pack **upwards** with an equal force

(b) at a steady height, upward force = weight = $90 \text{ kg} \times 9.81 \text{ m s}^{-2} = 883 \text{ N}$, so $\Delta m / \Delta t = 883 \text{ N} / 20 \text{ m s}^{-1} = \mathbf{44 \text{ kg s}^{-1}}$

(c) upward force = $m(g + a) = 90 \text{ kg} \times (9.81 + 1.5) \text{ m s}^{-2} = 1018 \text{ N}$, so $\Delta m / \Delta t = 1018 \text{ N} / 20 \text{ m s}^{-1} = \mathbf{51 \text{ kg s}^{-1}}$

3.5

(a) the resultant force on an object is equal to its **rate of change of momentum**

(b) resultant force = $2600 - 350 - 450 = 1800 \text{ N}$, so $a = 1800 \text{ N} / 2000 \text{ kg} = \mathbf{0.90 \text{ m s}^{-2}}$

(c) caravan on its own: $T - 450 \text{ N} = 900 \text{ kg} \times 0.90 \text{ m s}^{-2}$, so $T = 810 \text{ N} + 450 \text{ N} = \mathbf{1260 \text{ N} \approx 1300 \text{ N}}$

(d) 1260 N **backwards**

- Newton's **third** law

(e) the resultant force is zero, so the driving force = $350 + 450 = \mathbf{800 \text{ N}}$

3.6

(a) gradient of the graph: $a = \frac{2.0 \text{ m s}^{-1}}{2.0 \text{ s}} = \mathbf{1.0 \text{ m s}^{-2}}$

(b)(i) up positive: $R - mg = ma$

$$R = 55 \text{ kg} \times (9.81 + 1.0) \text{ m s}^{-2} = \mathbf{595 \text{ N}}$$

(ii) constant velocity: $R = mg = 55 \text{ kg} \times 9.81 \text{ m s}^{-2} = \mathbf{540 \text{ N}}$

(iii) $a = \frac{0 - 2.0 \text{ m s}^{-1}}{4.0 \text{ s}} = -0.50 \text{ m s}^{-2}$

$$R = 55 \text{ kg} \times (9.81 - 0.50) \text{ m s}^{-2} = \mathbf{512 \text{ N}}$$

(c) the lift slows down while it moves up, so the student's acceleration is **downwards**

- by the second law the resultant force on the student is downwards, so $W > R$ and the scales read less than the weight