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CHAPTER 1 :DIMENSIONS

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By the end of this chapter, the student should be able to :

- define the term dimensions of a physical quantity.
- check for dimensional consistency of equations.
- use dimensional analysis to eliminate wrong equations from a set of given equations.
- use graphical methods to identify the correct equation out of the dimensionally consistent ones.
- use dimensional analysis to establish a relation between given quantities.
- solve problems involving dimensions

Physical quantities are divided into two groups:

(i) **Fundamental quantities.**

(ii) **Derived quantities.**

Fundamental quantities are those which can not be expressed in terms of any other quantities e.g mass (M), time (T), length (L) and temperature (q).

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Derived quantities are those which can be expressed in terms of the fundamental quantities of mass, length, and time.

Examples:

Area = $(\text{length})^2$, Volume =$(\text{length})^3$

velocity = $\frac{\text{length}}{\text{time}}$, Density = $\frac{\text{mass}}{(\text{length})^3}$,Force = mass x $\frac{\text{length}}{(\text{time})^2}$

Dimensions of a physical quantity show the way the physical quantity is related to the fundamental quantities of mass, length and time.

The symbol [ ], is read as dimensions.

[Force] = MLT^{-2} , [Density] = ML^{-3}

[Pressure] = [force/Area] = MLT^{-2}/L^2 = $M'L^{-1}T^{-2}$

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The term dimensions of a physical quantity, actually refer to the powers to which fundamental quantities are raised.

Example: The dimensions of pressure are 1 in mass, -1 in length and -2 in time.

N.B: Quantities like refractive index, strain, relative density and efficiency of a machine which possess no units are also dimensionless quantities.

Trigonometrical ratios, indices, logarithms and all pure numbers like p are also dimensionless.

Applications of method of dimensions

Dimensional analysis can be used:

(i) to check the validity of equations. Obviously wrong equations can be eliminated from a set of possible equations.

(ii) to deduce admissable relationships between the variables of a physical system (or derive equations).

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Checking the validity of equations

In a correct equation, the units on the left hand side (L.H.S) must balance with the units on the right hand side (R.H.S). Likewise the [L.H.S] = [R.H.S] in a correct equation. All correct equations must be dimensionally consistent.

N.B: All correct equations must be dimensionally consistent but not all dimensionally consistent equations are correct.

Dimensional consistency therefore can be used to eliminate the wrong equations but cannot be used to prove the correctness of an equation.

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Example:

A student in S.5 recalls the following equations of motion.

1. $v = u + at^2$ 3. $v^2 = u^2 + 2as$

2. $s = ut + ½ at^2$ 4. $s = ut + 2at^2$

where **v** is final velocity, **u** is initial velocity, **a** is acceleration, **s** is distance and **t** is time.

Check the dimensional consistency of the above equations and comment on your answers.

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Consider eq.(1)

$\mathbf{v = u + at^2}$

[R.H.S] = [u] + [at^2] = LT^{-1} + (LT^{-2} x T^2) = LT^{-1} + L

[L.H.S] = [v] = LT^{-1}

[R.H.S] ^{1} [L.H.S] \ equation (1) is obviously wrong.

Consider equation (2)

$\mathbf{s = ut + ½ at^2}$

[L.H.S] = [s] = L

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$[R.H.S] = [ut] + [at^2] = (LT^{-1} \times T) + (LT^{-2} \times T^2) = L + L = L$

[R.H.S] = [L.H.S] \ equation (2) is possibly correct.

Consider equation (3)

$\mathbf{v^2 = u^2 + 2as}$

$[L.H.S] = [v^2] = (LT^{-1})^2 = L^2 T^{-2}$

$[R.H.S] = [u^2] + [as] = L^2 T^{-2} + L^2 T^{-2} = L^2 T^{-2}$

[R.H.S] = [L.H.S] \ equation (3) is possibly correct.

Consider equation (4)

$\mathbf{s = ut + 2at^2}$

$[L.H.S] = [s] = L$

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$[R.H.S] = [ut] + [at^2] = LT^{-1}\,T + LT^{-2}\,T^2 = L$

[R.H.S] = [L.H.S] \ equation (4) is possibly correct.

The student should note:

1. Equation (2) and equation (3) are dimensionally consistent and correct.

2. Equation (4) is dimensionally consistent but wrong. Dimensional consistency does not prove the correctness of an equation.

3. The check for the consistency of dimensions does not provide any information about the correctness of numerical factors like the ½ in equation (2) or in equation (4).

Checking for correctness of an equation:

After eliminating the obviously wrong equations,the correct equation can then be obtained from the remaining equation by a graphical method.

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Example 1:

The velocity of propagation, c, of ripples on the surface of a liquid is given by **one** of the following equations.

1. $c^2 = Arl/g$

2. $c = Arlg^2$

3. $c^2 = Ag/rl$

4. $c = Arg/l$

where **A** is a dimensionless constant, **g**is the surface tension of the liquid, **r** is its density and **l** is the wavelength of the ripples.

(i) Use the method of dimensions to determine which equation is correct.

(ii) By a graphical method, use the following figures for water to confirm your choice, and to determine the value of A

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c (ms^{-1})	0.67	0.45	0.36	0.27
l x 10^{-3} (m)	1.0	2.2	3.5	6.1

(coefficient of surface tension of water = 7.2 x 10^{-2} Nm^{-1} and density of water = 10^3 kg/m^3)

SOLUTION

$[c] = LT^{-1}$, $[r] = ML^{-3}$,$[l] = L$, g = force per unit length.

$[g] = [force]/[length] = MLT^{-2}/L = MT^{-2}$

Consider equation (1) $c^2 = Arl/g$

$[L.H.S] = [c^2] = (LT^{-1})^2 = L^2 T^{-2}$

$[R.H.S] = [rl/g] = ML^{-3}L = L^{-2} T^2$

[L.H.S] ^{1} [R.H.S] \ equation (1) is wrong.

Consider equation (2) $c = Arlg^2$

[L.H.S] = $[c] = LT^{-1}$

[R.H.S] = $[rlg^2] = ML^{-3}LM^2T^{-4} = M^3L^{-2}T^{-4}$

[L.H.S] ^{1} [R.H.S].

\ equation (2) is wrong.

Consider equation (3) $c^2 = Ag/rl$

[L.H.S] = $[c^2] = L^2\ T^{-2}$

[R.H.S] = $[\ g/rl] = MT^{-2}/ML^{-3}L = L^2\ T^{-2}$

Equation (3) is dimensionally consistent.

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Consider equation (4) c = Arg/l

$[L.H.S] = [c] = LT^{-1}$

$[R.H.S] = [\, rg/l \,] = (ML^{-3}MT^{-2})/L = M^{2}L^{-4}\, T^{-2}$

Equation (4) is dimensionally inconsistent and therefore wrong.

Note: Since equation (3) is the only one which is dimensionally

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consistent, it is the correct one.

(ii) **Using equation (3) c^2 = Ag/rl**

c^2 = (Ag/r)1/l of the form y = mx

A graph of **c^2** against 1/l should be linear with a slope **s** = Ag/r

c (ms^{-1})	**0.67**	**0.45**	**0.36**	**0.27**
c^2(m^2s^{-2})	**0.45**	**0.20**	**0.13**	**0.07**
l x 10^{-3}(m)	**1.0**	**2.2**	**3.5**	**6.1**
1/l x10^2(m^{-1})	**10.0**	**4.55**	**2.86**	**1.64**

(The student should plot a graph of c^2 against 1/l)

The graph is linear, which confirms the choice of equation (3).

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Slope s = 44×10^{-5} m^3s^{-2}

Using A = sr/g = $(44 \times 10^{-5} \times 10^{3})/(7.2 \times 10^{-2}) = 6.1$

N.B: It is possible for more than one equation to be dimensionally consistent. Graphical methods can then be used to identify the correct equation out of all the possible equations.(see example 2 below.)

Example 2:

In an attempt to describe the variation of pressure P with velocity v in the streamline flow of a non- viscous incompressible fluid, along a horizontal pipe, a student formulated the following equations:

1. P + Ag rv = X

2. P + Brv^2 = Y

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3. $P + cggv^{-2} = Z$

In which A, B and C are dimensionless constants. X, Y and Z are constants with the dimensions of pressure, g is the acceleration due to gravity, r is the density of the liquid, g is the coefficient of surface tension of the liquid.

(i) Which of the equations are dimensionally consistent?

(ii) The following results were obtained in an experiment in which P and v were measured for water flowing along a pipe of varying area of cross-section.

$P \times 10^3$ Nm^{-2}	2.0	1.5	1.2	0.7	0.3
v (ms^{-1})	1.0	1.4	1.6	1.9	2.1

Use these results to distinguish which of the above equations is correct and find the value of the constants in the equation.

(Density of water = 1.0×10^3 kg m^{-3}, coefficient of surface tension of water = 7.4×10^{-2} Nm^{-1})

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SOLUTION

$[P] = ML^{-1} T^{-2} = [X] = [Y] = [Z]$

$[g] = LT^{-2}$, $[r] = ML^{-3}$, $[v] = LT^{-1}$

Consider the dimensional consistency of each equation.

1. $P + Agrv = X$

$P - X = - Agrv$

$[L.H.S] = [(P - X)] = ML^{-1}T^{-2}$

$[R.H.S] = LT^{-2} \times ML^{-3} \times LT^{-1} = ML^{-1} T^{-3}$

\ [L.H.S] ¹ [R.H.S]. Hence equation (1) is dimensionally inconsistent and is therefore wrong.

2. $P + Brv^2 = Y$

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$$P - Y = Brv^2$$

$$[L.H.S] = [(P - Y)] = ML^{-1}\, T^{-2}$$

$$[R.H.S] = [rv^2\,] = ML^{-3} \times L^2\, T^{-2} = ML^{-1}\, T^{-2}$$

[L.H.S] = [L.H.S]. \ equation (2) is dimensionally consistent and is possibly correct.

3. $P + Cgv^{-2} = Z$

$$P - Z = - Cggv^{-2}$$

$$[L.H.S] = [P - Z] = ML^{-1}\, T^{-2}$$

$$[R.H.S] = MT^{-2} \times LT^{-2} \times L^{-2}\, T^2 = ML^{-1}\, T^{-2}$$

\ equation (3) is dimensionally consistent and is possibly correct.

Either equation (2) or equation (3) is correct since both are dimensionally consistent. The correct equation can be identified by

a graphical method.

Suppose equation (2) is the correct one, then

$P + Brv^2 = Y$

$P = - Brv^2 + Y$ is of the form $y = mx + c$ where y º P, m º - Br and c º Y

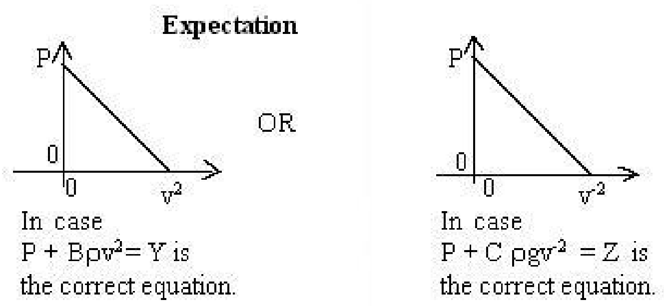
A graph of P against v^2 should be a straight line with a P - intercept = Y and a gradient = -Br

Suppose equation (3) is the correct one, then

$P + Cggv^{-2} = Z$

$P = - (Cgg)\ 1/v^2 + Z$ of the form $y = mx + c$

A graph of P against v^{-2} should be a straight line of gradient = - Cgg and with a P - intercept = Z.



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The student should draw the two graphs viz. a graph of P against v2 and a graph of

P against v-2 using the values in the table below.

P x 10^3 Nm^{-2}	**2.0**	**1.5**	**1.2**	**0.7**	**0.3**
v ms^{-1}	**1.0**	**1.4**	**1.6**	**1.9**	**2.1**
$v^2 m^2 s^{-2}$	**1.00**	**1.96**	**2.56**	**3.61**	**4.41**
$(1/v^2) m^{-2} s^2$	**1.00**	**0.50**	**0.39**	**0.28**	**0.23**

Results:

A plot of the experimental values of P against v^{-2} yields a curve contrary to what is predicted by equation (3). Therefore equation (3) is wrong.

A plot of P against v^2 yields a straight line with a negative gradient as predicted by equation (2). Therefore P + Brv^2 = Y is the correct equation.

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Gradient of the graph = - 2.48 x 10^3 /5.0 = - Br

Given r = 10^3 kgm^{-3}

B = (0.5 x 10^3)/10^3 = 0.5

when v^2 = 0, P = Y, the intercept on the P - axis.

Y = 2.48 x10^3 Nm^{-2}

Deducing relationships between variables of a physical system:

The first step is to specify the various factors involved. The unknown functional relationship is then determined by the method of dimensional analysis, except for the dimensionless constants.

Illustrations of the application of method of dimensional analysis.

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(a) It is required to obtain an expression for the period T, of oscillation of a simple pendulum.

We can reasonably assume that the period T will depend on: the length L of the string, the mass m of the bob and the acceleration g due to gravity.

The relation between T and these variables can be expressed as

$T = kL^{x} m^{y} g^{z}$ where x, y and z are numbers and k is a dimensionless constant.

This assumes that each quantity enters a definite power in the function.

Balancing the dimensions of both sides of the function.

$$T = [L]^{x} [M]^{y} [LT^{-2}]^{z}$$

$$M^{0} L^{0} T^{-1} = L^{x+z} M^{y} T^{-2z}$$

Hence, equating the indices for M,L,T separately on both sides of

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the equation.

M: 0 = y ; L: 0 = x +z ; T : -1 = -2z

Solving y = 0 ; x = - ½ ; z = - ½

y = 0 means that the period T does not depend on the mass m as earlier assumed.

$T = kL^{½} g^{-½} = k$ Ö(L/g)

Note: k can not be obtained by dimensional analysis since it is dimensionless. The value of k can be found by experiment or from a detailed mechanical solution of the problem.

Experimental determination of the value of k.

Using T = k Ö(L/g)

$T^2 = (k^2/g)L$ of the form y = mx.

A graph of T^2 against L is linear with a slope $s = k^2/g$

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$k = (sg)^{1/2}$

In the experiment, the length L of the simple pendulum is varied and the time for (say) 10 oscillations is obtained in each case, and the period T calculated. A graph of T^2 against L is plotted and k is obtained.

The following set of data is obtained for different lengths L of a simple pendulum.

length L(m)	0.20	0.40	0.60	0.80	1.00
Period T (s)	1.00	1.34	1.61	1.84	2.03

Plot a graph of T^2 against L and use it to determine the value of k.

(use $g = 9.8 m/s^2$)

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length	Period	$(Period)^2$
L (m)	T (s)	T^2 (s^2)
0.20	1.00	1.00
0.40	1.34	1.80
0.60	1.61	2.59
0.80	1.84	3.39
1.00	2.03	4.12

(The student should plot a graph of T^2 against L and determine its slope s)

Slope s = 4.0 s^2m^{-1}

k = (sg)½ = 6.26 (note k is about 2p)

k = 2p

T = 2pÖ (L/g)

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Problem: A simple pendulum was suspended from the ceiling of a laboratory. The following readings for the period of oscillations T of the pendulum were obtained for various lengths of the pendulum. The length was not measured directly, but the height x of the bob above the floor was recorded.

x (cm)	10	40	80	120	160
Period T(s)	3.38	3.20	2.95	2.66	2.34

By a graphical method, find the value of the acceleration due to gravity and the height of the laboratory.

Hint: L = (H - x) where H is the height of the laboratory.

(Answers: g = 9.86 ms^{-2}, H = 2.95m)

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1.(a)(i) Explain the meaning of dimensions of a physical quantity.

(ii) The velocity v of waves of wavelength l, on the surface on the pool of liquid, whose surface tension g and density r respectively is given by

v^2 = lg/2p + 2pg/lr where g is the acceleration due to gravity.

Show that the above equation is dimensionally correct.

(iii) A sphere of radius, a, moving through a density r with high velocity v experiences a retarding force F given by

F = k a^x r^y v^z where k is a non-dimensional coefficient.

Use the method of dimensions to find the values of x, y and z.

(b)(i) Define coefficient of viscocity h and obtain its dimensons.

(ii) The viscous drag F on a solid sphere moving through a viscous medium may be considered to depend on the velocity v of the sphere, its radius r and the coefficient of viscocity h of the medium.

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$F = k\ v^a\ r^b\ h^c$ where a, b and c are numbers and k is a numerical constant.

Use dimensional analysis to solve for a, b and c.

2.(a) Assuming conditions of streamline flow, the volume rate of flow (V/t) of a liquid issuing from the tube will depend on the pressure gradient (P/L) along the tube, the radius r of the tube and the coefficient of viscocity h of the liquid.

Show that $(V/t) = kP\ r^4/(hL)$ where k is some numerical constant.

(b) The characteristic of wave motion in deep water is such that

$$v = \left[\frac{l}{2p} \left(A + (4p^2 g)/l^2 r \right) \right]^x$$

where A is a constant which has dimensions, v is the velocity of the wave, l is its wavelength.

g is the surface tension and r is the density.

Using a method of dimensions, obtain a value for x and obtain the

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(c) Use dimensional analysis to show how the velocity of transverse vibrations of a stretched string depend on its length (L), mass (m) and the tensional force (F) in the string.

Answers:

1. (a)(ii) x = 2, y = 1, z = 2 (b)(ii) a = 1, b = 1, c = 1

2. (b) x = ½, [A] = LT^{-2} (c) v = k Ö (FL)/m

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CHAPTER 2: LINEAR MOTION

Assessment objectives

By the end of chapter 2, the student should be able to:

- Derive from the definitions of velocity and acceleration,

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equations which represent uniformly accelerated motion in a straight line.

- Use equations of motion.
- State each of Newton's laws of motion.
- Draw force-diagrams and use them to obtain the acceleration.
- Use Newton's laws of motion in solving problems of linear motion
- State the principle of conservation of mechanical energy.
- Give examples illustrating the principle of conservation of mechanical energy.
- Apply the principle of conservation of mechanical energy in solving problems.
- State the laws of solid friction (both static and kinetic friction).
- Describe simple experiments to determine coefficients of static and kinetic friction between two solid surfaces.
- Apply the laws of solid friction in solving problems involving motion on rough surfaces.

Linear motion deals with motion of bodies moving in a straight line.

Problems in this section involve the use of :-

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1. Equations of motion.
2. Newton's laws of motion.
3. Principle of conservation of mechanical energy.
4. Laws of solid friction.

Equations of motion for uniformly accelerated rectilinear motion

The following symbols are used in this textbook:

t = time, v = final velocity, u = initial velocity

s = distance and a = acceleration.

(i) Relation between **v, u, a** and **t** .

a = (v - u)/t

v = u + at ---------------------- (1)

(ii) Relation between **s, u, t** and **a**.

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Average velocity = s/t = (v + u)/2

$s = ½(v + u)\,t$ but $v = u + at$

$s = ½(u + at + u)t$

$s = ut + ½\,at^2$ ----------------- (2)

(iii) Relation between **s, v, u** and **a**.

Combining equation (1) and equation (2)

$s = u\,(v - u)/a + ½\,a(v - u)^2/a$

$2as = 2u\,(v - u) + (v - u)^2$

$2as = v^2 - u^2$

$v^2 = u^2 + 2as$ ------------------- (3)

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NEWTON'S LAWS OF MOTION

Law 1: A body in its state of rest or moving in a straight line continues to do so unless acted on by an external force.

This inherent reluctance of matter to any change of motion is called **inertia** and **law 1** may be referred to as the "**Principle of inertia**". The inertia of a body increases with mass.

The effects of inertia can be observed by passengers in a bus. There is a forward jerk when the vehicle stops (the motion of the passengers tending to persist), and a backward jerk when the vehicle re-starts (the passengers tending to remain stationary).

Law 2: The rate of change of momentum of a body is proportional to the resultant force on the body and takes

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place in the direction of the force.

Momentum is the product of mass and velocity of a moving body.

Force = (change in momentum)/time

F = (mv - mu)/t = m(v - u)/t = ma.

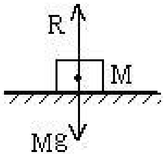
F = ma

N.B: F is resultant force obtained by identifying forces acting on the system and finding the net force in the direction of motion.

Law 3: Action and reaction are equal but opposite.

Some illustrations of identification of forces and the application of Newton's laws of motion.

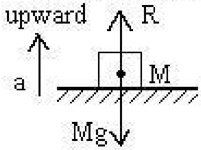
(i) Body of mass **M** placed on either a stationary platform or a platform moving at constant speed.



Due to the pull of gravity, the body exerts a force **Mg** on the platform. The platform exerts an equal but opposite force.

Reaction **R = Mg**.

(ii) Body of mass **M** placed on a platform having an upward acceleration, **a**.



The body exerts a force **Mg** on the platform. The platform exerts an equal but opposite force on the body. In addition the platform exerts a force **Ma** in order to accelerate the mass upwards.

Total force exerted by the platform = Reaction **R = M(g + a)**

N.B: An upward acceleration has the same effect as a downward retardation.

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(iii) Body of mass **M** placed on a platform having a downward acceleration **a**

The platform can not accelerate the body downwards. The body has to use part of its weight to accelerate itself.
The body exerts a force **M(g -a)** on the platform. The platform exerts the same force.

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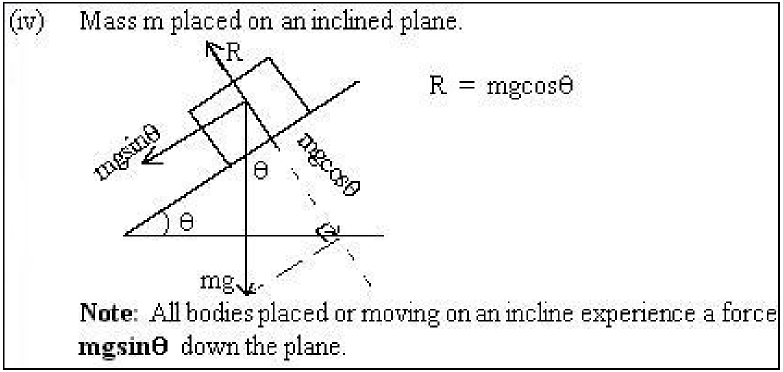
Reaction **R = M(g - a)**

NB: A downward acceleration has the same effect as an upward retardation.

(iv) Mass m placed on an inclined plane.



Note: All bodies placed or moving on an incline experience a force **mgsinθ** down the plane.

(v) Connected bodies ($m_1 > m_2$)

NB: connected bodies move with a common acceleration.

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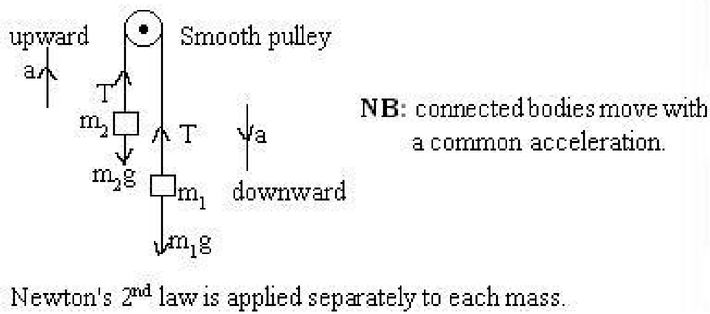
(v) Connected bodies ($m_1 > m_2$)



Newton's 2nd law is applied separately to each mass.

For mass m_2: Net upward force = $T - m_2g = m_2a$.

$m_2a = T - m_2g$ ---------------------- (1)

For mass m_1 : Net downward force = $m_1g - T = m_1a$

$m_1a = m_1g - T$ ---------------(2)

Eq(1) + Eq(2)

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

$a = (m_1 - m_2)g \;/\; (m_1 + m_2)$

WORKED EXAMPLES

1(a) A body of mass 30 kg lies on a smooth table at a distance of 10 m from the edge of the table.
The mass is connected to another of mass 10 kg by a light inelastic string passing over a small
smooth pulley at the edge of the table.
Find:

(i) the acceration of the system
(ii) the tension in the string
(iii) the time taken for the 30 kg mass to reach the edge of the table.

(b) P is a smooth fixed pulley , over which passes a light inextensible string. Each end of the string supports a scale pan of mass m kg. One scale pan contains a particle of mass m_1 kg, the other contains a particle of mass m_2 kg.

Given $m_1 > m_2$.

(i) Determine an expression for the magnitude of the acceleration of the scale pan and its contents.

(ii) Show that the reaction R_1 of the scale pan on the particle of mass m_1 kg is given by

$R = 2m_1 (m + m_2)g/ (2m + m_1 + m_2)$

(c) Sand is deposited at a uniform rate of 20 kgs^{-1} and with negligible kinetic energy onto an empty conveyor belt moving horizontally at a constant speed of 10 m per minute. Find

(i) the force required to maintain the constant velocity.

(ii) the power required to maintain the constant velocity.

(iii) the rate of change kinetic energy of the moving sand. Why are the latter two quantities unequal.

2(a)(i) State Newton's law of motion.

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(ii) A man of mass 80 kg stands on a platform of mass 40 kg. He pulls a rope that is fastened to the platform and runs over a pulley on the ceiling. With what force does he have to pull in order to give himself and the platform an upward acceleration of $1ms^{-2}$?

b(i) Water leaves a hose at a rate of 5.0 kgs^{-1} with a speed of 20m/s and is directed horizontally on a vertical wall which stops it.

Calculate the force exerted by the water on the wall.

(ii) Rain is falling vertically at 8.0 ms^{-1} relative to the ground. The rain drops make tracks on the side window of a car at an angle of 30° below the horizontal.

Calculate the speed of the car.

c(i) State the work-energy theorem.

(ii) The fig. below shows three forces acting on a particle P of mass

5 kg initially at rest.

Determine the magnitude and direction of the of resultant force on the particle and its kinetic energy after moving 10 m.

(d) A rectangular block of mass 10.0 kg is pulled from rest along a smooth inclined plane by a light inelastic string which passes over a light frictionless pulley P, and carries a mass of 20.0 kg as shown in the figure below.

The inclined plane makes an angle of 30^0 with the horizontal.

Determine

(i) the acceleration of the block.

(ii) the tension T, in the string.

(iii) the kinetic energy of the 10 kg block when it has moved a distance of 2 m along the inclined plane.

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