

Forces

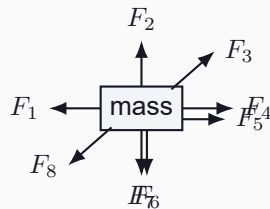
Chapter 04 / AS Level / Apollo Physics 9702



Newton's First Law and Equilibrium Examples

Newton's 1st Law of Motion

- a.k.a. **law of equilibrium**
- a.k.a. **law of inertia**

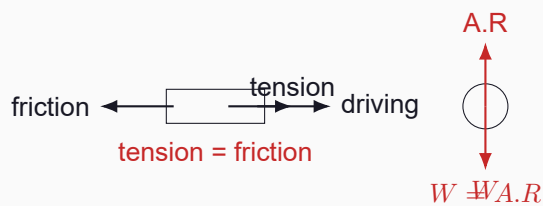


An object continues in a state of rest or uniform motion unless acted upon by a resultant force.

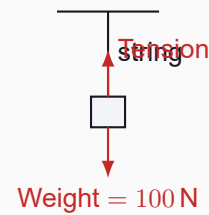
- **Rest:** speed = 0.
- **Uniform motion:** constant speed + straight line.

Keywords: rest, hanging, constant speed, terminal velocity.

$$\boxed{\sum F = 0} \quad \Rightarrow \quad \boxed{\sum F_x = 0}, \quad \boxed{\sum F_y = 0}$$



Example #1



Box is in equilibrium:

$$\boxed{\text{Tension} = \text{Weight} = 100 \text{ N}}$$

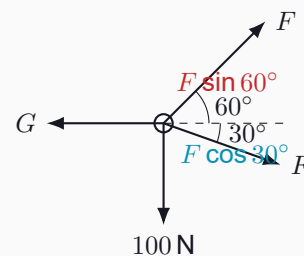
Tension force acts away from the point and towards the centre of the string.

Similarly, if a lift is moving upwards at **constant speed**,

$$\boxed{\text{Tension in rope} = \text{weight of man} + \text{lift} .}$$

Example #2

The ball is in equilibrium. Find F and G .



$$x\text{-axis: } F \cos 60^\circ + F \cos 30^\circ = G,$$

$$y\text{-axis: } F \sin 60^\circ - F \sin 30^\circ = 100.$$

$$F = \frac{100}{\sin 60^\circ - \sin 30^\circ} = 273.2 \approx \boxed{273 \text{ N}},$$

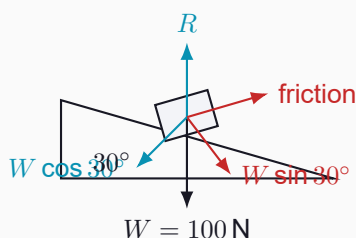
$$G = 273.2(\cos 60^\circ + \cos 30^\circ) = 373.2 \approx \boxed{373 \text{ N}}.$$

Inclined Plane and Newton's Second Law

Example #3

A box of weight 100 N rests on a rough inclined surface. Calculate:

- the friction force between box and surface,
- the normal contact force.



$$W \sin \theta = \text{friction}, \quad 100 \sin 30^\circ = \text{friction}$$

$$\boxed{\text{friction} = 50 \text{ N}}$$

$W \sin \theta$ is responsible to make the object slip down the plane.

$$R = W \cos \theta = 100 \cos 30^\circ = \boxed{86.6 \text{ N}}$$

- smooth surface: no friction;
- rough surface: friction exists.

Newton's 2nd Law of Motion

Rate of change of momentum is directly proportional to resultant force.

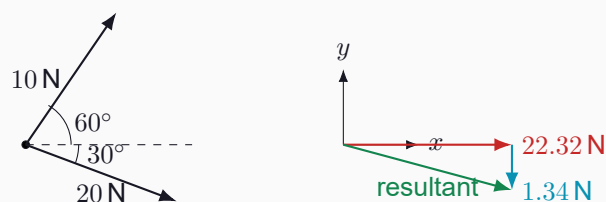
$$F_{\text{net}} \propto \frac{\Delta p}{\Delta t} \quad \Rightarrow \quad \boxed{F_{\text{net}} = ma}$$

$$\boxed{\text{forward force} - \text{backward force} = ma}$$

Keywords: speeding up, slowing down, accelerate, decelerate.

Example #1

Find the resultant of the two forces.



$$R_x = 10 \cos 60^\circ + 20 \cos 30^\circ = 22.32 \text{ N}$$

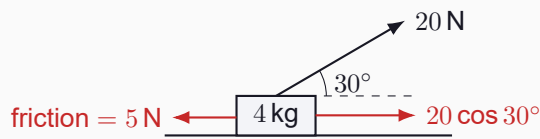
$$R_y = 10 \sin 60^\circ - 20 \sin 30^\circ = -1.34 \text{ N}$$

$$R = \sqrt{(1.34)^2 + (22.32)^2} = \boxed{22.36 \text{ N}}$$

Systems, Pulleys, and Tension

Example #2

A 4 kg block is pulled by 20 N at 30° and friction is 5 N. Find acceleration.



$$F_{\text{net}} = ma, \quad 20 \cos 30^\circ - 5 = 4a$$

$$a = 3.08 \approx 3.1 \text{ m s}^{-2}$$

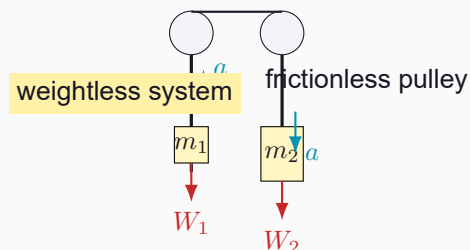
Example #3

A transport system contains a powered vehicle of mass 200 kg and four baggage carts, each of mass 400 kg. The system accelerates at 2.0 m s^{-2} . Find the tension between carts 1 and 2, ignoring friction on the carts.



$$F_{\text{net}} = ma, \quad T = (400 \times 3)(2) = \boxed{2400 \text{ N}}.$$

Example #4



For the acceleration of the system:

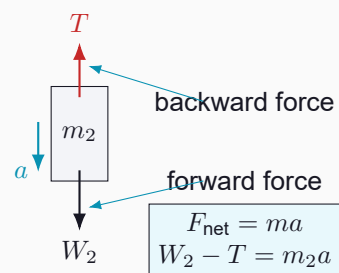
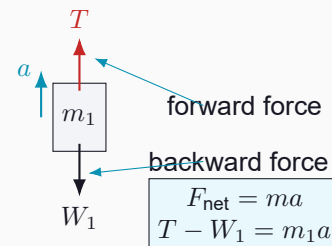
$$F_{\text{net}} = ma, \quad W_2 - W_1 = (m_2 + m_1)a.$$

$$W_2 - W_1 = m_2g - m_1g = (m_2 + m_1)a$$

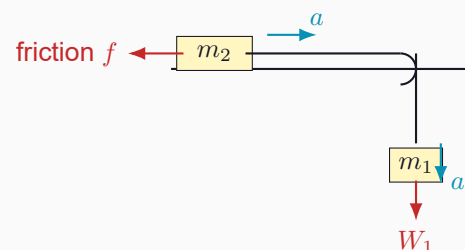
$$(m_2 - m_1)g = (m_2 + m_1)a$$

$$a = \frac{(m_2 - m_1)g}{m_2 + m_1}$$

For finding the tension in the string



Example #5



If $W_1 > f$, the system accelerates even if $m_2 > m_1$.

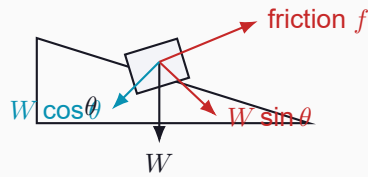
$$F_{\text{net}} = ma, \quad W_1 - f = (m_1 + m_2)a.$$

If friction = 0,

$$W_1 = (m_1 + m_2)a.$$

Inclined Planes and Newton's Third Law

Example #6



If the surface is smooth:

$$F_{\text{net}} = ma, \quad W \sin \theta = ma.$$

Since $W = mg$,

$$mg \sin \theta = ma \quad \Rightarrow \quad a = g \sin \theta.$$

For smooth surfaces, acceleration depends only on the angle of the ramp.

If the surface is rough:

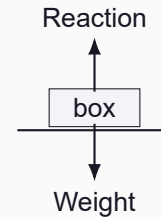
$$F_{\text{net}} = ma, \quad W \sin \theta - f = ma.$$

Newton's 3rd Law of Motion

If body A exerts a force on body B, B exerts the same force on A, equal in magnitude but opposite in direction.

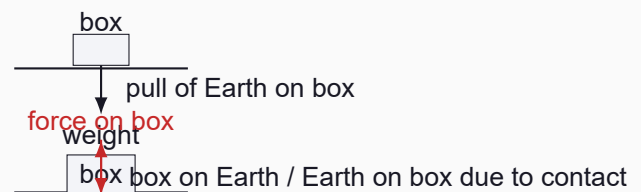
- Forces act on different bodies.
- Type of force is the same.
- Magnitude is equal.
- Direction is opposite.

Weight and reaction are not a third-law pair



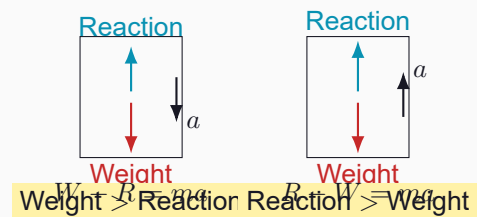
Both forces act on the box, so they are different types of forces and are not a Newton's 3rd-law pair.

Action–reaction pair



Lift examples

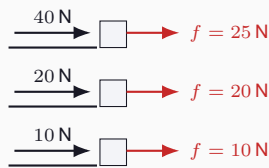
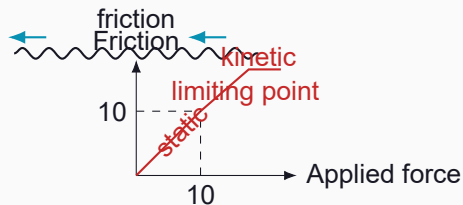
If a body is at rest or moving at constant speed, **weight = reaction**.



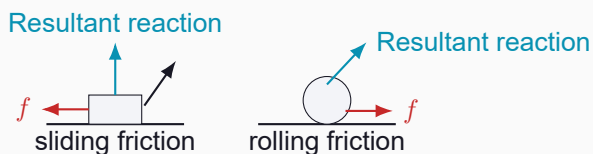
Friction, Mass, Inertia, and Drag Force

Friction Force

- It is a **resistive force** that tends to slow down moving objects.
- It is a **contact** and a **reaction force**.



Normal contact/resultant reaction:



Mass

It is the measurement of inertia.

More inertia $\Rightarrow$ More mass in the body.

Inertia is a property of matter such that it resists sudden changes in its state of rest or motion.

SI unit: kg Scalar

Drag Force

When an object moves in a fluid, it experiences a drag force.

- drag force $\rightarrow$ viscous drag
- air resistance
- viscous drag: water, oil, glycerine

Factors affecting drag force

1. Viscosity of fluid

more viscosity $\rightarrow$ thicker fluid $\rightarrow$ more drag force.

$$\text{drag force} \propto \text{viscosity}$$

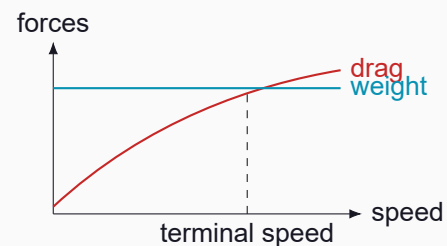
2. Surface area

greater surface area $\rightarrow$ more drag force. More molecules collide with the body, so cumulative force increases.

3. Speed of object

greater speed $\rightarrow$ greater drag force.

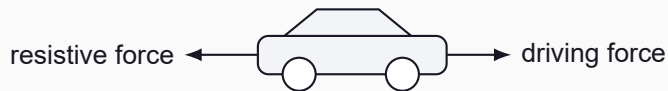
Air resistance increases on a falling body until the body reaches terminal velocity, when weight = air resistance.



Multiple Choice: Driving Force, Resistive Force, Terminal Speed

9702/01 May/June 2008 – Paper 1 Multiple Choice

11. A car of mass 750 kg has a horizontal driving force of 2.0 kN acting on it. It has a forward horizontal acceleration of 2.0 m s^{-2} . What is the resistive force acting horizontally?



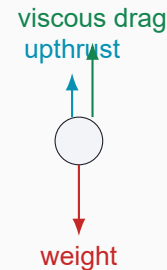
$$F_{\text{net}} = ma, \quad F_D - F_R = ma.$$

$$2000 - F_R = 750 \times 2, \quad 2000 - F_R = 1500, \quad F_R = 500 \text{ N}.$$

$$F_R = 0.5 \text{ kN}$$

Answer: A.

12. A ball is falling at terminal speed in still air. The forces on the ball are upthrust, viscous drag and weight. What is the order of increasing magnitude of these three forces?



At terminal speed, acceleration is zero, so

$$W = \text{upthrust} + \text{viscous drag}.$$

The upthrust is very small for a ball in air, and viscous drag is larger than upthrust but smaller than the total weight.

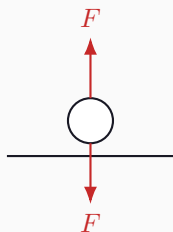
upthrust $\rightarrow$ viscous drag $\rightarrow$ weight

Answer: A.

Multiple Choice: Third Law and Pulley Acceleration

9702/01 October/November 2008 – Paper 1 Multiple Choice

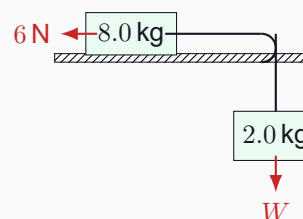
9. A ball falls vertically and bounces on the ground. Which statement about the forces acting while the ball is in contact with the ground is correct?



The force the ball exerts on the ground is always equal in magnitude and opposite in direction to the force the ground exerts on the ball.

Answer: B

11. A box of mass 8.0 kg rests on a horizontal rough surface. A string passes over a smooth pulley and supports a 2.0 kg mass. Friction on the box is 6.0 N. Find the acceleration of the box.



$$F_{\text{net}} = ma, \quad W - f = (m_1 + m_2)a.$$

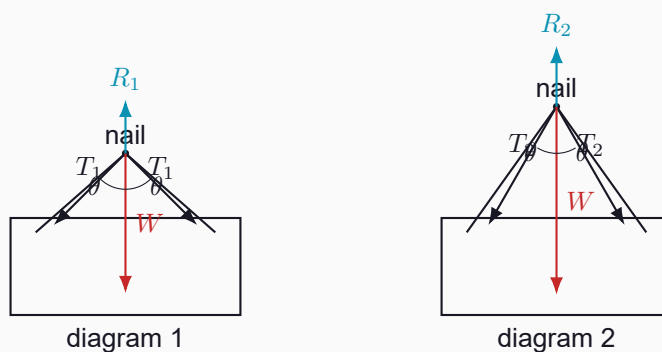
$$2(9.81) - 6 = (8 + 2)a, \quad a = 1.36 \text{ m s}^{-2} \approx \boxed{1.4 \text{ m s}^{-2}}.$$

Answer: A.

Multiple Choice: Hanging Picture Tension

9702/11 October/November 2009 – Paper 1 Multiple Choice

12. The diagrams show two ways of hanging the same picture. In both cases, a string is attached to the same points and looped symmetrically over a nail. Diagram 1 has the shorter loop. Forces shown are those that act on the nail.



For the nail, horizontal components cancel. The vertical components support the picture:

$$T \cos \theta + T \cos \theta = W$$

$$T = \frac{W}{2 \cos \theta}$$

A wider angle gives more tension. A smaller angle gives less tension.

In diagram 1 the string is shorter and the angle is wider, so

$$T_1 > T_2.$$

The vertical resultant on the nail equals the same weight in both cases:

$$R_1 = R_2.$$

$$R_1 = R_2, \quad T_1 > T_2$$

Answer: B.

Multiple Choice: Definition of Force and Pulley Motion

9702/11 May/June 2012 – Paper 1 Multiple Choice

10. Each option gives a correct word equation involving force. Which option gives the definition of force?

A. force = energy divided by displacement

B. force = mass $\times$ acceleration

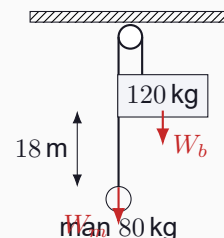
C. force = pressure $\times$ area

D. force = rate of change of momentum

Definition of force: rate of change of momentum

Answer: D.

12. A barrel of mass 120 kg hangs from a frictionless pulley. The rope is secured to a stake, and a man of mass 80 kg holds the rope after untying it. The bottom of the barrel is 18 m above the man's head. Find the man's upward speed when his head is level with the barrel. Take $g = 10 \text{ m s}^{-2}$.



For the system:

$$F_{\text{net}} = ma, \quad W_b - W_m = (120 + 80)a.$$

$$1200 - 800 = 200a \Rightarrow a = 2 \text{ m s}^{-2}.$$

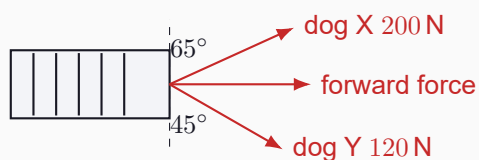
$$v^2 - u^2 = 2as, \quad v^2 = 2(2)(9), \quad v = \boxed{6 \text{ m s}^{-1}}.$$

Answer: A.

Multiple Choice: Resultant Components and Weight Graph

9702/11 May/June 2018 – Paper 1 Multiple Choice

3. Two dogs pull a sledge along an icy track. Dog X pulls with 200 N at 65° to the front edge. Dog Y pulls with 120 N at 45° .

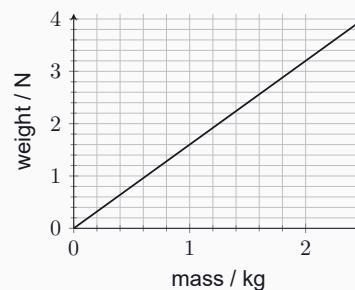


Forward component:

$$200 \sin 65^\circ + 120 \sin 45^\circ = 266.1 \approx \boxed{270 \text{ N}}.$$

Answer: C.

7. The graph shows the variation with mass of the weight of objects on a particular planet. What is the acceleration of free fall?



Since $W = mg$, gradient of the weight–mass graph equals g .

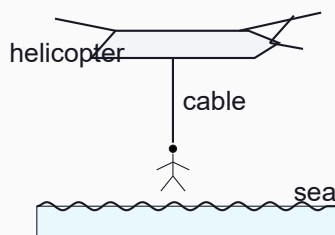
$$g = \frac{4}{2.5} = \boxed{1.6 \text{ ms}^{-2}}.$$

Answer: B.

Structured Question: Helicopter Cable Lift, Part 1

9702/23 May/June 2011 – Question 3

A helicopter has a cable hanging from it towards the sea below. A man of mass 80 kg rescues a child of mass 50.5 kg. The two are attached to the cable and are lifted from the sea to the helicopter. The lifting process consists of initial uniform acceleration, constant velocity, and final uniform deceleration.

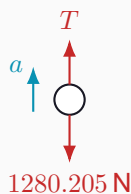


- (a) Calculate the combined weight of the man and child.

$$W = mg = (80 + 50.5)(9.81) = 1280.205 \text{ N} \approx \boxed{1300 \text{ N}}.$$

- (b) Calculate the tension in the cable during:

- (i) the initial acceleration of 0.570 m s^{-2} .



$$F_{\text{net}} = ma, \quad T - W = ma.$$

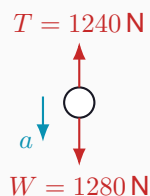
$$T - 1280.205 = 130.5(0.570), \quad T = 1354.6 \text{ N} \approx \boxed{1400 \text{ N}}.$$

- (ii) the period of constant velocity of 2.00 m s^{-1} .

$$F_{\text{net}} = 0 \Rightarrow T = W = 1280 \text{ N} \approx \boxed{1300 \text{ N}}.$$

Structured Question: Helicopter Cable Lift, Part 2

(c) During the final deceleration, the tension in the cable is 1240 N. Calculate the deceleration.



$$F_{\text{net}} = ma, \quad T - W = ma.$$

$$1240 - 1280 = 130.5a, \quad a = -0.31 \text{ m s}^{-2}.$$

The negative sign shows the acceleration is downward, so the **deceleration** is

$$\boxed{0.31 \text{ m s}^{-2}}.$$

(d) Calculate the time over which the man and child are:

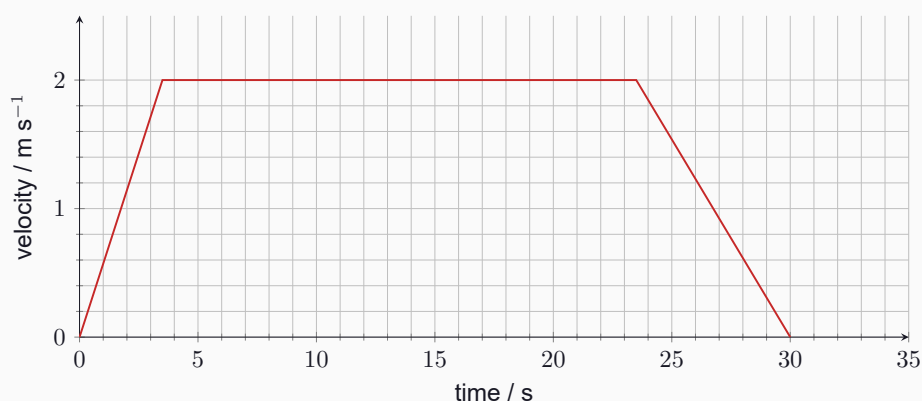
- moving with uniform acceleration from rest to 2.0 m s^{-1} ,

$$v = u + at, \quad 2 = 0 + 0.57t, \quad t = \boxed{3.5 \text{ s}}.$$

- moving with uniform deceleration from 2.0 m s^{-1} to rest,

$$0 = 2 + (-0.306)t, \quad t = \boxed{6.5 \text{ s}}.$$

The time at constant velocity is 20 s. Sketch the velocity–time graph for the complete lifting process.



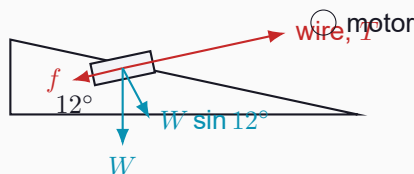
Structured Question: Log Pulled Up a Slope

9702/22 May/June 2012 – Question 3

- (a) State Newton's first law.

An object continues in a state of rest or uniform motion unless acted upon by a resultant force.

- (b) A log of mass 450 kg is pulled up a slope by a wire attached to a motor. The slope makes an angle of 12° with the horizontal. The frictional force acting on the log is 650 N. The log travels with constant velocity.



- (i) Discuss whether the log is in equilibrium.

Yes, it is in equilibrium because it is moving at constant velocity. Hence resultant force and acceleration are zero.

- (ii) Calculate the tension in the wire.

$$T = f + W \sin 12^\circ.$$

$$T = 650 + (450 \times 9.81) \sin 12^\circ = 1567.8 \text{ N} \approx \boxed{1600 \text{ N}}.$$

- (iii) Is the gain in potential energy per unit time equal to the output power of the motor?

No. The motor output must supply both the gain in gravitational potential energy and work done against friction. Hence motor output power is greater than the rate of gain of GPE.

Structured Question: Mass, Weight, and Rope Equilibrium

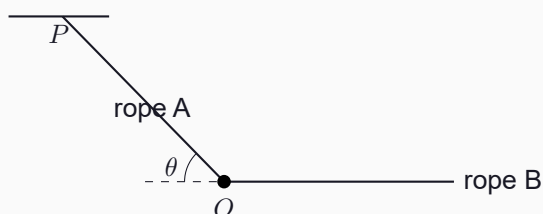
9702/21 May/June 2013 – Question 2

- (a) Distinguish between mass and weight.

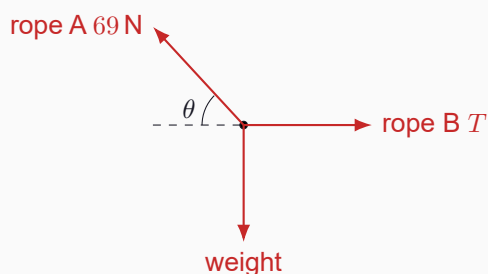
mass: measurement of inertia; scalar; SI unit kg.

weight: effect of gravitational force on a mass; vector; $W = mg$; SI unit N.

- (b) An object O of mass 4.9 kg is suspended by rope A fixed at point P . It is pulled to one side and held in equilibrium by a second rope B. Rope A is at angle θ to the horizontal, rope B is horizontal, tension in rope A is 69 N , and tension in rope B is T .



- (i) Draw arrows showing all forces on O .



- (ii) Calculate:

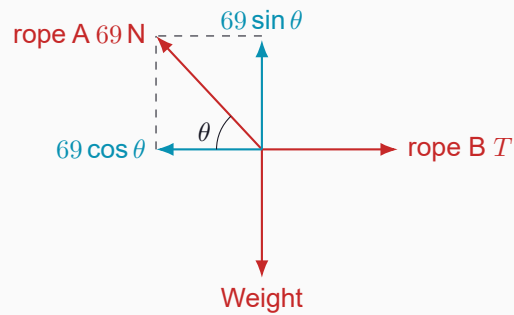
1. the angle θ .

$$W = mg = 4.9 \times 9.81 = 48.069\text{ N}.$$

$$69 \sin \theta = W, \quad \sin \theta = \frac{48.069}{69}, \quad \theta = \boxed{44.1^\circ \approx 44^\circ}.$$

Structured Question: Resolving Rope Forces

Continuing the rope equilibrium example:



1. Angle θ

Horizontal equilibrium gives:

$$W = mg = 4.9 \times 9.81 = 48.069 \text{ N}$$

$$69 \sin \theta = W$$

$$\sin \theta = \frac{48.069}{69}$$

$$\theta = 44.1^\circ \approx 44^\circ$$

$$69 \cos \theta = T.$$

$$T = 69 \cos 44.1^\circ = \boxed{49.5 \text{ N}}.$$

2. Tension T

Chapter 4 conversion note: All handwritten theory, worked examples, diagrams and exam-style questions from the Forces notes have been converted into live LaTeX text, equations, tables and TikZ/PGFPlots diagrams.